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Exploring Intercropping in Market Gardening

A story of combinations

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LIST OF ACRONYMS

AES – Agricultural experiment station

CEC – Cation exchange capacity

IC – Intercropping

iPAR – intercepted photosynthetically active radiation

LER – Land equivalent ratio

PAR – Photosynthetically active radiation

PC – Pure crop

PCA – Principal component analysis

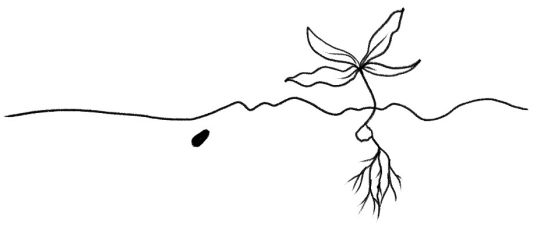
RUE – Radiation use efficiency

RUE_{fw} – Radiation use efficiency based on fresh weight

VOC – Volatile organic compound

YR – Yield ratio

Chapter 1 |
General introduction



CHAPTER 1 | GENERAL INTRODUCTION

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1.1. AN INTRODUCTION TO INTERCROPPING

1.1.1. DEFINITION, INTEREST AND CHALLENGES OF INTERCROPPING

Intercropping consists in growing two or more distinct crops on the same plot at the same time (Coll et al., 2012; Hauggaard-Nielsen & Jensen, 2005; Malézieux et al., 2009; Mead, 1979; Willey, 1990). It draws its inspiration from two main characteristics of natural ecosystems. Firstly, a natural ecosystem supports the growth of different species. Thanks to their morphological and physiological differences, two distinct species do not occupy the same niche in the environment and therefore, do not compete fully for the resources they need (Hooper & Dukes, 2004; Vandermeer et al., 1998). Secondly, in a natural ecosystem, the diversity of species creates some redundancy, i.e. each function of the ecosystem is supported by more than one species (Loreau et al., 2001; Vandermeer et al., 1998; Walker, 1995). This redundancy is key to the ecosystem stability: when a perturbation arises, each species will react in a different way according to its own characteristics and the diversity of reactions buffers the impact of the perturbation and maintains the ecosystem functioning (Vandermeer et al., 1998; Walker, 1995).

The main assumption behind the concept of intercropping is based on these two observations and states that, thanks to the physiological and architectural differences that exist between crops, the interspecific competition for resources – light, water and nutrients for the plants – should be lower than the intraspecific one. This is the concept of "complementarity": as two different crops do not develop at the same pace and will not have the same root and shoot architectures, they will not take the resources they need from the same place (Fridley, 2001; Trenbath, 1976) – i.e. spatial complementarity –, at the same moment (Fridley, 2001; Trenbath, 1976; Yu et al., 2015) – i.e. temporal complementarity – and/or in the same form (Fridley, 2001; Tofinga et al., 1993; Trenbath, 1976) – i.e. nutritive complementarity –.

Intercropping can be implemented in many ways (Figure 1), which can be differentiated based on (i) the types of plants – either a mix between two marketable crops or a mix between a marketable crop and a service plant –, (ii) the longevity of the plants – either a mix between two annual crops (e.g. a wheat + soybean intercrop), between one annual crop and one perennial crop (e.g. agroforestry) or between two perennial crops (e.g. grassland) –,

(iii) the temporal organisation of the intercrop – the crops spend a significant proportion of their growth cycle together or the second crop is sown after the flowering of the first crop and the crops only spend a small proportion of their growth cycle together (i.e. relay intercropping) –, (iv) the spatial organisation of the intercrop – either in rows (i.e. each species is sown in a row and the rows of the different species are alternated), in strips or patches (i.e. each species is sown in strips or patches consisting of several rows and the patches/strips of the different species are alternated) or completely mixed (i.e. the seeds of the different species are mixed and sown with no clear organisation – and (v) the density of each crop – either the density of the intercrop is higher than the density of the pure crop of the main species (i.e. additive intercrop) or the density of the intercrop is equal to the density of the pure crop of the main species, each species accounting for a certain proportion of this total density (i.e. replacement intercrop) – (Jodha, 1980; Malézieux et al., 2009; Snaydon, 1991).

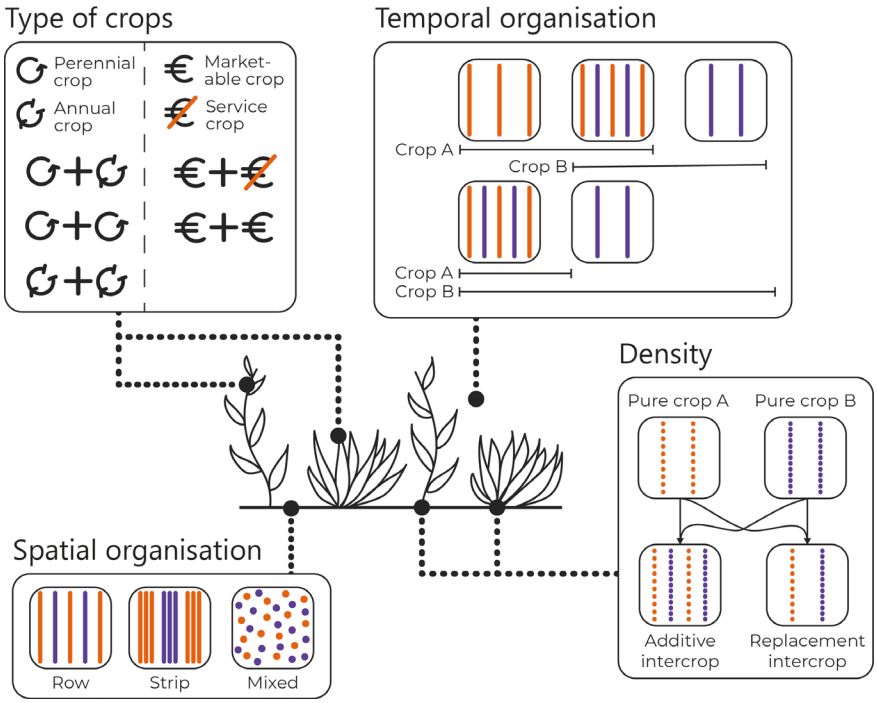


Figure 1 - Characteristics and types of intercrops. Intercrops are differentiated based on (i) the types of the crops used, i.e. either with or without market value, annual or perennial, (ii) their temporal organisation, i.e. the percentage of its growth cycle that each crop spends in intercropping, (iii) their spatial organisation, in rows, strips or mixed and (iv) their density, the two major systems being the additive intercrop, in which the crops are at the same density than in pure crop, and the replacement intercrop, in which a certain proportion of a crop is replaced by the same proportion of another crop.

From the differences and the complementarity and the facilitation relationships, i.e. processes through which one crop exerts a positive effect on another one (Callaway, 1995; Vandermeer, 1995), between companion crops emerge some properties of the intercrop system. Examples of such properties are the ability to draw resources from a larger pool than pure crops by exploiting more entirely the environment or the increase in the resilience of the system compared to pure crops thanks to differences in sensitivities to biotic and abiotic stresses between crops (Hauggaard-Nielsen & Jensen, 2005; Malézieux et al., 2009). These emergent properties, i.e. resulting from the differences and interactions between associated crops, can then provide greater benefits to the farmer, the consumer and the environment than the corresponding pure crops, e.g. higher yield (e.g. Rao & Willey, 1980; Reddy & Willey, 1981; Thole, 2012; Zhang & Li, 2003), reduction of the impact of pests and diseases (Hauggaard-Nielsen & Jensen, 2005; Lin, 2011; Malézieux et al., 2009; Okigbo & Greenland, 1976; Tofinga et al., 1993; Trenbath, 1974), preservation of the soil (Coll et al., 2012; Malézieux et al., 2009; Willey, 1990), improvement of product quality (Lin, 2011; Malézieux et al., 2009), etc., which will be describe further in a subsequent chapter (cf. Chapter 2). With all these effects, intercropping could play a role in the transition towards more sustainable food systems and is therefore relevant for study.

However, several reasons pushed farmers into choosing pure crop cultivation over intercropping. Firstly, Intercropping is difficult to handle because it involves managing the sometimes conflicting demands of two crops at the same time. This requires a high level of skill and knowledge on the part of the farmer and the need to make compromises (de Liedekerke de Pailhe, 2014; Malézieux et al., 2009; Morel et al., 2020; Theunissen, 1997a; Trenbath, 1999). Secondly, in other systems than strip intercropping, the use of mechanisation may be difficult or impossible (Anil et al., 1998; Lithourgidis, Dordas, et al., 2011; Singh et al., 2013). Some tasks that are mechanised in pure crop may therefore have to be done by hand in intercropping, thereby increasing the workload (Gebru, 2015; Malézieux et al., 2009). If labour is expensive and/or if the increase in yield is not high enough, intercropping may lead to a decrease in hourly wage and/or financial yield (Gebru, 2015; Theunissen, 1997a). Thirdly, some say that by producing more biomass per square meter than pure crops, intercrops could deplete the soil faster, which could result in increased fertiliser requirements in the long term (Li et al., 2014; Trenbath, 1999; Willey, 1990). Last but not least, although they each

have their own characteristics, plants all rely on the same resources – CO_2, O_2, light, water and nutrients – for their growth. If the physiological and architectural complementarities between crops may alleviate the competition for these resources, they do not completely rule it out. It may always be possible for the withdrawal of a resource by one of the crop to prevent the other one from acquiring it in turn, therefore causing competition relationships and losses of yield for one or both crops (Coll et al., 2012; Gebru, 2015). For an intercrop to be beneficial, the gain from complementarity and facilitation must be high enough to compensate for the potential (i) management complexity, (ii) increased workload and (iii) yield loss of the crop(s).

It is in this balance between benefits and drawbacks that lies the main problem of intercropping. On the one hand, on an operationalisation point of view, which balance is optimal is likely to depend on each farmer and on each intercrop. Firstly, as said above, not all farmers have the same yield objective for a given intercrop and not all intercrops fall under the same production objective for a given farmer. Secondly, each farmer will have its own "drawback acceptance scale", e.g. different farmers may tolerate a different increase in workload for the same increase in yield. On the other hand, on a theoretical point of view, it is still hard to understand how the balance changes, as it may depend on many variables, e.g. the choice of the crops and varieties, the planting distances, the spatial organisation of the plot, the climate, the soil properties, the biotic environment, etc., that interact with one another. The yield in pure crop also depends on all these variables. However, in intercropping, as the possibilities of combination are extremely numerous – each crop could theoretically be associated to any other crop – so are the possibilities of interactions. If we are nowadays able, in many cases, to explain the likely causes of the results of a specific intercrop in a specific context, we are still far from being capable to provide farmers with appropriate guidelines for intercropping, as it is more complicated to understand and predict the impact of a change in any of the cropping system variables on intercrop results than on pure crop results. Both this lack of understanding of intercropping and the risks and uncertainties when setting up intercropping that derives from it are identified by farmers as barriers to the use of this cultivation method (Morel et al., 2020).

1.1.2. STATE OF SCIENTIFIC RESEARCH ON INTERCROPPING

Given that the lack of understanding and knowledge of intercropping is one of the barrier to its use by farmers, scientific research has an important role to play in the spreading of this cultivation method by palliating to the lack of information.

Intercropping has been studied for more than seventy years, the publication of the first scientific papers related to it dating back to 1952 according to the Discovery website (https://bib.uclouvain.be/discovery/) of the UCLouvain.

Doing a research on this website including all the peer-reviewed papers and book chapters, written in English, including "intercrop" or "intercropping" in their title, published before the 11th of November 2021 and classified in the "Agriculture", "Environmental science", "Ecology", "Botany", "Biology" or "Forestry" category resulted in 3335 publications. Although the first papers focusing on intercropping date back to the fifties, intercropping became trendy about twenty years ago, with 75% of the total number of papers published after 2000 (Figure 2).

Unsurprisingly, the majority of intercropping-related publications fall under the "Agriculture" category and are found in agriculture-related journals, the top one so far being "Field Crops Research", which alone accounts for almost 10% of publications (Figure 2). A quick analysis of the words used in the titles of the 3335 publications reveals three main trends in the scientific research regarding intercropping. Firstly, studies mainly focus on the biomass production of intercrops, as shown by the high frequency of words such as "Yield", "Production" or "Productivity", all three of which appear in the top ten most used words. Secondly, there is a predominance of some crops, as illustrated by the six crops that appear in the 25 most used words: "Maize/corn", "Bean", "Soybean", "Wheat", "Sorghum" and "Cowpea" (Figure 2). The first four are even part of the top ten most used words. This reflects that the majority of intercropping-related studies so far concentrated on cereal-legume intercrops, probably because of the economic importance of cereals. Thirdly, the fact that specific crop names occur so frequently in the titles of publications suggests that many of these publications focus on a specific intercrop or main crop rather than taking a comprehensive approach.

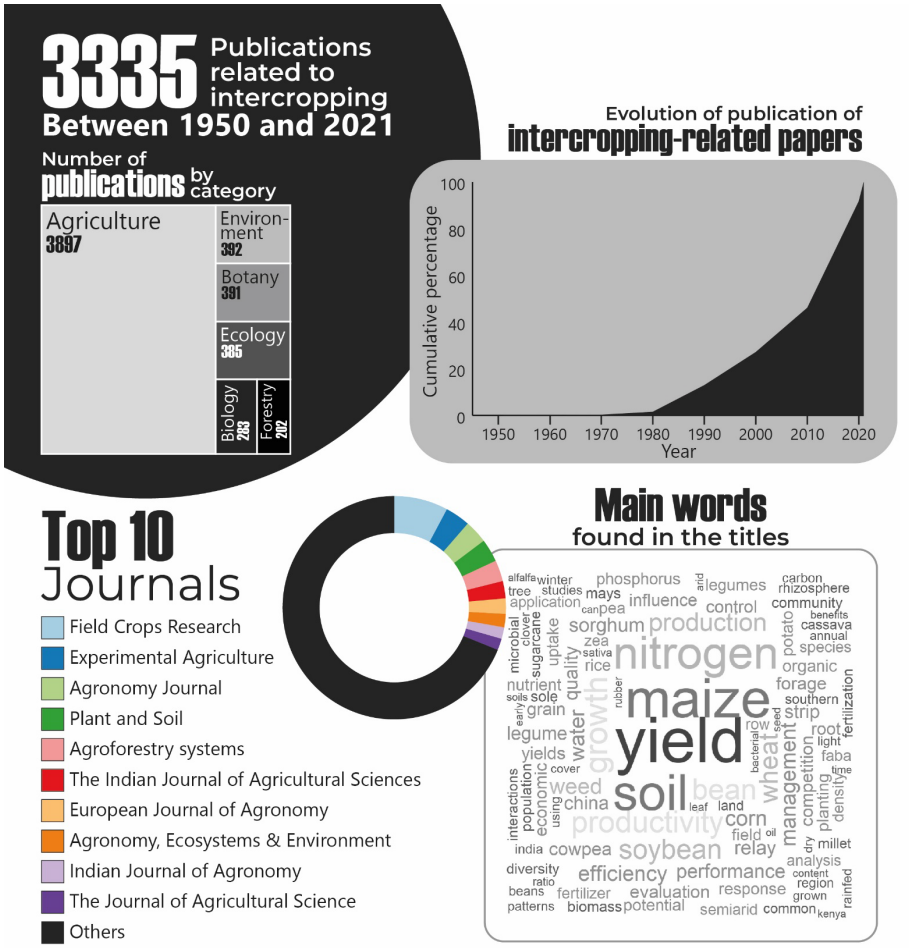


Figure 2 - State of scientific research on intercropping based on a research performed on https://bib.uclouvain.be/discovery/ on 11th of November 2021. The research included all peer-reviewed papers and book chapters published before 11th November 2021 , written in English, classified in the "Agriculture", "Environmental science", "Ecology", "Botany", "Biology" or "Forestry" category and including "Intercrop" or "Intercropping" in their title.

The intercropping research conducted to date is leading to a better understanding of the interactions that can take place when two crops are grown together and the impacts these interactions can have on the biotic environment, the abiotic environment and crop growth. However, they also highlight the huge complexity of intercropping, underlining the many variables that can intervene and influence the productivity of an intercrop as well as its associated benefits. Because of this complexity, current research mainly focus on either understanding the growth and explaining the outcome of a given intercrop in a given context or on comparing, at most,

two to three crops, usually legumes, to intercrop with a main crop, usually a cereal. The studies are therefore mainly descriptive rather than predictive – for example, no paper was found on Google scholar for a request with "Intercropping" and "Predict" or "Predicting" in the title – and very few studies are dedicated to finding general intercropping principles that could allow farmers to make informed choice when choosing intercrops and facilitate their implementation.

1.2. MARKET GARDENING

1.2.1. THE MARKET GARDENING SECTOR IN BELGIUM & WALLONIA

According to Statbel (2020), the Belgian statistical office, the area on which vegetables are grown in Belgium was equal to 52,520 ha in 2020, with less than 2% of this area dedicated to greenhouse cultivation. The vegetable production is unevenly distributed between Wallonia and Flanders – Flanders accounts for 63% of the total area under vegetable cultivation and 98% of the total area under greenhouse vegetable cultivation – and is mainly dedicated to the processing market (Statbel, 2020), i.e. vegetables dedicated to the production of frozen or canned food (Riera et al., 2020). At Belgium level, four crops account for more than 50% of the area under vegetable cultivation: peas, green beans, carrots and onions (Statbel, 2020).

In Wallonia, the area under vegetable cultivation accounts for 3% of the total area used for agriculture (Statbel, 2020). Around 12% of this vegetable area is cultivated under organic farming. Cultivation of vegetables in greenhouses is anecdotal (27 ha in 2020 (Statbel, 2020)) and peas, green beans, carrots and onions are, as for Belgium, the four major vegetable crops, which occupy 83% of the Walloon area under vegetable cultivation (Statbel, 2020). The majority of the production of peas and green beans is dedicated to the processing market whereas the majority of the production of carrots and onions is dedicated to the fresh market, i.e. vegetable commercialised without any or with minor transformation (washing, cutting, packaging) (Riera et al., 2020). In total, 85% of the Walloon vegetable area is dedicated to the processing market and 15% to the fresh market (Riera et al., 2020).

The Walloon vegetable production is mainly located in the North of Wallonia, where the terrain is gentler than in the South (DGARNE, 2019). The precise number of Walloon farms dedicated, partly or entirely, to vegetable production is not known. However, it is estimated at 2000 farms for the processing market (Riera et al., 2020) and around 300 farms for the fresh

market (Dumont, 2017; Riera et al., 2020). These 300 producers seem to be mainly organic market gardeners – with or without certification – who work on small areas (Dumont, 2017).

According to Dumont (2017), four production systems can be distinguished in the Walloon vegetable sector dedicated to the fresh market, each one existing in both conventional and organic farming: field crop producer, market gardening on large areas, market gardening on medium areas and market gardening on small areas. The description of the characteristics of these systems that follows is based on the PhD thesis of Dumont (2017).

These four orientations are differentiated based on (i) the total area under vegetable cultivation, (ii) the mean area per vegetable, (iii) the total number of full-time equivalents, (iv) the number of full-time equivalents per hectare of vegetable, (iv) the number of vegetables and the (v) the level of mechanisation. Overall, the total area under vegetable cultivation, the mean area per vegetable and the level of motorisation decrease from field crop producer to market gardening on small areas whereas the number of full-time equivalents per hectare of vegetable and the diversity – either in terms of species or of varieties – of cultivated crops increase. Field crop producers, unlike the other three systems, are not market gardeners in the strict sense, as they include in their rotations other crops than vegetables or non-permanent fruit crops, e.g. cereals.

Regarding commercialisation, field crop producers grow vegetables for both the processing and fresh market and sell their products to producer organisations – mainly Interbio, the only organic vegetable wholesaler in the Walloon region, for organic producers –, supermarkets and auction houses. Market gardeners on large areas sell their production to Interbio, supermarkets and through on-farm shops and market gardeners on medium areas via markets and on-farm shops. Market gardening on small areas is the only system in which more than half of the producers sell more than 20% of their vegetables via direct selling producer organisations and joint buying groups. Producers from all four systems base their selling prices more on the market price than on their production costs.

Field crop producers in organic farming and market gardeners on medium areas in organic farming generate the highest turnover. Market gardening on small areas generates the lowest turnover whereas it is in the upper range of annual hours worked per partner, because of its low motorisation level. Therefore, its average hourly income per partner is low (8.62€/hour). It is

also in this system that the gap between the production ideal of the producers and the reality they experience is the greatest and where producers struggle most to find a satisfactory balance between social justice, environmental sustainability and economic viability.

1.2.2. CHALLENGE OF INTERCROPPING IN MARKET GARDENING

There is currently an undeniable growing interest in market gardening among the general public, and more particularly in organic market gardening: who hasn't seen the slew of books on "How to grow your own organic vegetable garden?" that fill the shelves of bookstores these days? Probably popularised by the expansion of the permaculture movement (Ferguson & Lovell, 2014) – one of the key concept of which is to make a natural ecosystem productive by favouring positive interactions and complementarities between the components of a system (Holmgren, 2002) – the term “intercropping” nowadays appears in more and more mainstream gardening books and is presented as a key technique in vegetable growing. These books convey a positive image of intercropping, which is now seen by some people from the general public nearly as a “miracle practice”.

Considering the amount of books dedicated to or mentioning intercropping between vegetables, there is a great deal of information available on the subject. However, if this information is probably enough for a hobby gardener, it is problematic when moving to commercial systems. Mainstream gardening books tackling intercropping are in fact rarely used by professional market gardeners As explained in section 1.1.1, intercropping may bring many benefits but is also a very challenging cultivation method that requires many different variables and their interactions to be taken into account to achieve the expected result. However, many of the mainstream gardening books dedicated, entirely or partly, to intercropping usually include only a short description of the complementarity concept on which intercropping is based. They tend to oversimplify it by formulating some very general principles regarding intercropping design and sometimes elude the competition that can arise between associated crops. Besides these pieces of advices, intercropping-related books usually include either a list or a table of intercrops that are advisable and not advisable. In most cases, the rationale for the given recommendations is not stated or relies on allegations regarding the protective potential of one plant against the enemies of another (e.g. tomatoes protect cabbage from the whitefly, Wagner (2004)).

As an illustration, here are some examples of pieces of advice found in market gardening books:

- In his book “Le poireau préfère les fraises”, Wagner (2004) advises to combine crops that “mutually enhance their biological potential and also protect them against their enemies”, to “always have a green garden” and to verify if the crops will “be in a good neighourbood” when organising the plot. This information is completed by recommendations regarding which crops to combine, based mainly on potential positive and negative allelopathic effect, with very little consideration regarding the competition for resources between crops and the spatial and temporal organisation of intercrops;
- In the book “Les tomates aiment les carottes”, Riotte (2010) reviews a series of crops and indicates which other crops to grow with them. Again, the rationale for these recommendations is not given or based solely on a presumed protection against pests and diseases. She also gives some intercropping principles, such as “do not intercrop two crops that need a lot of water”, “do not intercrop two crops that will use the same stratum in the soil or in the air” or “intercrop crops with fast growth with crops with slow growth”. Very little consideration is given to the spatial and temporal organisation of intercropping.
- In the book “Les cultures associées au potager", Weinrich (2020) recommends to intercrop crops with different root depths and nutrient requirements and to favor soil coverage. She provides a list of recommended and non-recommended partners, without clear justification, for about thirty crops and describes a series of intercrops, with information regarding spatial and temporal organisation.

Besides the oversimplification of intercropping, the lack of explanations regarding the recommendations found in books and the lack of guidelines for intercropping design, including spatial and temporal organisation, when intercrops are described, their results, e.g. yield gain, vegetable size, asymmetry of yield between the crops, comparison with pure crops, etc., are usually not presented. It is therefore complicated, if not impossible, to understand the added value of an intercrop compared to the corresponding pure crops and to determine what productive purpose it could serve. Finally, there is also the problem of inconsistency: the pieces of advice given in the books sometimes contradict one another. The table in Appendix A as well as

the RShiny app that we developed on the basis of this table (https://associations-cultures-maraichage.shinyapps.io/reseaux-associations-fr/) illustrate the diversity of recommendations found in market gardening books and technical sheets and their discrepancy. There surely is an explanation about these differences, based on the source of the advice, the context in which crops were cultivated or the production objective. Unfortunately, this information is usually not stated. Therefore, it is particularly hard to understand where these differences come from and which book is the best for a given market gardener to follow based on his/her own context and objectives. To summarise, there is a substantial body of knowledge regarding intercropping between vegetables that is, however difficult to use because (i) it rests on hypotheses that, in some cases, have not been proved in a rigorous way and (ii) it lacks the framework and rigour needed to draw relevant and trustworthy general principles facilitating the operationalisation and the informed choice of intercropping.

These shortcomings could be addressed, at least partially, by scientific research. Unfortunately, market gardeners in temperate regions cannot either count on relevant, sound and objective scientific data regarding intercropping in market gardening. Until now intercropping studies mainly focused on cereal-legume intercrops (cf. 1.1.2) and the current scientific literature about intecropping between vegetables is poor: a research on Google Scholar for papers with “Intercropping” and the name of a crop in the title resulted in a mean of 392 papers per cereal crop (i.e. barley, corn, maize, millet, oat, rice, rye, sorghum and wheat), 320 per legume crop (i.e. bean, chickpea, cowpea, fababean, groundnut, pea and soybean) and only 26 per vegetable crop (i.e. beetroot, broccoli, Brussels sprouts, carrot, cauliflower, Chinese cabbage, collard cabbage, cucumber, eggplant, fennel, garlic, kale, kohlrabi, lamb’s lettuce, leek, lettuce, onion, parsnip, pepper, pumpkin, radish, rutabaga, savory, scorsonera, spinach, squash, tomato, zucchini). The issue of intercropping outside the classic cereal-legume scheme has been relatively more studied in the Tropics, e.g. 197 papers found on Google Scholar for “Intercropping”+”cassava”, 58 for “Intercropping”+”sweet potato” and 164 for “Intercropping”+”sugarcane”. Findings from these studies may be interesting for enriching knowledge about intercropping between vegetables in temperate regions. However, the challenges and main issues are likely to be very different in the tropics and in temperate regions due to differences in the spatial organisation of the plots and the number of associated crops (mixed *vs* in strips or rows), in the main production objective

(food subsistence *vs* marketing) and mainly, in the climate and the resource for which competition will be the highest (water *vs* light).

These observations show that there is a gap between the current interest in intercropping in market gardening and the quality of the information available at its subject. Consequently, market gardeners willing to implement intercropping in their farm are left with no other choice than experimenting by themselves. However, experimenting takes time, which is a valuable resource for many market gardeners. It may also cost money: an intercrop cause yield losses, i.e. money losses. Moreover, market gardeners may not be qualified to design experiment correctly, which can lead them to wrong conclusions. Finally, given the number of vegetables crops cultivated in some market gardening farm (up to 45 in organic market gardening on small areas (Dumont, 2017)), it is easy to get overwhelmed by the possibilities. For all these reasons, the lack of trustworthy information regarding intercropping in market gardening results in a second gap, this time between the general public's perception of intercropping and its actual use by professional market gardeners.

1.3. KNOWLEDGE ABOUT INTERCROPPING IN MARKET GARDENING, A GAP THAT NEEDS TO BE FILLED?

The first section emphasises (i) the potential benefits of intercropping, (ii) the complexity of intercropping and the vagueness that remains around its understanding despite many years of research. The second section underlines the gap between the place of vegetable intercropping in the media at the moment and what we actually know about them.

In our opinion, these observations highlight two current problems. On the one hand, intercropping is presented as one of the solutions to make our farming systems more sustainable but our understanding of it remains limited. On the other hand, although intercropping is mostly seen by the general public as a key practice in market gardening, to our knowledge its use by professional market gardeners remains low, at least in Wallonia.

We think that filling the gap in the knowledge about intercropping in market gardening through scientific studies might help to solve these two problems. Firstly, regarding market gardening, studying intercropping between vegetables in a sound and scientific way should help to put things in perspective, objectify the numerous statements found about this practice in mainstream gardening books and convey a more realistic image of this

practice. Secondly, it could help to promote the relevant use of intercropping in market gardening farms by providing market gardeners with data based on sound, objective and reliable information. In particular, it seems that rather than providing them with a list of which vegetables to intercrop or not, market gardeners are willing to have at their disposal (i) some trustworthy guidelines on the basis of which they will be able to conceive their own intercrops, adapted to their objectives and context, (ii) some information on how to experiment correctly and (iii) the basic knowledge required for them to make informed choices regarding intercropping. There is a desire to understand rather than simply apply. At the same time, we believe that the study of intercropping between vegetables goes beyond the scope of market gardening itself and should provide useful information about intercropping as a whole – particularly in order to achieve a predictive logic – by studying it in a context other than the classic "cereal-legume" one (cf. 1.1.2). All these reasons convinced us to make of intercropping in market gardening the focus of our work.

1.4. FOCUS, OBJECTIVE, RESEARCH QUESTIONS AND GENERAL METHODOLOGY OF THE THESIS

Our aim, through this thesis, is to increase the available knowledge in intercropping between vegetables. In order for this objective to fit in the framework of a thesis, we had to narrow our objects of study, i.e. intercropping and market gardening. We decided to focus only on intercrops between two annual crops, both with economic value – e.g. intercrops between a marketable crop and a cover crop with no commercial value were not considered – and designed in such a way that at least one of the crops spend the majority of its growth cycle in intercropping.

Regarding market gardening, our study was designed in the context of market gardening on small areas (as described by Dumont (2017), cf. 1.2.1), both organic and conventional, in temperate regions, in Wallonia. Thanks to its high crop diversity (cf. 1.2.1), this system is the one in which the use of intercropping would require a reorganisation of the spatial design and the workload rather than a complete reorientation of the farm, on the opposite of low-diversified systems. It is also the one in which the problems of mechanisation linked to the use of intercrops should not be a barrier, as market gardening farms on small areas usually are poorly mechanised (Dumont, 2017). Moreover, as explained by Dumont (2017) in her thesis, many of the market gardeners on small areas have strong expectations for

their crop management regarding sustainability and environmental protection. Therefore, it is likely that these market gardeners are the most willing to implement intercrops but are restricted by the lack of trustworthy information. Finally, this system gathers the highest number of market gardeners in Wallonia (Dumont, 2017) and is therefore the one in which we were most likely to find enough market gardeners willing to take part in our study.

According to us, there are two dimensions in the knowledge regarding intercropping: a theoretical one – How does intercropping work in theory? – and an operational one – How to design intercropping in practice? –. In this thesis, we decided to tackle these two dimensions through three research questions. Our first research question is the broader one and is related to the first dimension:

(A) **Which interactions influence outcome and benefits in intercropping?**
Intercropping being such a complex theme, we thought it would be interesting to list all the known interactions involved in it and influencing the benefits it could bring.

Our two other research questions are focused on the operationalisation dimension. As our main motivation was to provide reliable information to professional market gardeners, it seemed only logical to include them in the thesis. We made the choice to involve them from the very beginning of our research process. From our discussions with market gardeners emerged the main questions and doubts they had regarding intercropping. We chose, among the identified points of interest, the following two research questions, based on what seemed the most interesting based on our review of the mainstream and scientific literature and what was feasible based on the available resources (i.e. time, human resources):

(B) **Which criteria use to choose productive intercrops?**
Market gardeners usually use root and shoot spatial complementarities and temporal complementarity to select which crops to combine. However, as far as we know and even if these criteria seem logical, one has never proven their relevance and the mixed results from intercrops among participating market gardeners as well as the diversity of advice regarding intercropping in market gardening books call into question their adequacy.

(C) Is the productivity of an intercrop more dependent on environmental conditions and crop management practices than the productivity of pure crops?
Market gardeners have more conflicting opinions on the performance of intercrop than on the performance of the corresponding pure crops, even though they most likely do not grow the pure crops exactly in the same way. Consequently, we wanted to verify if the variability of the results of an intercrop was indeed higher from one market gardener to another than the variability of results of the corresponding pure crop.

We chose to answer these questions using an exploratory approach: instead of focusing on one precise intercrop or mechanism, we decided to develop a less in-depth approach studying many intercrops at once. This choice is justified by the observation that research in intercropping has so far mainly focused on one particular situation, i.e. one intercrop in one context. Such an approach is helpful to understand perfectly how to design a specific intercrop in a specific context but does little to advance the overall understanding of intercropping and only provides keys to its use to a limited number of farmers. Besides, an exploratory approach seemed particularly relevant in the context of diversified market gardening, given the many intercropping possibilities that market gardeners face.

We based our approach on two pillars (Figure 3). The first one was theoretical and aimed at answering research question (A) by identifying, through a thorough review of the currently available scientific literature about intercropping, the interactions at stake when associating crops. It intended to be as comprehensive as possible and was not restricted to intercropping in market gardening. The second pillar was meant to address research questions (B) and (C) via the setting up of on-field experimental trials. It was purposely less inclusive than the first pillar – although it still included various intercrops – but more effective to answer research questions that are more precise.

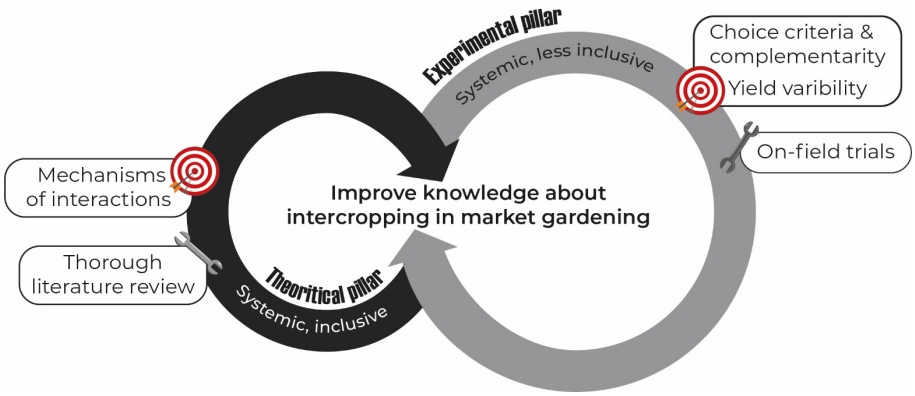


Figure 3 - Pillars of the PhD thesis, with their associate topics of interest and tools.

1.5. A FEW WORDS ON ASSESSING THE RELEVANCE OF AN INTERCROP

In many papers about intercropping, yield is the main focus, i.e. studies aim to verify whether the intercrop is as or more productive than the corresponding pure crops (e.g. Baumann et al., 2002; Carr et al., 1998; Jensen, 1996; Wu et al., 2017; Zhang & Li, 2003). Therefore, intercropping is mainly known and promoted for its effect of increasing the biomass production per square meter thanks to complementarity between crops (Trenbath, 1974; Willey, 1990). In a sense, this approach is easily justified: yield is a reference indicator in agronomy and is of great interest to farmers. Nevertheless, given the complexity of intercropping and the many effects a switch from pure crop to intercrop can have on the biotic and abiotic environments, reducing the assessment of the relevance of an intercrop to its biomass production alone can seem very simplistic.

Intercropping can indeed increase the biomass production per square meter, for example by (i) reducing the impacts of pests and pathogens (Duchene et al., 2017; Gómez-Rodríguez et al., 2003; Kinane & Lyngkjaer, 2002; Theunissen, 1997a; Trenbath, 1974) and (ii) by reducing the impacts of weeds (Bulson et al., 1997; Liebman & Dyck, 1993; Malézieux et al., 2009). Nevertheless, beside this effect, intercropping may also stabilise the yield of the plot thanks to the differences in sensitivity to biotic and abiotic stress between the associated crops (Himanen et al., 2016; Paut et al., 2019; Rao & Singh, 1990; Trenbath, 1999), improve the quality of the harvested products (e.g. Bulson et al., 1997; Jensen, 1996; Muschler, 2001) and diminish the costs of management by reducing fertilisers and crop protection products requirements (Khan, 2008; Liebman & Dyck, 1993).

However intercropping also has drawbacks (cf. 1.1.1), such as its complexity of management (Malézieux et al., 2009; Trenbath, 1999) – both crops need to be managed at the same time although they sometimes have conflicting needs –, the difficulty of choosing which crops to combine, with the risk of yield losses due to competition (Coll et al., 2012; Gebru, 2015; Khan, 2008), the loss of market value due to size reduction, the difficulty of mechanisation and the potential increase in workload (Gebru, 2015; Malézieux et al., 2009).

In the selection process of intercrops by market gardeners, yield is therefore balanced by other criteria, e.g. market value of the crops, difficulty of crop management, quality of the products, etc., practical indicators that researchers may overlook during their studies. In addition, focusing only the yield component of intercropping may lead researchers to disregard its other benefits (cf. 1.1.1) when intercropping could be valued specifically for these benefits, regardless of its impact on productivity, and could be promoted as a biodiversity-based agricultural practice, i.e. a practice that "seeks to develop diversity in cultivated species and genotypes at multiple spatial and temporal levels to favour functional complementarities in resource use and biological regulation" (Duru et al., 2015).

In this thesis, we decided to take the yield as an anchor point, for both the depiction of the interactions in intercropping and the experimental trials. This position is justified by five arguments. Firstly, making the land profitable and producing vegetables that are suitable for commercialisation is the objective of market gardeners. Even though they do not all attach the same importance to productivity, they all need products to sell to make a living. Yield therefore remains a valuable indicator for them, although it may not always be the one of primary importance. Secondly, as written above, yield remains the top one indicator in agronomy. It is in fact easily measured or estimated, objective, and make it easy to compare trials and studies. Moreover, it is a common indicator for researchers and market gardeners, which facilitates the reporting of results. Besides, as scientific research about intercropping in market gardening is nearly non-existent and as our study was mainly exploratory, we think it was essential to start by focusing on the simple and essential variable of yield. Finally, reducing the number of variables measured and using yield as the main indicator allowed us to monitor a large number of plots and to compare easily the results of different crop combinations.

Nevertheless, in order to avoid falling into the trap of using yield as the only indicator of relevance of an intercrop, we also introduced the measurement of other variables, e.g. size of the harvested vegetables, working time, financial yield, etc. and tried, when relevant, to qualify conclusions based on yield using these.

1.6. OUTLINE OF THE THESIS

The organisation of the chapters is shown in Figure 4.

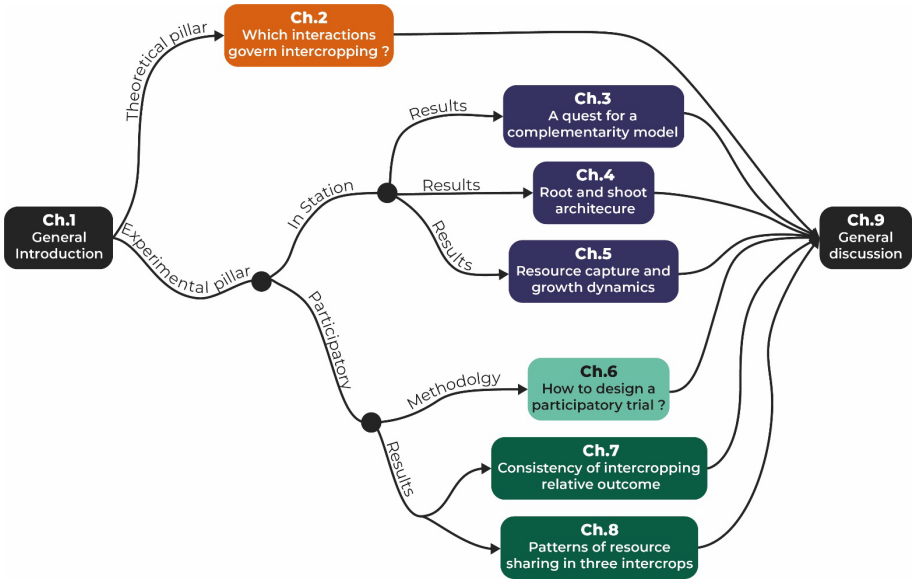


Figure 4 - Organisation of the chapters of the thesis.

We begin this thesis by its theoretical pillar, addressing our first research question (A) in Chapter 2. In this chapter, we introduce the concept of intercropping system, i.e. a system comprising the crops of an intercrop, their interactions and all the elements of the biotic and abiotic environment that influence them and that they influence, and present the main interactions between the components of this system, identified through a thorough literature review. The presentation of these interactions using two forms – a text and some networks of interactions – allows to have a comprehensive view of the functioning of the intercropping system.

From Chapter 3 to Chapter 8, we dive into the experimental pillar of the thesis. Chapter 3 to Chapter 5 are dedicated to the trials designed to tackle our second research question (B).

In Chapter 3, we present the results of the first of the two on-field trials set up in agricultural experiment station (AES). We explain the development of a complementarity model using qualitative data, based on the theoretical concept of complementarity developed in Chapter 2 and on intercropping advice found in mainstream market gardening books. We then explore the potential of this model in explaining the differences in outcome between a series of intercrops.

In Chapter 4, we present the results of the second of the two on-field trials set up in AES. We explain how we classified market gardening crops according to their shoot and root architectures using quantitative architectural data and a principal component analysis (PCA). We then analyse whether the relative positions of crops in the PCA can explain the differences in outcome between intercrops, using an analogue to a diallel design, i.e. each one of the crops we studied was intercropped with each one of the other crops.

In Chapter 5, we explore the issue of explaining the differences in intercropping outcomes in the reverse direction: instead of verifying the explanatory potential of some hypothesis, we identify, using the data of our second on-field trial in AES (cf. Chapter 4), characteristics or set of characteristics that were common to intercrops that performed in the same way. We then validate the identified characteristics against the data of our first on-field trial in AES (cf. Chapter 3).

From Chapter 6 to Chapter 8, we move to the participatory part of this thesis and present the results of the trials designed to tackle our third research question (C).

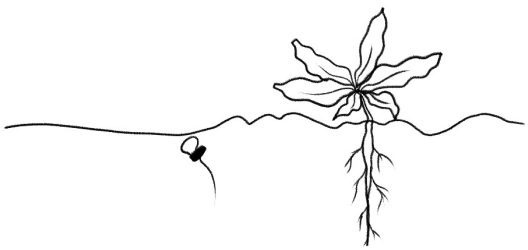
In Chapter 6, we present the course of the participatory part of the thesis, from the creation of the network of market gardeners to the set up and evaluation of the participatory on-farm trials. We highlight the difficulties we encountered as well as the strengths of the approach we developed.

In Chapter 7, we show the results of the two participatory on-farm trials we conducted and explore the question of the consistency of intercropping relative outcome in a range of environmental conditions and crop management practices for three different intercrops.

In Chapter 8, we push further the analysis of the results from our two participatory on-farm trials by identifying the patterns of resource use and sharing in the intercrops we studied.

Finally, in Chapter 9, we discuss the limitations of our exploratory approach and of the different methods we used throughout this thesis. We emphasise our main findings and highlight our contribution to (i) the scientific knowledge regarding intercropping and (ii) the operationalisation of intercropping and we propose some avenues to follow regarding intercropping study.

Chapter 2 |
Which interactions govern intercropping? A visualisation via interaction networks and global system map



In the introduction, we emphasised the many benefits attributed to intercropping as well as the difficulties linked to its implementation. We presented the overall state of intercropping research, which focused so far on intercrops between cereals and legumes, and highlighted the fact that despite being studied for more than 70 years, intercropping is still poorly understood and its results difficult to predict.

The outcome of intercropping relies on many interactions – between the crops but also between the crops and their biotic and abiotic environment – that may be different from those in pure crops. In this chapter, we introduce the notion of intercropping system, i.e. a system comprising the crops of an intercrop, their interactions and all the elements of the biotic and abiotic environments that influence them and that they influence, and we present the interactions that can intervene in it and influence its outcome and benefits. For this purpose, we conducted an extensive literature review based not only on papers about intercropping but also on papers on other related topics, e.g. phenotypic plasticity, in order to describe the mechanisms in comprehensive terms.

In order to provide a better understanding of the interactions between the different compartments of the intercropping system, we decided to supplement the text that broadly describes the interactions involved in intercropping by a graphic representation. In this purpose, we drew fifteen networks of interactions (cf. Appendix B), each one focused on one theme related to intercropping. In addition, the interactions represented in the thematic networks were compiled in a global system map. Our approach allows (i) to understand the processes involved in intercropping, (ii) to visualise the complexity of the intercropping system and the potential connections between its components and (iii) for researchers studying intercropping to situate themselves in the global map and identify the key processes to be considered.

This chapter presents first our methodology regarding the literature review (section 2.2.1 & 2.2.2) and the drawing of the networks and of the global system (section 2.2.3). We then present the characteristics of our literature review (section 2.3.1), explain, in a written form, the interactions governing intercropping (section 2.3.2), show the global system map of intercropping (section 2.3.3) and discuss the use of the networks (section 2.4).

CHAPTER 2 | WHICH INTERACTIONS GOVERN INTERCROPPING? A VISUALISATION VIA INTERACTION NETWORKS AND GLOBAL SYSTEM MAP

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2.1. INTRODUCTION

The response of many crops to their environment is well understood and crop management practices are adapted to adjust to it and make the best out of these crops. Given the knowledge we already accumulated about crop physiology and crop management, one could think that the introduction of mixed crops should not be a huge challenge. However, this is far from reality. Intercropping is a very complex subject. A given crop, when grown with another one, does not necessarily behave as expected based on its growth as a pure crop. In fact, the introduction of another crop in a cultivated field modifies many of the relationships that existed, before its introduction, between the other cultivated crop and its environment, either biotic or abiotic.

Intercropping has been studied for over 70 years (e.g. Arny, 1929; Luthra & Vasudeva, 1940) and thousands of papers have been published about it. Despite this significant body of knowledge, we are still unable to predict adequately the result of a given intercrop and a real consensus on how to design and how to manage productive intercrops is still lacking, except maybe for cereal-legume intercrops, which have drawn the most attention (cf. 2.3.1 & Chapter 1). In fact, the result of an intercrop relies on the identity of each crop and the effects each one of the crops from the intercrop can have on the other one, but also on the impacts of each crop and of their interactions on the microclimatic conditions, the soil characteristics, the soil microorganisms, the surrounding fauna, etc., all of which can vary according to the crop species and varities, the (relative) timing of sowing/plantation, the environmental conditions, the planting distances, the densities of the crops, the crop management practices, etc. The possibilities are endless.

Making an inventory of all the processes that may intervene in an intercrop and may influence its outcome is needed to disentangle the imbroglio of intercropping and to work towards predicting the results of a combination of crops and facilitating the use of modelling. According to us, a first step should be to depict all the possible processes and interactions, regardless of their relative significance. In fact, interactions in an intercrop are so complex and diverse that it seems hazardous to let some aside. A systemic and comprehensive approach pushes one not to leave anything out and allows to have a vision of all possibilities. In the same way, considering not only the findings from agronomical papers related to intercropping but also the ones from ecology papers studying mixed natural communities can help give a

more realistic and complete picture of what is possible when two crops are grown together, although this creates some tension between physiological processes et ecological concepts.

With this in mind, we defined the concept of “intercropping system”, i.e. a system comprising the crops of an intercrop, their interactions and all the elements of the biotic and abiotic environments that influence them and that they influence, and engaged in a system analysis approach whose objective was to depict all the processes that can operate in an intercrop. Our will was to present them in a descriptive and systematic way rather than in a quantitative and hierarchical way, on the basis of a review of the literature in both the fields of agronomy and ecology. The present chapter describes the methodology we used for this analysis and shows its results, which are three in number: a text explaining the possible interactions in intercropping, thematic networks of interactions in intercropping and a “system map” of intercropping. The main purposes of these three tools is to give a realistic view of what can happen in an intercrop and to be used as a starting point for further studies about intercropping.

2.2. METHODOLOGY

2.2.1. EXTENSIVE LITERATURE REVIEW

The first step of our methodology was to perform an extensive literature review to get a global view of the intercropping system and to identify the elements – whether processes, relationships or objects – involved in this system. We began our literature review by reading some review papers about intercropping and we identified, in these papers, the possible interactions in intercropping. Then, we proceeded in a heuristic way and by saturation, searching for further information about the identified interactions until it seemed we had reviewed the relevant information available.

2.2.2. INTERACTIONS IN INTERCROPPING

The second step of our methodology was to summarise the papers read into a text explaining the possible interactions in intercropping. This was done in three stages. First, each paper we read was summarised as bullet points and/or key sentences. Then, we divided our literature review into distinct research themes and we wrote, for each of these themes, a continuous text gathering all the information about this theme based on the bullet points and

key sentences from the papers we read. Finally, we grouped and summarised these texts into a single one, presented hereunder (cf. 2.3.2).

2.2.3. Creation of the networks of interactions and of the intercropping system map

In an effort to facilitate the understanding of the interactions taking place in an intercrop, we created, in addition to the written summary, fifteen interaction networks. These networks aim at presenting the processes described in the text in a graphic and visual format to get an idea of the main interactions at a glance. We designed two types of networks: (i) thematic networks, which are available in Appendix B and illustrate the different sections of the text presented in section 2.3.2 and (ii) one system map, which shows the global structure of the interactions in intercropping and which will be presented in section 2.3.3.

One of our aims being to provide market gardeners with intelligible and reliable information on the functioning of intercropping, we have deliberately chosen to keep the processes described and the terms within the networks general so that they are understandable to farmers. Moreover, to facilitate links between the written text and the interaction networks, we kept the same structure and draw a thematic network for the majority of the subdivision of section 2.3.2. In few cases, the processes from one section were integrated into the network of another section to avoid redundancy.

The networks were constructed as follows.

Firstly, we identified, within each section of the written summary, the mentioned processes.

Secondly, we associated to each process the corresponding boxes, i.e. the elements that needed to be present in the networks to represent the process in the shortest possible way to remain understandable and accurate. This translation of processes into nodes was co-decided by three researchers using expert knowledge and led us to a mean of 30 boxes per thematic network, which seemed to be an acceptable number to keep the network readable.

Thirdly, we identified the type of the relationship between each pair of boxes of each network. We retained four types of interactions (Figure 5): (i) quantitative synergistic relationships, where the increase of the box #1 leads to a quantitative increase of the box #2, e.g. “Level of root aggregation” and

"Closeness of roots" have a quantitative synergistic relationship as if the level of root aggregation increases, so does the closeness of the roots (Figure 5), (ii) qualitative synergistic relationships, where the box #1 triggers box #2, e.g. "Composition of root exudates" and "Solubilisation of nutrients" have a qualitative synergistic relationship as the composition of root exudates may trigger the solubilisation of nutrients (Figure 5), (iii) antagonistic relationships, where the increase of the box #1 leads to a decrease in the box #2, e.g. "Level of competition for nutrients" and "Level of yield" have an antagonistic relationship as an increase in competition for nutrients leads to a decrease in yield (Figure 5), (iv) undertermined relationships, where the box #1 can cause non-quantifiable changes or can either make increase or decrease the box #2, e.g. "Architecture of roots" and "Level of root aggregation" have an undetermined relationship as according to the root architecture, the level of root aggregation may increase or decrease (Figure 5). Beside these four types of links, there is an another relationship, named characteristic/component relationships, where the box #2 is a characteristic/component of the box #1, e.g. "Height of the shoot" is a characteristic of "Architecture of shoots".

Fourthly, we engaged ourselves in an iterative process, where each thematic network was drawn and then improved to attain the good balance between readability, complexity and accuracy.

Final networks were drawn by hand using Adobe Illustrator 2021. In order to facilitate both reading and construction of the networks, we classified the boxes in six categories: characteristics of plant A, characteristics of plant B, emergent properties and interactions of the intercrop, abiotic environment, biotic environment and farmer- and crop management-related variables. In each network, each category is located at the same place and distinguished from other categories by the same colour code (Figure 5). Besides, we distinguished the different types of relationships by using different types of arrows and segments (Figure 5). Finally, once the final networks were drawn, we created an index of all the boxes (cf. Appendix B.16).

The global system map was made on the basis of the networks of interactions. Among all the nodes from the networks, we choose the most important ones. Again, this selection was co-decided by three researchers and based on expert knowledge. In order to keep a maximum of about 100 nodes, which is the number of nodes in the widely referred "Obesity System Map" (Vandebroeck et al., 2007), we tried to select the nodes at the lowest

level of accuracy, i.e. the ones allowing us to represent adequately a process without going into the details of the precise interactions leading to it. For example, instead of using the nodes “Architecture of shoots”, “Height of shoots”, “Angle of leaves” and “Area of leaves” to describe the competition for light between crops, as was done in the thematic network about competition for aboveground resource (cf. Appendix B.7), only the node “Architecture of shoots” was used in the global system map (Figure 8). Bearing the same objective of simplification in mind, some nodes were gathered in one, e.g. the nodes “Level of soil stability” and “Level of soil aggregation” (cf. B.14) were gathered as “Quality of soil physical properties” (Figure 8). Secondly, the map was drawn by hand on Adobe Illustrator 2021, using the same spatial organisation as the networks of interactions. The written summary was used as a guide to ensure the representation of all major processes.

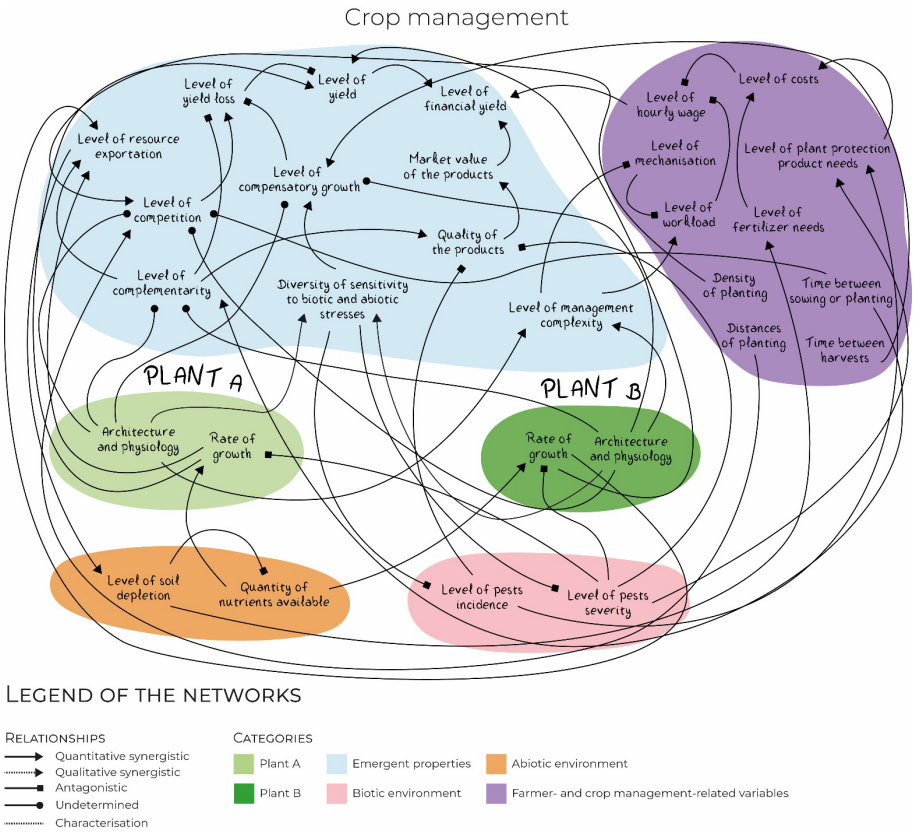


Figure 5 - Network of interactions regarding the management of the crops with its legend for links and node categories.

2.3. RESULTS

2.3.1. PAPERS FROM THE EXTENSIVE LITERATURE REVIEW

At the end of our literature review process, we had read 253 peer-reviewed papers, split fairly evenly between review and experimental papers. Of these 253 papers, 54% were directly related to intercropping. The remaining 46% were papers about processes and mechanisms that are identified in review papers about intercropping as influencing the outcome of intercropping, such as phenotypic plasticity. Moreover, 39% of our sample of papers came from the field of ecology rather than the field of agronomy, as the study of natural diversified communities can greatly help understand interactions between plants species and, therefore, the interactions taking place in an intercrop. Regarding intercropping-related papers, more than 60% of the studied intercrops were intercrops between a legume and a cereal, with maize, barley, pea, wheat, faba bean and soybean being the six most studied crops. Rather than a desire on our part, this preponderance of legume-cereal intercropping reflects the current trend of scientific research on intercropping. Other characteristics of our sample of papers are available in Figure 6. Not all the 253 papers are listed in the bibliographic reference of the written summary presented hereunder (cf. 2.3.2) but they have all played a part in building our understanding of the intercropping system and were used for the development of the interaction networks and the system map.

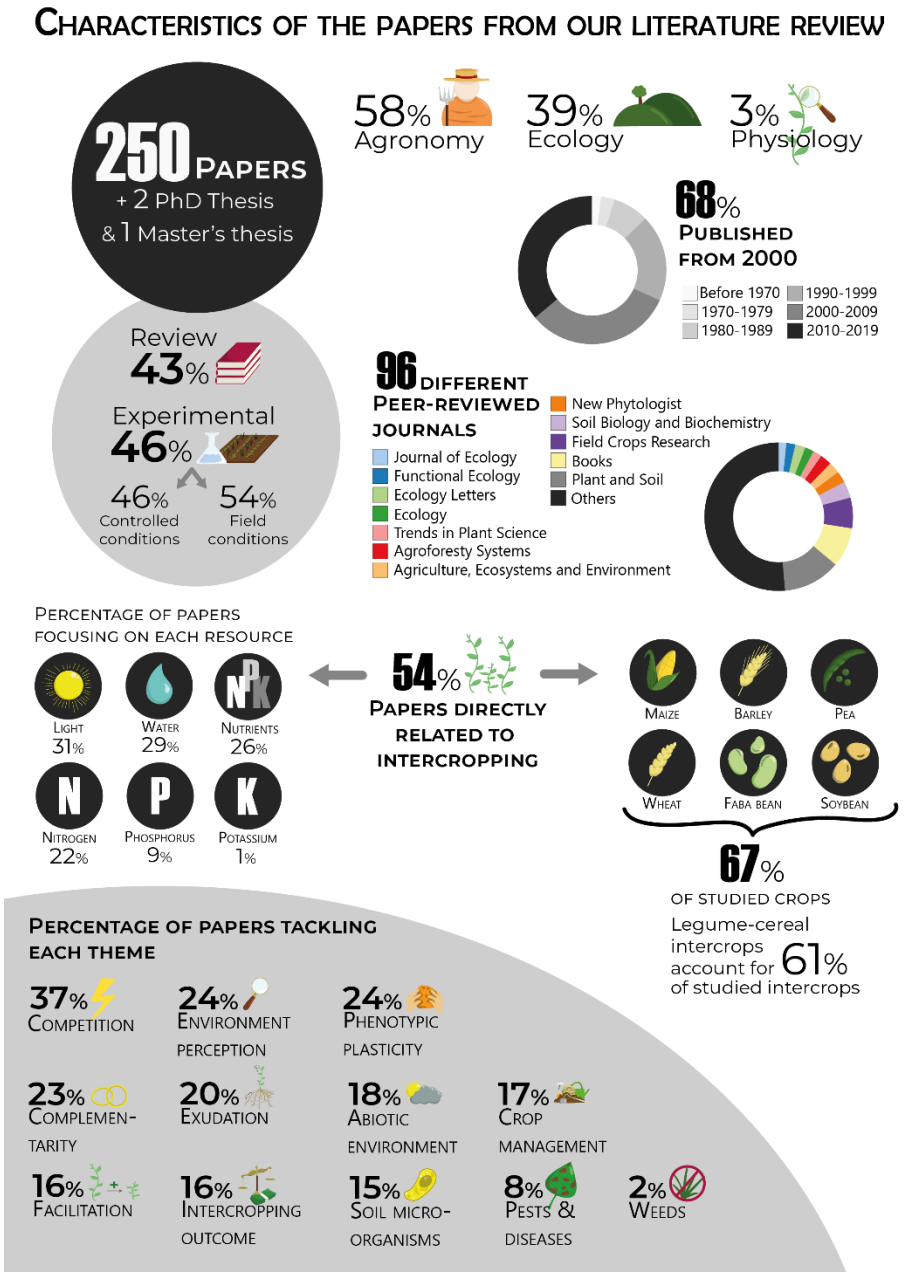


Figure 6 - Main characteristics of the papers from our extensive literature review on intercropping.

2.3.2. INTERACTIONS IN INTERCROPPING

The main concepts and elements of the text and how they fit together are summarised in Figure 7. As shown in Figure 6, 39% of the papers from our extensive literature review came from the field of ecology and the study of mixed natural communities. The text from this section, summarising and explaining the interactions and processes that take place when combining plants therefore includes findings derived from these type of papers but is written in an agronomical perspective, as the subject of this thesis is the study of crop mixtures.

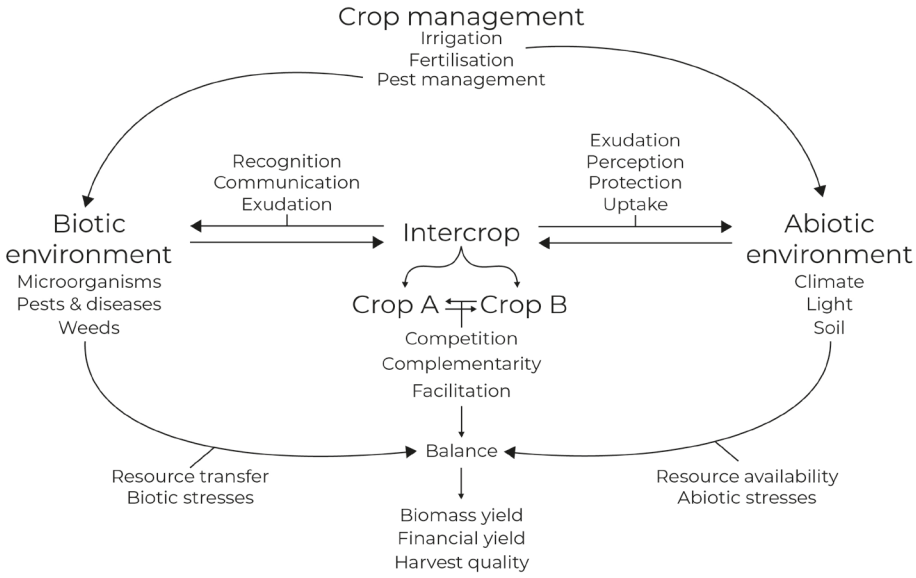


Figure 7 - Main concepts and elements of the text describing the main interactions in intercropping.

2.3.2.1. Perception and reaction of plants to their environment

2.3.2.1.1. Perception of signals and phenotypic plasticity

Plants may sometimes be seen as "passive" organisms, unable to react to their environment and forced to cope with whatever can happen. The reality is quite different, as plants are in fact able to perceive many different signals, to which they may or may not respond – from a subcellular level to a morphological level (Karban, 2008) – in order to increase their survival and their competitive ability in a given environment (Pierik et al., 2012; Walker et al., 2003). A telling example of such ability is the positioning of the leaves

and roots of plants in a heterogeneous environment, which answers to different signals in order to optimise the uptake of light, water and nutrients (Karban, 2008; Kegge & Pierik, 2010).

As plants are unable to move in space, their reactions to their environment is allowed by their modular construction. Plants are indeed constituted of a series of autonomous modular units that allow them to transform themselves in radically different ways in response to local environmental signals (Hodge, 2009; Holopainen & Blande, 2012; Silvertown & Gordon, 1989). This phenomenon is called "phenotypic plasticity" and refers to the ability of a single genotype to produce various physiological and morphological phenotypes according to the environmental conditions (Agrawal, 2001; Bradshaw, 1965; Schlichting, 1986). As the modular units are independent from each other, each one can react to its local conditions. However, the overall condition of the plant may also be taken into account (Karban, 2008). The phenotypic plasticity allows the plants to react to many different stimuli – parasitism, availability in water and nutrients, presence of microorganisms, presence of other plants, etc. (Biedrzycki & Bais, 2010b; Callaway et al., 2003; Schroth, 1998) – and it may confer a higher competitive ability to plants in changing environments (Poorter & Lambers, 1986). Nevertheless, its impacts are still largely unknown: there are so many stimuli to which plants can respond and between which trade-offs must be made (Mommer et al., 2016) that it is difficult to predict their behaviour (Hodge, 2009). Moreover, each species is likely to respond in a different way to the stimuli (Caldwell et al., 1996; Callaway, 1990; Schenk et al., 1999).

2.3.2.1.2. Perception and communication[1] with neighbouring plants

Related network in Appendix B.1.

The ability of plants to perceive their environment allow them to sense the presence of neighbouring plants and to react to it. This capacity is linked to two types of signals: either a change in the abiotic environment (Callaway et al., 2003; Kegge & Pierik, 2010; Pierik et al., 2012; Schenk et al., 1999), e.g. the reduction of the red/far-red ratio due to the interception of incident light

[1] The use of the term "communication" is arguable and may be a misnomer in this context, as a real communication implies that the emission of the signal is intentional and beneficial (Karban, 2008), which may not be the case as far as the emission and perception of signals by plants are concerned (Gagliano, 2013).

by the neighbouring plant (Franklin, 2008; Franklin & Whitelam, 2005; Keating & Carberry, 1993), or the perception of molecular compounds emitted by the neighbouring plant (Callaway et al., 2003; Kegge & Pierik, 2010; Pierik et al., 2004, 2012; Schenk et al., 1999). Plants indeed emit many different molecules through their leaves and roots, that can be either volatiles, such as the volatile organic compounds (VOCs), or not, such as many root exudates (Badri & Vivanco, 2009; Bais et al., 2006; Holopainen & Blande, 2012; Pierik et al., 2012; Walker et al., 2003). These compounds are classified according to their effect, either positive or negative, on both the sender and receiver (Whittaker & Feeny, 1971) and can have many different functions: reaction to (a)biotic stresses (Holopainen & Blande, 2012; Ramovš, 2013; Walker et al., 2003), attraction of soil microorganisms (Bais et al., 2006; Broeckling et al., 2008; Buee et al., 2000; Dakora & Phillips, 2002; Peters et al., 1986) or pollinators (Simpson & Neff, 1981), mobilisation of nutrients (Dakora & Phillips, 2002), etc.

The plants located around the sender can potentially intercept all these compounds but for the receiving plant to respond to them, it must perceive them in a sufficient concentration (Barney et al., 2009; Barto et al., 2012; Hodge, 2009; Perry et al., 2007). However, in the soil, the concentration of an exudate decreases rapidly as one moves away from the source of production (Barto et al., 2012; Perry et al., 2007). Therefore, the interactions mainly take place at the scale of the rhizosphere (Badri & Vivanco, 2009; Chen et al., 2012; Perry et al., 2007), unless some mycorrhiza networks allow the exudates to be conveyed further (cf. 2.3.2.5.2) (Babikova et al., 2013; Barto et al., 2011, 2012; Simard et al., 2012; Thirkell et al., 2017). The problem remains for the VOCs. In an open area, the concentration of VOCs is likely to diminish quickly as one moves away from the sender, due to air fluxes and oxidisation (Barney et al., 2009; Holopainen & Blande, 2012; Kegge & Pierik, 2010). Some experiments show a distance of action ranging from 10 cm up to 60 cm (Heil & Adame-Álvarez, 2010; Karban et al., 2003, 2006), which supposes that VOCs mainly serve for intra-plant communication (Heil & Adame-Álvarez, 2010).

In addition to being able to sense the presence of neighbouring plants, it seems that at least some plants are also capable of distinguishing between their own organs and those of other plants, i.e. self-recognition (Biedrzycki et al., 2010; Biedrzycki & Bais, 2010a; Mahall & Callaway, 1991) and between kins and foreign plants, i.e. kin recognition (Biedrzycki et al., 2010; Biedrzycki & Bais, 2010a; Mahall & Callaway, 1991), and of reacting accordingly, e.g.

reduction of the root proliferation to limit the overlapping of uptake areas between kins (Dudley & File, 2007; Mahall & Callaway, 1991; Bruce E. Mahall & Callaway, 1996) or between the roots of a same plant (Schenk, 2006).

The perception of their environment, as well biotic as abiotic, by the plants is of course of importance when studying intercropping, as it influences the relationships between neighbouring plants and, therefore, the outcome of an association of crops. However, before addressing this question, it is important to describe and explain the interactions that can happen between associated crops. Therefore, we will focus first on the three types of relationships that are usually considered as major to explain the interactions between plants in intercropping, i.e. complementarity (cf. 2.3.2.2), competition (cf. 2.3.2.3) and facilitation (cf. 2.3.2.4), and second on the influence of the biotic and abiotic environment on the balance between complementarity, competition and facilitation (cf. 2.3.2.5). Finally, we will tackle the question of the influence of intercropping on the biotic and abiotic environment (cf. 2.3.2.6).

2.3.2.2. Complementarity relationships

2.3.2.2.1. Concept

Complementarity refers to the physiological and architectural differences that exist between crops and allow them to use resources in different ways in space and time (Andersen et al., 2007; Hooper, 1998; Michel Loreau & Hector, 2001; Trenbath, 1974), by such reducing the competition (cf. 2.3.2.3) (Ashton et al., 2010; Smith et al., 1999; Trenbath, 1974). The concept of complementarity is the basic foundation of intercropping. Thanks to their differences, it should be possible to grow two or more crops in the same field, close to one another, without experiencing yield losses, as the complementarity between them should improve the use of space and resources compared to pure crops (Bulson et al., 1997; Reddy & Willey, 1981; Trenbath, 1974; Willey, 1990). The niche complementarity between plants can be based on their fundamental niches, i.e. the niche theoretically occupied by each plant, but the challenge is to maintain this complementarity also between their realised niches, i.e. the actual niche occupied by each plant, influenced by the environmental conditions and the reactions of the plants to them through phenotypic plasticity (Ashton et al., 2010). In other words, plants have a theoretical architecture – e.g. tomato plants do not look like maize plants – that can be influenced by their biotic and abiotic environment and their interactions with the neighbouring plants

– e.g. not all tomato plants are identical –. There is a dynamic equilibrium between associated plants, whose architecture and needs evolve according to their surroundings.

In intercropping, three complementary types are often distinguished (Duchene et al., 2017; Liebman & Dyck, 1993; Tofinga et al., 1993):

- The *spatial complementarity*, which refers to the fact that resource extraction takes place at different locations for each crop of the mixture (Duchene et al., 2017; Malézieux et al., 2009; Trenbath, 1974; Willey, 1990; Willey, 1996). It can be separated into shoot spatial complementarity and root spatial complementarity;
- The *nutritive complementarity*, which exists when the associated crops have different nutrient solubilisation capacities or use different chemical forms of the same resource (Duchene et al., 2017; Trenbath, 1974; Willey 1996);
- The *temporal complementarity*, which appears when the peaks of resource requirements occur at different times for each crop in the mixture (Duchene et al., 2017; Trenbath, 1974; Willey, 1990; Willey 1996).

All the complementarity types and their implications are described more precisely hereunder.

2.3.2.2.2. Shoot spatial complementarity

Related network in Appendix B.2.

The shoot spatial complementarity mainly depends on two characteristics of the plants: their height and the inclination of their leaves. By combining crops with contrasting shoot architectures – e.g. a high crop with erected leaves and a short crop with plane leaves (Awal et al., 2006; Keating & Carberry, 1993; Trenbath, 1974; Willey, 1996) – one can expect to get close to an ideal canopy. The effect of such complementarity can be twofold: (i) the radiation use efficiency (RUE) can increase (Malézieux et al., 2009), thanks to a better penetration and distribution of the incident light on the leaves (Reddy & Willey, 1981; Willey, 1990) and (ii) the amount of intercepted light can raise thanks to a better soil coverage (Gebru, 2015; Zhang et al., 2008). The RUE of the intercrop can be further improved by combining a C4 high crop with a C3 short crop (Keating & Carberry, 1993; Tofinga et al., 1993; Willey, 1990), so that each crop is exposed to the intensity of radiation that maximises its RUE (Keating & Carberry, 1993; Monteith et al., 1991; Willey, 1990; Zhang et

al., 2008). In general, the spatial shoot complementarity minimises the proportion of light that reaches the ground (de Liedekerke de Pailhe, 2014).

However, one have to keep in mind that if two crops should be complementary based on their shoot architecture in pure crop, it might not be the case in intercropping: the shadow casted by the high crop on the short crop can lead to architectural modifications of this short crop (Awal et al., 2006; Keating & Carberry, 1993), e.g. internodes elongation. This is an example of the difference between fundamental and realised niches presented above.

2.3.2.2.3. Root spatial complementarity

Related network in Appendix B.3.

The root spatial complementarity is often associated with differences in root architecture and rooting depth between crops (Duchene et al., 2017; Malézieux et al., 2009; Trenbath, 1974; Willey, 1990; Willey, 1996). As crops do not have the same root architecture and if the soil profile allows them to express their specificity, they will not exploit the same portions of the soil, which should allow to decrease competition for water and nutrients between crops. An illustration of that is provided by the experiment of Fargione & Tilman (2005): they observed a better coexistence between bunchgrasses that had different rooting depths than between those with similar rooting depths.

Besides the differences in root architecture and rooting depth between crops inherent to the phenotype of the crops, the root spatial complementarity is also often associated with the phenomenon of "vertical niche differentiation". It suggests that one crop of the mixture could force the other to root deeper than in pure crop in order to avoid competition (Mommer et al., 2010; Schroth, 1998; Trenbath, 1974; Willey, 1996). This phenomenon would be triggered either by the perception of the presence of a competitive neighbour through root exudates (Callaway et al., 2003; Depuydt, 2014; Kegge & Pierik, 2010) or by the existence of a depletion zone around the roots of the neighbouring crop (Mommer et al., 2010; Schroth, 1998).

The hypothesis of vertical niche differentiation as a driver of root spatial complementarity is however controversial. Firstly because numerous conditions have to be met for one plant to have the ability to force another one to root deeper, e.g. the soil must allow a deep root growth, the first

species must be sufficiently competitive (Schroth, 1998). Secondly because a distinction must be made between the maximum rooting depth and the root distribution: a deep-rooting system can still have the majority of its lateral roots in the first centimetres of the soil (Barron-Gafford et al., 2017; Gao et al., 2010; Schroth, 1998; Smith et al., 1999). Therefore, a difference of rooting depth is not always a guarantee for reduced competition and, more than the rooting depth, it is the root activity of each crop in the different soil horizons that should be taken into account when evaluating spatial root complementarity (Van Noordwijk et al., 2015).

It is however true that deeper rooting has already been observed for some crops in some intercrops (e.g. Gao et al., 2010; Hauggaard-Nielsen et al., 2001; Li et al., 2006). However, in the studies of Gao et al. (2010), Hauggaard-Nielsen et al. (2001) and Li et al. (2006), it was the highest-yielding and fastest-growing crop that rooted deeper, thus contradicting the hypothesis of vertical niche differentiation.

When present, the spatial root complementarity increases the volume of soil explored (Hauggaard-Nielsen et al., 2001; Hinsinger et al., 2011; Li et al., 2006) and therefore the amount of resources exploitable by plants, whether nutrients (Gao et al., 2010; Li et al., 2006) or water (Gao et al., 2010; Gebru, 2015; Hauggaard-Nielsen & Jensen, 2005; Li et al., 2006).

2.3.2.2.4. Nutritive complementarity

Related network in Appendix B.4.

As stated above, the nutritive complementarity arises when the associated crops use different chemical forms of a given resource (Duchene et al., 2017; Trenbath, 1974; Willey 1996), therefore alleviating the competition for this resource. The most common example is the intercrop between a legume and a non-legume: the legume relies on the atmospheric nitrogen, leaving the soil nitrogen for the non-legume crop it is mixed with (Jensen, 1996; Martin & Snaydon, 1982; Tofinga et al., 1993). This form of intercropping appears to be the one that provides the highest benefits (Trenbath, 1974).

A nutritive complementarity can also happen for other nutrients, such as phosphorus, as some crops are able to use inorganic phosphorus (Duchene et al., 2017; Hinsinger et al., 2011). Moreover, a nutritive complementarity can also result from differences in the quantity of resources required by each crop (Gebru, 2015; Malézieux et al., 2009; Trenbath, 1974): calcium needs can vary by a factor of four, these of potassium and phosphorus by a factor

of two and these of nitrogen by a factor of three (Gebru, 2015) between crops.

Like spatial complementarity, the nutritive complementarity allows a better use of resources, e.g. use of both the atmospheric and the soil nitrogen in an intercrop between legume and non-legume (Jensen, 1996; Weidlich et al., 2018).

2.3.2.2.5. Temporal complementarity

Related network in Appendix B.5.

The temporal complementarity is based on the spreading over time of the use of resources of the associated crops (Duchene et al., 2017; Trenbath, 1974; Willey, 1990; Willey 1996), i.e. the crops will not use the same resource at the same time. There are two common ways to obtain a temporal complementarity in a mixture. The first one is to choose to associate crops which have differences in their growth cycle lengths (Zhang & Li, 2003). According to Gebru (2015), a difference of at least 45 days is required for an efficient temporal complementarity. The second one consists in staggering the sowing/plantation dates of the paired crops (Duchene et al., 2017; Hinsinger et al., 2011; Li et al., 2014), therefore shifting also their resource needs. However, this practice can be risky, as it may favour the pre-emption of resources by the crop implemented first (Huang et al., 2017).

If the time between the harvests of the two crops is long enough, temporal complementarity can be associated with compensatory growth, i.e. the growth delay accumulated by the crop harvested second, due to competition with the other crop, can be compensated after the harvest of the latter (Awal et al., 2006; Huang et al., 2017; Zhang et al., 2017). Sometimes however, the growth delay may be too important to be overcome (Zhang et al., 2008).

The temporal complementarity induces a more complete use of resources (Willey, 1990) and an increase in resource removal – e.g. nutrients (Vandermeer et al., 1998; Zhang & Li, 2003), water (Willey, 1990) –. Nevertheless, for the spreading of the resource requirements over time to have a beneficial effect on the outcome of an intercrop, the resources must be renewable. This means that the uptake of a given resource by one crop should not prevent the other crop of the intercrop from recovering it later (Zhang et al., 2017). To avoid that, a well-thought crop management is required (Mao et al., 2015). Temporal complementarity is thought to be the most important for the interception of light, as the absorption of light by one

crop at one moment will not prevent the other crop from intercepting light later. There is a possibility of maximising the use of incident radiation by combining two crops with different growth rates (Awal et al., 2006; Keating & Carberry, 1993; Willey, 1990), as this will allow either a faster closure of the canopy and a reduction of the proportion of light reaching the ground or a longer occupation of the land and a longer period of radiation use.

2.3.2.3. Competition relationships

2.3.2.3.1. Concept

Related network in Appendix B.6.

All plants broadly use the same resources for their growth: light, water, soil nutrients, CO_2 and O_2. Competition can be defined as a process during which two plants, or two populations of plants, interact with each other in such a way that at least one has a negative impact on the growth, the survival and/or the reproduction of the other (Depuydt, 2014). For there to be competition for a resource between two plants, the uptake of this resource by one of the plants must prevent the other plant from recovering it in turn (Mommer et al., 2010; Schenk, 2006; Smith et al., 1999). Therefore, we do not consider CO_2 and O_2 as resources for which plants compete, as air fluxes are assumed to be quick enough to allow a standardisation of their concentration around all plants (Trenbath, 1974). On the other hand, plants can compete for light, water and soil nutrients (Schenk, 2006; Trenbath, 1974; Wilson, 1988). In experiments where root and shoot compartments are studied individually, the root competition, i.e. for nutrients and water, seems usually stronger than the shoot competition, i.e. for light (Martin & Snaydon, 1982), but both types of competition are linked, take part in a general balance and are, usually, mutually reinforcing (Donald, 1958). The competition for light, nutrients and water are further explained hereunder (cf. 2.3.2.3.2, 2.3.2.3.3).

Competition in intercropping is closely linked to the competitive ability of the paired crops (Andersen et al., 2007; Zhang & Li, 2003), which is the capacity of a plant to tolerate the presence of competitors and reduce their fitness (Dudley et al., 2013). It depends on many different characteristics of the plants, among which are:

- Their speed of establishment (Andersen et al., 2007; Doll et al., 1995), linked to the size and weight of their seed (Andersen et al., 2007; Baldwin, 1976; Bulson et al., 1997; Tofinga et al., 1993), their relative emergence date compared to the other crop of the intercrop (Andersen et al., 2007; Zhang et al., 2017) and their speed of root settlement (Andersen et al., 2007);
- Their growth rate (Huang et al., 2017);
- Their root biomass (Fargione & Tilman, 2005);
- Their root activity, linked to their root growth rate (Mommer et al., 2016; Pierik et al., 2012; Zhang et al., 2017) and root turnover (Mommer et al., 2016);
- Their nutrient uptake, linked to their speed of removal (Pierik et al., 2012), their efficiency of removal (Snaydon, 1996) and their selectivity of root positioning (Kegge & Pierik, 2010; Mommer et al., 2016);
- Their root architecture, linked to the number and length of root hairs (Trenbath, 1974), the fineness of their roots (Martin & Snaydon, 1982; Trenbath, 1974) and their root spreading (Trenbath, 1974);
- Their shoot architecture, linked to their height and leaf area (Huang et al., 2017; Tofinga et al., 1993; Van Noordwijk et al., 2015) and the structure of their canopy (Bulson et al., 1997);
- Their phenotypic plasticity (Callaway et al., 2003).

In general, a crop with a low competitive ability will have a positive or neutral impact on a more competitive crop, which will therefore produce as much biomass as in pure crop (Wendling et al., 2017). On the contrary, a competitive crop will cause yield losses to the less competitive crop (Wendling et al., 2017). It would therefore be interesting to know the competitive abilities of two crops before intercropping them but given the many variables on which it depends, the competitive ability of a crop is probably not quantifiable.

The competition has usually a negative impact on the yield of the intercrop (Weidlich et al., 2018; Wendling et al., 2017; Zhang & Li, 2003) as, by definition, it reduces the availability of some resources for at least one of the crops, and therefore its yield (Trenbath, 1974). However, the existence of a competition may also, in some cases, favour the allocation of the assimilates to the reproductive organs – which are usually the harvested organs – (Gebru, 2015; Huang et al., 2017; Keating & Carberry, 1993; Natarajan & Willey, 1985) and therefore lead to an increase of the harvest index (e.g. increase in the harvest index of the sorghum in a sorghum-groundnut intercrop (Azam-Ali et al. 1990)) and, thereby, of the use efficiency of the resources, in the sense that, thanks to the change in the allocation of the biomass, more harvestable biomass could be produced with the same amount of resources (Gebru, 2015; Willey, 1990).

2.3.2.3.2. Competition for aboveground resources

Related network in Appendix B.7.

Aboveground, plants compete for light, a competition that seems unavoidable (Duchene et al., 2017). In many cases, in an intercrop, one of the crop is dominant – its growth is not limited by the lack of radiation (Depuydt, 2014; Trenbath, 1974) – whereas the other crop is under the shadow casted by the dominant one and has its growth affected both by the lack of incident light (Duchene et al., 2017; Tsubo et al., 2001; Zhang et al., 2008) and by the lower temperatures it faces (Zhang et al., 2008). Competition for light is referred as “size-asymmetric” (Dudley et al., 2013; Huang et al., 2017; Pierik et al., 2012) because the competitive ability of plants regarding light is more than proportional to their size: high plants will shade the shorter ones and intercept disproportionally more light (Dudley et al., 2013; Huang et al., 2017).

2.3.2.3.3. Competition for belowground resources

Related network in Appendix B.8.

Belowground, plants compete for water and nutrients. The competition for nutrients occurs for as many as 20 different nutrients, each one with its own properties and mobility in the soil (Malézieux et al., 2009). However, plants are more likely to compete for mobile nutrients, e.g. nitrogen, than for immobile nutrients, e.g. potassium, phosphorus, as the root depletion zones for mobile nutrients are more likely to overlap quickly (Bray, 1954; Fusseder et al., 1988; Schroth, 1998; Trenbath, 1974). The competition for nutrients

can take two forms: (i) either one of the plant develops quicker, removes nutrients faster – often at the expense of the use efficiency – and exhausts the soil, (ii) or some mechanisms prevent the roots from the other plant to access the resources (Schenk et al., 1999; Schenk, 2006). In the first case, we talk about "scramble competition" or "exploitation competition" whereas in the second one, we speak of "contest competition" or "interference competition" (Schenk, 2006).

The competition for nutrients is not referred as "size-asymmetric" (Dudley et al., 2013; Huang et al., 2017) but is associated with the ability of each plant to develop rapidly in the nutrient-rich patches of the soil (Mommer et al., 2016; Pierik et al., 2012; Schroth, 1998) and therefore, to uptake resources before the others (Hodge, 2009). The competition for nutrients is also influenced by soil properties, e.g. the spatial heterogeneity of resources in the soil (Schenk, 2006), and by crop management (Schroth, 1998; Wendling et al., 2017). It can promote the root proliferation – which can therefore be higher than in pure crop – and thanks to this, may cause an increase in the total uptake of nutrients and an improvement in biomass production (Ren et al., 2017). In the case of an intercrop between a legume and a non-legume, the competition for nitrogen can even promote the nutritive complementarity by forcing the legume to rely more on the atmospheric nitrogen than in pure crop (Latati et al., 2016; Trannin et al., 2000): Latati et al. (2016) observed a better efficiency in the use of the rhizobial symbiosis for cowpeas intercropped with maize than for cowpeas in pure crop.

2.3.2.3.4. Allelopathy

Besides the competition for resources, intercropping may also have a negative impact due to allelopathy, i.e. chemical interactions between plants (Molisch, 1937, cited by (Jabran, 2017)). Some crops may indeed release compounds that prevent the growth of their companion crops (Rice, 2012). A well-known example, among many others (e.g. Rice, 2012) is the one of black walnut, whose juglone reduces the growth of many other crops (Jose & Holzmueller, 2008). Negative allelopathic effects are therefore a phenomenon that one must take into account when designing intercrops, keeping in mind that the nature of the exuded allelopathic compounds and the sensitivity to different allelopathic compounds are crop specific, i.e. a crop A releasing allelopathic compounds may be detrimental, in intercropping, to a crop B but not to crop C, insensitive to its allelopathic compounds. In addition to the negative effect the exudates from one crop

can have on another crop, there can also be negative allelopathic effect between plants of the same crop. This is a specific form of allelopathy called autotoxicity, i.e. the inhibition, by a plant, of the germination and growth of other individuals from the same kind through the release of secondary metabolites (Singh et al., 1999). Because of the autotoxicity of some crops, allelopathy is a challenge not only in intercrops but also in pure crops (e.g. Ben-Hammouda et al., 2002; Hedge & Miller, 1990; Miller, 1996; Singh et al., 1999).

2.3.2.4. Facilitation relationships

2.3.2.4.1. Concept

The facilitation refers to the positive interactions that can occur between crops (Duchene et al., 2017; Li et al., 2006; Wendling et al., 2017), i.e. mechanisms through which one plant can improve the growth and/or the survival of others (Hauggaard-Nielsen & Jensen, 2005; Hinsinger et al., 2011; Malézieux et al., 2009). Examples of such mechanisms include resource transfers (Callaway, 1995; Li et al., 2014; Van Noordwijk et al., 2015; Weidlich et al., 2018), solubilisation of nutrients (Duchene et al., 2017; Hinsinger et al., 2011; Latati et al., 2016; Li et al., 2014; Schenk, 2006) or improvement of plant defences (Hauggaard-Nielsen & Jensen, 2005). In intercropping, facilitation may help to counteract for the effects of competition and contribute to a higher yield (Duchene et al., 2017; Erskine et al., 2006). However, some conditions are required in order for the facilitation to have an impact.

Firstly, some facilitation processes depend to a certain extent on the rhizosphere microbial biomass: increasing the diversity of plants may change the composition of the soil microbiomass (cf. 2.3.2.6.2) and promote the beneficial interactions between crops and soil microorganisms (Duchene et al., 2017). However, for these facilitation interactions to settle, undisturbed soil and time may be needed and for these reasons, they seem to be more frequent in perennial systems (Duchene et al., 2017).

Secondly, some interactions require the roots of the two plants to be close (Hauggaard-Nielsen & Jensen, 2005; Hinsinger et al., 2011; Zhang & Li, 2003). Nevertheless, if the closeness of the roots of two plant species may favour the facilitation, it can also increase the competition between them: a balance must be found between a complete segregation or a complete aggregation of the roots of the two crops (Zhang & Li, 2003). Facilitation is also thought

to be more frequent when the environmental stresses are high, as stated by the "stress gradient hypothesis" (Hinsinger et al., 2011).

Four groups of facilitation processes are often discussed in intercropping: mobilisation and transfer of nutrients, transfer of water, reduced impact of pests and diseases and reduced impact of weeds, which are all described hereunder.

2.3.2.4.2. Mobilisation and transfer of nutrients

Related network in Appendix B.9.

The transfer of nutrients between crops can be direct or indirect: either plants are connected to one another – e.g. through mycorrhizal network (cf. 2.3.2.5.2) or root grafts (Callaway, 1995; Simard et al., 2012) – and they can exchange nutrients directly through this connection or one plant increases the availability of nutrients for the other through the physical, chemical and/or biological changes it causes to the soil (Duchene et al., 2017). Direct transfers of nutrients between plants have mostly been observed either in controlled environments or in diversified grasslands, which stay in place much longer than annual intercrops. The results of these studies is of course of interest, but they must be analysed with caution, as many more factors that can influence the transfer of nutrients intervene in a real field (Barto et al., 2012; Giller et al., 1991) and as such interactions may not develop between annual plants.

The indirect transfers of nutrients may depend on the solubilisation of nutrients by mycorrhizal fungi (Thirkell et al., 2017; Van Noordwijk et al., 2015) (cf. 2.3.2.5.2) but they can also rely on "mobilising plants", which are plants that are able, through the secretion of some compounds in the rhizosphere (Tarafdar & Jungk, 1987), to convert a poorly available soil resource into a directly available form (Duchene et al., 2017; Hauggaard-Nielsen & Jensen, 2005; Li et al., 2014; Pierik et al., 2012). If the roots of a neighbouring plant are close enough to these of a mobilising plant (Jensen, 1996b), it can benefit from a higher resource availability (Li et al., 2007, 2014; Mommer et al., 2016; Pierik et al., 2012; Zhang & Li, 2003), which can then lead to a higher biomass production (Li et al., 2007).

Among mobilising species, one type is particularly studied: the legumes. Firstly, thanks to their ability to fix the atmospheric nitrogen, legumes can enrich the soil in nitrogen through the decomposition of the legume root system once it is harvested (Cong et al., 2015; Duchene et al., 2017; Weidlich

et al., 2018) and/or through the root and nodule turnover (Duchene et al., 2017; Hauggaard-Nielsen & Jensen, 2005). This additional nitrogen is then available for the paired crop (Li et al., 2009). Nevertheless, it seems that the amount of nitrogen recovered in this way by the non-legume remains small or undetectable (Giller et al., 1991; Jensen, 1996b). Secondly, legumes are also able to mobilise phosphorus as they excrete protons, during the nitrogen fixation process, and carboxylates in the rhizosphere (Hauggaard-Nielsen & Jensen, 2005; Hinsinger et al., 2011). This mobilisation can be enhanced in intercropping: the competition for nitrogen with the non-legume crop can force the legume to rely more on the atmospheric nitrogen, which increases the excretion of protons and, therefore, the solubilisation of phosphorus (Hinsinger et al., 2011; Latati et al., 2016). On the other hand, the phosphorus reinforces the symbiosis between the legume and the Rhizobium bacteria (Duchene et al., 2017). There are some evidence of indirect transfer of phosphorus between intercropped legume and non-legume in controlled environment (wheat/sorghum + pigeon pea, wheat + chickpea, maize + groundnut) and in field (maize + faba bean) (Li et al., 2007, 2014). However, to take place, they require a close proximity between the roots of the two species (Hauggaard-Nielsen & Jensen, 2005; Hinsinger et al., 2011).

Indirect transfer of nutrients can also happen for iron – some crops are able to solubilise the iron (III) (Li et al., 2014; Qiao et al., 2016) – calcium, potassium, magnesium, aluminium and zinc – through the acidification of the rhizosphere, the excretion of carboxylates (Hauggaard-Nielsen & Jensen, 2005) or the excretion of phytosiderophores (Li et al., 2014) –.

2.3.2.4.3. Transfer of water

Related network in Appendix B.10.

The main phenomenon of water transfer described in intercropping is the “hydraulic lift”: some deep-rooting crops can bring the water from deep wet horizons to shallow dry horizons through a passive movement – through their roots – which tends to homogenise the water distribution in the rooting zone (Barron-Gafford et al., 2017; Callaway et al., 2003; Pang et al., 2013; Sekiya et al., 2011; Van Noordwijk et al., 2015). In intercropping, this process may increase the water availability of shallow-rooting species (Pang et al., 2013; Schroth, 1998; Sekiya et al., 2011), thereby potentially improving their chances of survival in dry conditions (Pang et al., 2013; Sekiya et al., 2011; Van Noordwijk et al., 2015) as well as their water uptake (Barron-Gafford et al., 2017; Schroth, 1998) and, by extension, their production of biomass

(Sekiya et al., 2011). However, the extent of the beneficial effect of the hydraulic lift may remain small (Callaway, 1995; Van Noordwijk et al., 2015) or may even be non-existent (Sekiya et al., 2011). Moreover, even if we generally speak about a hydraulic "lift", this phenomenon can also take place in the other way around: if the shallow horizons are wetter than the deep horizons of the soil, water can flow from the surface to the deep soil through the roots of the deep-rooting crop, thereby reducing the water availability for the shallow-rooting intercropped species (Barron-Gafford et al., 2017; Pang et al., 2013). Therefore, the term "hydraulic redistribution" would be more adapted than "hydraulic lift" (Barron-Gafford et al., 2017; Sekiya et al., 2011).

Despite these multiple demonstrations of the hydraulic lift phenomenon in intercropping, the complexity of the process makes it hard to predict its extent and consequences in a particular intercrop.

2.3.2.4.4. Reduced impact of pests and diseases

Various processes intervene in the reduction of the impact of pests and diseases in intercropping (Gómez-Rodríguez et al., 2003; Hauggaard-Nielsen & Jensen, 2005; Kinane & Lyngkjaer, 2002; Liebman & Dyck, 1993; Theunissen, 1994), among which some depend on the excretion of chemical compounds by one of the plants and can be categorised as facilitation mechanisms. This section will focus on this type of mechanisms whereas the others will be explained in section 2.3.2.6.2.

Firstly, some crops can deliver in the rhizosphere or in the air allelopathic compounds that reduce the incidence and/or severity of some pests and diseases (Boudreau, 2013; Gómez-Rodríguez et al., 2003; Malézieux et al., 2009). This is the case of the plants from the Brassicaceae family, which excrete in the soil isothiocyanates that have a suppressive effect on some pathogens (Hauggaard-Nielsen & Jensen, 2005; Motisi et al., 2009; Rumberger & Marschner, 2003; Singh et al., 2001). Introducing such crops in an intercrop could therefore help to act against some pathogens and pests.

Secondly, a crop can also benefit from the volatile organic compounds that its companion crop secrete to attract predators of a pest after being attacked (Ramovš, 2013).

Finally, plants around a wounded plant can perceive the compounds that it emits in the soil and in the air and react by reinforcing their immune defences (Dicke et al., 2003; Heil & Adame-Álvarez, 2010; Kegge & Pierik, 2010; Pierik

et al., 2012; Ramovš, 2013), therefore creating a healthy and resistant plant shield around the injured plant and reducing the dispersion of the pest or pathogen (Barto et al., 2012).

2.3.2.4.5. Reduced impact of weeds

Just as for pests, some plants have the ability to reduce the growth of weeds through the excretion of allelopathic compounds (Gebru, 2015; Liebman & Dyck, 1993; Malézieux et al., 2009; Singh et al., 2001). This is illustrated by the decrease in the growth of purple nutsedge observed by Iqbal et al. (2007) in cotton field when cotton was intercropped with either soybean, sorghum or sesame. Introducing such crops in an intercrop could therefore help to reduce the weed management required. However, this demands that the weeds are more sensitive to these allelopathic compounds than the intercropped species (Liebman & Dyck, 1993). Other processes intervene in the reduction of weed impact in intercropping but cannot be classified as "facilitation", as they are secondary consequences of competition and complementarity interactions between companion plants. They are therefore described in section 2.3.2.6.2.

2.3.2.4.6. Other examples of facilitation

Some other forms of facilitation exist: for example, the germination of seeds can be enhanced by the presence of another crop (Gagliano et al., 2012), the growth of some plants (Hauggaard-Nielsen & Jensen, 2005; Mommer et al., 2010; Ries et al., 1977; Søgaard & Doll, 1992), as well as the symbiosis with soil microorganisms (Jiao et al., 2017) can be stimulated by neighbouring plants and the presence of a taller companion crop can protect the shorter one from the direct sunlight which can lead to a better quality of the products at harvest (e.g. more uniform ripening of coffee in agroforestry (Muschler, 2001)).

2.3.2.5. Influence of the environment on the complementarity-competition-facilitation balance in intercropping

The first part of this summary focused on the presentation of the processes taking part in complementarity, competition and facilitation interactions between intercropped plants. Its second part will deal with the balance between these three types of interactions, which determines the outcome of an intercrop. This balance depends on many factors, among which are the

abiotic environment (Azam-Ali et al., 1990; Callaway, 1995; Callaway & Walker, 1997; Hinsinger et al., 2011; Malézieux et al., 2009), the biotic environment (Schenk, 2006) and the crop management practices (Ren et al., 2017), whose effects are described in the following sections.

2.3.2.5.1. Abiotic environment

Related network in Appendix B.11.

The abiotic environment has an impact on the balance between competition, complementarity and facilitation, both aboveground and belowground. In fact, aboveground, plants are able to evaluate the quality of the light (cf. 2.3.2.1). Thanks to their phytochromes, they perceive the reduction of the red/far red ratio in the light transmitted and/or reflected by the leaves of another plant (Franklin, 2008; Franklin & Whitelam, 2005; Keating & Carberry, 1993) and they can react accordingly: internodes elongation, increase in the allocation to shoot biomass compared to root biomass, leaf thinning, increase in the leaf area, etc. (Keating & Carberry, 1993; Kegge & Pierik, 2010; Pierik et al., 2012; Tsubo et al., 2001). All these modifications aim at directing the foliar organs of the plant to the holes in the canopy so that its light interception can be enhanced (Karban, 2008; Zhu, 2015). Apart from the reduction of the red/far red ratio, plants are also able to perceive, thanks to cryptochromes, the reduction of the blue photons rate in the incident light (Chen et al., 2012; Kegge & Pierik, 2010; Pierik et al., 2012; Zhu, 2015).

At the belowground level, plants are able to orientate the growth of their roots according to the availability of nutrients, in order to proliferate in nutrient-rich zones (Fitter, 1976; Hodge, 2009; Pierik et al., 2012; Schroth, 1998) and to get away from the depleted zones of the soil (Hauggaard-Nielsen & Jensen, 2005; Semchenko et al., 2014). This feature is important in intercropping, as the first crop to establish its roots in a nutrient-rich patch is likely to get a competitive advantage over the crop it is paired with (Callaway et al., 2003; Pierik et al., 2012), as long as the cost of rapid proliferation is compensated by the uptake of nutrients from the patch (Hodge et al., 1999). As roots are able to react in many different ways – modification of the root exudation, position, density, absorption, etc. – to many different signals – nutrients availability, nutrient identity, physical obstacles, etc. – the abiotic environment can completely change the root architecture of plants in a way that is difficult to predict (Hodge, 2009; Schenk et al., 1999) and can

therefore increase or decrease both the root spatial complementarity and the root competition between associated crops.

2.3.2.5.2. Biotic environment

Related network in Appendix B.12.

Plants are able to recognise and to differentiate between pests and facilitators thanks to elicitors, i.e. molecules excreted by these organisms and present at their surface (Perry et al., 2007). In the soil, plants can also be influenced by volatile compounds secreted by microorganisms (Perry et al., 2007; Venturi & Keel, 2016). The micoorganisms can influence the quantity and the composition of the root exudates of the plants (Badri & Vivanco, 2009; Mommer et al., 2016; Perry et al., 2007; Schenk et al., 1999). The interaction between a plant and another organism can lead to different reactions: activation and stimulation of plant defences (Duchene et al., 2017; Perry et al., 2007; Venturi & Keel, 2016), production of volatile compounds (Karban, 2008; Ramovš, 2013), compensatory growth (Callaway et al., 2003), modification of the root architecture (Badri & Vivanco, 2009; Duchene et al., 2017; Perry et al., 2007; Venturi & Keel, 2016), etc. By having such impacts on the plants, as well as on the availability of nutrients in the soil (Bargaz et al., 2017; Brussaard et al., 2007; Hinsinger et al., 2011; Perry et al., 2007; Schenk, 2006), there is no doubt that the interactions between plants and microorganisms can have an impact on complementarity, competition and facilitation. However, the effects are so diverse that it is hard to predict which type of interactions the biotic environment will influence the most.

Among soil microorganisms, one seems to be of major importance in intercropping: the mycorrhizal fungi. Mycorrhizae consist of a symbiosis between the roots of a plant and a fungus (Gorzelak et al., 2015). The setting up of this symbiosis is dependent on environmental factors as well as on genetic characteristics of the plant (Tagu et al., 2001) and is therefore not guaranteed. However, when it happens, a symbiosis with mycorrhizal fungi allows plants to get access to a larger pool of soil resources (Gorzelak et al., 2015; Thirkell et al., 2017) through both an increase of the volume of soil explored and the solubilisation of unavailable nutrients (Thirkell et al., 2017; Van Noordwijk et al., 2015). Therefore, mycorrhizal fungi usually promote the growth of their host plant by increasing their uptake of nutrients (Qiao et al., 2016), mainly immobile ones (Van Noordwijk et al., 2015), and may influence the competition relationships between associated crops as well as indirect nutrient transfer (cf. 2.3.2.4.2). Mycorrhizal fungi can also repel pests

through the exudates they release (Perry et al., 2007; Wamberg et al., 2003) and activate the induced systemic resistance of their host (Duchene et al., 2017; Orrell & Bennett, 2013; Perry et al., 2007; Thirkell et al., 2017).

In intercropping, one of the most important feature of mycorrhizal fungi is their ability to form a network linking several plants from the same or from distinct species (Gorzelak et al., 2015; Hinsinger et al., 2011; Qiao et al., 2016; Yao et al., 2003), therefore offering the possibility of a bidirectional transfer of biochemical signals, i.e. stress and allelopathic molecules, and resources, i.e. nutrients and water, between the different crops of a mixture (Gorzelak et al., 2015; Hinsinger et al., 2011; Li et al., 2014; Qiao et al., 2016; Simard et al., 2012; Thirkell et al., 2017; Yao et al., 2003). The direction of the transfer depends on the relative nutritional status of each plant and can vary throughout the season (Gorzelak et al., 2015; Simard et al., 2012). By facilitating transfers between crops, mycorrhizae are likely to influence the complementarity-competition-facilitation balance among intercrops, for example by rebalancing resource sharing between component crops (Gorzelak et al., 2015; Mommer et al., 2016; Qiao et al., 2016; Simard et al., 2012), by promoting the establishment of seedlings, i.e. nursing effect (Callaway, 1995; Callaway & Walker, 1997; Eason et al., 1991; Gorzelak et al., 2015; Simard et al., 2012), by favouring one of the crop (Qiao et al., 2016; Simard et al., 2012) or by transferring allelopathic molecules over longer distances (Gorzelak et al., 2015; Thirkell et al., 2017). Transfers of resources between mixed crops through mycorrhizal fungi have already been observed (Gebru, 2015; Li et al., 2009; Simard et al., 2012; Trannin et al., 2000; Yao et al., 2003) but their significance is under debate, as it seems that the transferred quantities are too negligible to influence the growth of the receiving plants (Giller et al., 1991; Trannin et al., 2000; Yao et al., 2003).

2.3.2.5.3. Crop management practices

Related network in Appendix B.13.

By modifying the abiotic environment, the crop management practices, e.g. fertilisation, irrigation, etc., can affect the complementarity, competition and facilitation relationships in the same way the abiotic environment does (cf. 2.3.2.5.1.). Besides, the choices made by the farmer regarding the spatial organisation, i.e. number of rows of each crop, density, orientation of the rows, planting distances, and the temporal shift between the plantation/sowing of the crops can influence the interactions between the associated crops (e.g. Addo-Quaye et al., 2011; Chaves et al., 2020; Cheriere

et al., 2020; Willey & Rao, 1981; Zhang et al., 2008). For instance, a high planting density may favour competition, but a low density leads to an inefficient use of resources (de Liedekerke de Pailhe, 2014); a large time gap between the plantation/sowing of the two crops may favour the dominance of one crop on the other but could also make compensatory growth possible (e.g. Addo-Quaye et al., 2011; Huang et al., 2017).

2.3.2.6. Impact of intercropping on the environment

If the abiotic and biotic environment can influence the interactions between associated crops, the reverse is also true and the set up of intercropping can modify the abiotic and biotic surroundings. This is the focus of the present section, with the description of the effect on the abiotic environment first and the biotic environment second.

2.3.2.6.1. Abiotic environment

Related network in Appendix B.14.

Regarding the abiotic environment, intercropping mainly has an effect on the soil and on the microclimate of the plot.

Regarding the soil, firstly, if an intercrop has a longer or a better soil coverage than the corresponding pure crops, it can protect the soil better against desiccation (Gebru, 2015), organic matter oxidisation (Trenbath, 1999) and erosion (Gebru, 2015; Malézieux et al., 2009; Theunissen, 1997b; Trenbath, 1999; Van Noordwijk et al., 2015). It can also increase the soil humidity (Callaway & Walker, 1997) by favouring water infiltration (Duchene et al., 2017; Willey, 1990) as well as improving soil stability (Callaway & Walker, 1997).

Secondly, crop mixtures can reduce nutrient leaching. As a mixture of crops can include plants with different rooting depth and induce an increase in total root biomass (Cong et al., 2015), some of the nutrient leached from the soil surface can be recovered in depth (Gebru, 2015; Malézieux et al., 2009; Schroth, 1998; Van Noordwijk et al., 2015; Wendling et al., 2017). The absorbed nutrients become available for shallow-rooted species once the roots and leaves of the plant that retrieved them decay (Callaway, 1995; Cong et al., 2015; Gebru, 2015; Malézieux et al., 2009; Van Noordwijk et al., 2015). Therefore, a shallow-rooted and slow-growing crop could benefit from the nutrients absorbed in depth by a deep-rooted and fast-growing crop. Through this phenomenon, intercropping allows for a better nutrient

cycling and a more efficient use of resources (Malézieux et al., 2009) than pure crops. By adapting the sowing/plantation dates of the mixed crops, one can favour the use of the residues of one of the crop by the other (Duchene et al., 2017).

Thirdly, the introduction of intercropping can affect the physical and chemical properties of the soil. In fact, plants affect their environment through the exudates they secrete and the decomposition of the residues they leave in the soil (Hauggaard-Nielsen & Jensen, 2005; Jensen, 1996a; Van der Krift et al., 2001; Wamberg et al., 2003). As the composition and the rate of deposition of the residues and the exudates vary according to plant species (Hauggaard-Nielsen & Jensen, 2005; Van der Krift et al., 2001), the impact on the soil will change when switching from a pure crop to an intercrop (Hauggaard-Nielsen & Jensen, 2005). The rate of organic matter mineralisation, for example, might change as the C/N ratio of the soil will be modified (Cong et al., 2015; Trannin et al., 2000; Wendling et al., 2017). Moreover, intercropping can lead to an increase in residues deposited on the soil (Cong et al., 2015) as well as an increase in root activity and root biomass and, therefore, in an increase in rhizodeposition (Duchene et al., 2017; Mommer et al., 2010; Van der Krift et al., 2001). Through these two phenomena, intercropping can improve soil carbon content, nutrient storage in soil and soil exchange capacity (Duchene et al., 2017) as well as soil aggregation (Duchene et al., 2017), root penetration (Duchene et al., 2017), water infiltration (Duchene et al., 2017), soil water distribution (Barron-Gafford et al., 2017, p.; Callaway et al., 2003; Van Noordwijk et al., 2015) and soil water storage (Callaway, 1995).

Through these effects, the introduction of intercropping might be positive both on a short-term scale, with the yield increase, and on a long-term scale, with the improvement of soil protection, fertility and stability through root activity.

Despite the many examples of positive effects of intercropping on the physical and chemical properties of the soil, some argue that intercropping, by producing more biomass and exporting more resources from the soil, might deplete the soil more rapidly than pure crops (Li et al., 2014; Reddy & Willey, 1981; Willey, 1990; Willey, 1996) and may increase the need for fertilisers (Willey, 1990). More research – especially long-term research – is required to come to a decision regarding this matter.

Regarding the microclimate, switching from a pure crop to an intercrop may affect the temperature, the shadow, the soil and air humidity and the wind (Boudreau, 2013; Duchene et al., 2017; Gómez-Rodríguez et al., 2003; Keating & Carberry, 1993; Ofori & Kyei-Baffour, 2010) due to the modification of the canopy architecture. These effects might be beneficial and promote crop growth (Hauggaard-Nielsen & Jensen, 2005; Liebman & Dyck, 1993). For example, a canopy with a better or a faster ground cover, as can be observed in intercropping, may reduce air and soil temperature (Boudreau, 2013; Gebru, 2015; Monteith et al., 1991; Ren et al., 2017) and air movement (Gebru, 2015; Monteith et al., 1991; Ren et al., 2017; Zhang et al., 2008), which, in turn, reduces soil evaporation (Callaway, 1995; Gebru, 2015) and may alleviate competition for water between component crops (Ren et al., 2017). These effects could also decrease the evaporative demand of the plants (Zhang et al., 2008) and improve the water use efficiency (Monteith et al., 1991). Nevertheless, microclimatic changes are complex and vary according to the density and the spatial organisation of the plot (Boudreau, 2013).

2.3.2.6.2. Biotic environment

Related network in Appendix B.15.

The diversity of root exudates and plant residues in intercropping can affect the composition of the soil microbial biomass (Badri & Vivanco, 2009; Fitter, 1976; Mommer et al., 2016; Schenk, 2006; Walker et al., 2003; Wamberg et al., 2003). When the roots of two different crops intermingle, the exudates of both crops influence the microbial biomass, therefore changing its composition (Christie et al., 1974) and creating microbial biomass common to both crops (Hinsinger et al., 2011). However, the common microbial biomass might not always be a mix of the microbial biomass of the component crops: Bargaz et al. (2017) observed, in a wheat-soybean intercrop, important changes in the composition of the microbial biomass for wheat but not for soybean. The microbial biomass associated to one of the component crops may become predominant in the mixture. Nevertheless, the microbial biomass usually tends to be more diverse and balanced in intercropping than in pure crop (Bargaz et al., 2017), with less pest emergence (Hauggaard-Nielsen & Jensen, 2005; Mommer et al., 2010) and more beneficial organisms (e.g. mycorrhizae (Thirkell et al., 2017)). The microbial biomass is also more active (Hauggaard-Nielsen & Jensen, 2005), stimulated by the the more varied and continuous supply of carbohydrates

in the soil and the higher nutrient flows (Duchene et al., 2017; Vandermeer et al., 1998), and larger (Christie et al., 1974) under crop mixtures than in pure crops.

Besides the impacts on the soil microbial biomass, intercropping can also have major effects on crop pests and their predators. Reduction of pest incidence has been observed in intercropping (Gómez-Rodríguez et al., 2003; Hauggaard-Nielsen & Jensen, 2005; Kinane & Lyngkjaer, 2002; Liebman & Dyck, 1993; Theunissen, 1994).

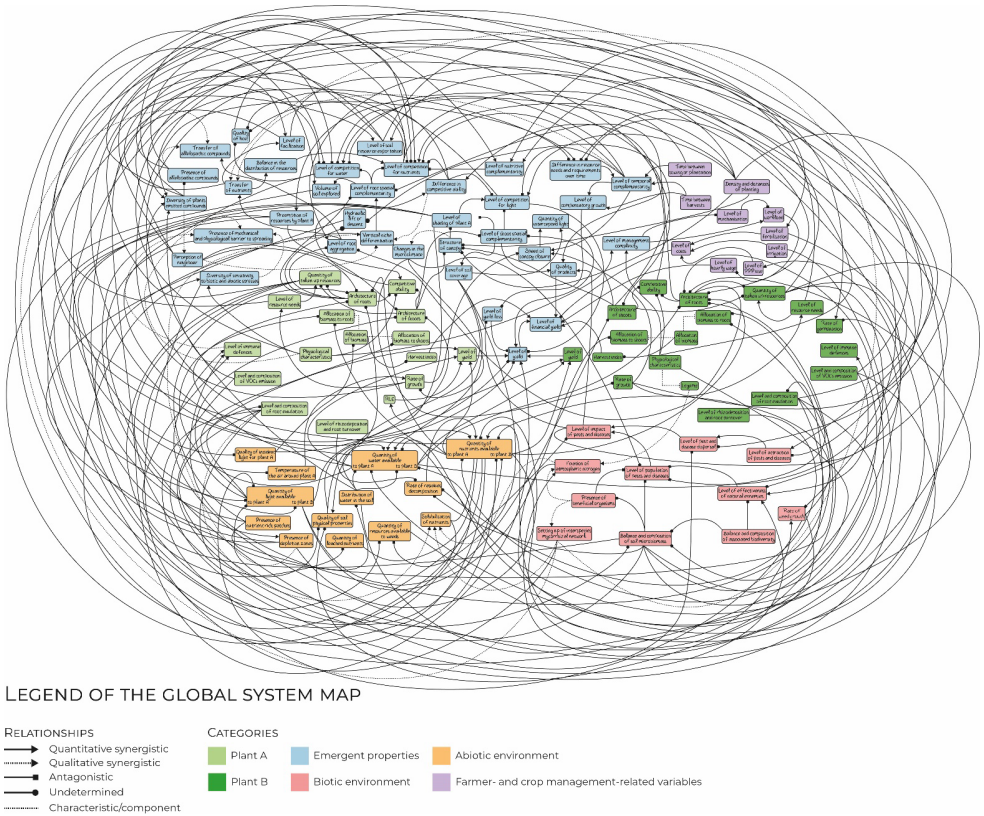
We already explained, in section 2.3.2.4.4, that some crops can have a negative impact on pests and diseases through their exudates. However, other mechanisms help reduce the impact of pathogens and insects on the crops in intercropping. Firstly, an intercrop can be designed to contain both trap plants (Khan, 2008; Poveda & Kessler, 2012), i.e. plants that will attract pests, therefore preventing them from attacking another crop of higher marketable value (Gurr et al., 2003; Malézieux et al., 2009; Smith & McSorley, 2000), and crops that, thanks to the volatile compounds they release, will push pests out of the field (Khan, 2008; Poveda & Kessler, 2012). This is called the "push-pull strategy" (Khan, 2008; Poveda & Kessler, 2012). Secondly, there can be, in intercropping, an olfactory interference for pests and pathogens. Pests and pathogens indeed use the volatile compounds emitted by plants to find their way (Holopainen & Blande, 2012; Perry et al., 2007) and may have difficulties distinguishing the molecules emitted by their host plant, as they can be masked by other molecules, released by the associated crop (Theunissen, 1994). However, the same can also happen to the natural enemies of the pests, which might therefore be less efficient. Thirdly, pests and pathogens may be less attracted by their host plant in an intercrop than in a pure crop due to changes in the quality of the host caused by competition in intercropping (Theunissen, 1994). Fourthly, the crop associated to the host plant may act as a mechanical barrier and prevent the spread of the pest/pathogen and the modification of the microclimate linked to the changes in the canopy architecture of the field may reduce its development (Theunissen, 1994). Finally, as different crops have different sensitivity to pests and pathogens, one specific pest/pathogen could develop more slowly in an intercrop than in a pure crop, as not all the plants surrounding the first plant to be attacked will be a potential host (Gómez-Rodríguez et al., 2003). The density of the host plant may also be reduced compared to the pure crop, e.g. in a replacement design (cf. Figure 1, Chapter 1), which may further decrease the spread of the pest/pathogen (Boudreau, 2013).

Finally, in intercropping, because of the better use of available light, water and nutrients than in pure crops (cf. 2.3.2.2) and/or thanks to the exudates of some crops (cf. 2.3.2.4), the impact of weeds can be reduced (Bulson et al., 1997; Gebru, 2015; Liebman & Dyck, 1993; Malézieux et al., 2009; Singh et al. 2013).

2.3.3. Thematic interaction networks & Intercropping system map

In order to complement the text presented above, which is linear and may not allow to sense the interconnections between the different processes that we described, we drew networks of interactions. The fifteen resulting networks are presented in Appendix B. They differ greatly in complexity according to their focus: the number of nodes ranges from 20 up to 51. All networks are spatially organised in the same way and show the relationships between six compartments: the two plants, the abiotic environment, the biotic environment, the interactions and emergent properties of the intercrop and the farmer- and crop management-related variables. Compartments are differentiated using a colour code, as explained in section 2.2.3.

The main interactions represented in the fifteen networks are gathered in a global system map (Figure 8), which reflects the complexity of the system and the many objects intervening in it: it comprises 106 nodes and 237 links. It is however possible to find somewhat organisation within this complexity. The yield of the intercrop was chosen as the central node of the system map, as it is the variable on which most papers focus. The nodes are organised and colored in the same way as in the thematic interaction networks, therefore distinguishing between the nodes linked to the crops, the emergent properties of the intercrop and interactions between crops, the crop management and the biotic and abiotic environments. Based on the current map, it should be possible to color the links according to the color of their starting/ending node so that it highlights, for example, which compartments interact the most together.


LEGEND OF THE GLOBAL SYSTEM MAP
RELATIONSHIPS
Quantitative synergistic
Qualitative synergistic
Antagonistic
Undetermined
Characteristic/component
CATEGORIES
Plant A
Plant B
Emergent properties
Biotic environment
Abiotic environment
Farmer- and crop management-related variables

2.4. DISCUSSION

This chapter aimed at making an inventory and explaining the interactions and processes that can take place in an intercrop, in a systemic way. In our opinion, it is its systemic and process-oriented nature that makes our review different from other reviews focused on intercropping. In fact, instead of focusing on one part of intercropping (e.g. advantages compared to monocropping (Gebru, 2015), pest management (Chi et al., 2021; Smith & McSorley, 2000), facilitative interactions (Hauggaard-Nielsen & Jensen, 2005)), on one crop or intercrop (e.g. Duchene et al., 2017; N. Iqbal et al., 2019; Mutsaers et al., 1993; Ouma, 2009) or on a specific resource (e.g. Yin et al., 2020), our centre of attention was the interactions and processes that underpin the outcome, benefits and drawbacks of intercrops, including all types of intercrops, resources and advantages. Our objective was to map, in the most comprehensive way, the functioning of intercropping. It is in order to achieve this goal and to be as accurate as possible in our descriptions that we dug into scientific literature targeting directly intercropping but also into scientific literature linked indirectly to intercropping, e.g. ecology papers, phenotypic plasticity papers, mycorrhiza papers, etc.

The text we wrote based on our literature review highlights the high diversity of mechanisms and objects involved in intercropping and how they interact. It is, according to us, an interesting starting tool for intercropping study, as it gives a global view of the intercropping system and should allow a researcher to make an informed choice regarding the object of his/her study and help him/her to formulate hypotheses.

2.4.1. NETWORKS OF INTERACTIONS & GLOBAL SYSTEM MAP

Besides our approach, another element that makes our review stand out is the creation of networks of interactions and of a global system map. According to us, the networks of interactions allow the reader (i) to see easily to which compartments – i.e. the plants, the interactions, the biotic and abiotic environments or the crop management and farmer-related variables – the objects mentioned in the text belong and (ii) to detect better the interconnections between these compartments. The networks and their index (cf. Appendix B.16) can also serve to find (i) on which intercropping-related theme a particular node, i.e. object, intervene and have an influence and (ii) to which other nodes this particular node is linked, i.e. the nodes it affects and is affected by.

The global system map further complements the networks of interactions by giving a global picture of the intercropping system and the main objects to be considered when studying it. This global system map is of course a simplification of the reality, as a balance must be found between readability and level of details. Nevertheless, it shows the high complexity of the system and the many connections that exist between its components. In our opinion, three readings of it are possible.

The first one consists in looking at the map in its entirety to (i) identify the main variables in each compartment and (ii) see, in the case of a map with colored links as proposed in section 2.3.3, the links coming from/arriving to one particular compartment. This first reading allows to have a global understanding of what are the main variables to be considered and which are the compartments that may interact the most.

The second one entails watching a particular node and, as proposed for the thematic networks, identifying the nodes to which it is linked. This enables a researcher to see on which variables a specific variable has an impact and by which variables it is affected. This could be an interesting reading for a researcher who is focusing on one particular node and wants to know what other elements he/she should consider in his/her study.

Finally, the third one is to focus on the central node, i.e. the yield of the intercrop, and to read the map in stages, as proposed by Vandebroeck et al., (2007) for the use of the "Obesity System Map". In the case of the intercropping system map we drew, this would mean starting by the node "Level of yield" and going every time a step further, i.e. a link further, to see which variables influence the "Level of yield", then which variables affect these variables, etc. In the "Obesity Sytem Map", this way of seeing the map allows to identify leverages to act against the obesity problem (Vandebroeck et al., 2007). In the case of intercropping, it allows to pinpoint important processes and, possibly, to highlight the potential role of some variables that may have been overlooked – or less studied – so far. It could guide researchers in their choice of focus and/or in their formulation of hypotheses in their studies about intercropping.

The networks of interactions and the global system map complement each other, as the thematic networks can be seen as a zoom on some of the interactions drawn in the global system map, and supplement the linearity of the text by allowing a better representation of the interconnections between the elements of the intercropping system. We are however aware

that there is a question of affinity as to the interest that this graphic representation of things represents for a given person but we stay convinced that it can be of help for some researchers.

Besides, we think that the global system map we drew could be seen as a "first draft" that could be enriched by the experience of both scientists and farmers, in order to create a collaborative mapping of the intercropping system.

2.4.2. Quantification of interactions, modelling & crop selection

As explained in the introduction, our objective was to make an inventory of all the interactions and processes that could affect the outcome of an intercrop and its potential benefits, regardless of their relative significance.

Our will not to focus on any particular crop, context, theme or resource was incompatible with any quantification of the interactions. In fact, the most important processes involved in shaping the performance and benefits of intercropping are so far difficult to identify and most probably depend on the type of intecrop and the context in which it is grown. As they are now, the networks and the system map we designed are adaptable to every context and this is their strength.

To go further in the identification of most significant processes, the networks and map we propose here could be use as a start and could be redrawn and adapted to different situations, e.g. focus on legume-cereal intercrops, highlighting and deleting some links based on the results of experimental papers related to the chosen situation.

With quantification also comes the idea of modelling. Modelling may be a promising tool in predicting the results – in a productive point of view – of an intercrop. The networks and the map however highlight the many variables that need to be taken into account in order to accuretly represent an intercropping system. Some models dedicated to intercropping currently exist (e.g. Baumann et al., 2002; Brisson et al., 2004; Carberry et al., 1996; Gou et al., 2017a; Tsubo et al., 2005; Van Noordwijk & Lusiana, 1999) but the interactions taking place in intercropping are so diverse and difficult to predict that it is still hard to get trustworthy results. The use of interaction networks and system map adapted to different contexts and intercrops, with a quantification of the links based on experimental results, may help to

identify the key processes that need to be modelled and how the different variables of the system may interact.

2.5. CONCLUSION

More than seventy years of scientific research on intercropping – and the growing interest in the subject – have enabled to identify a series of processes that are involved in intercropping and influence its outcome. This chapter highlights the diversity of mechanisms and objects involved in intercropping and how they interact. Its originality comes from the combination of text and networks of interactions, each object serving a different purpose. The text of the chapter extensively describes the interactions between the elements of the intercropping systems but is by nature linear, which makes it more difficult to understand the links between the different compartments of the system. This is why we complemented this classic approach with a visualisation of the interactions. The networks and the global system map effectively show the relationships linking the different elements of the intercropping system. They can also be used by researchers to situate their study within the intercropping system. The text and networks meet different needs and respond to each other to provide a thorough view of the actual knowledge about intercropping. The combination of these two tools emphasises the complexity of intercropping and underlines the need of a systemic and multidisciplinary approach to study intercropping.

*

* *

The literature review is an essential first step for all scientific research. In the framework of this thesis, we decided to perform a literature review in a heuristic way and using a systemic approach. We wanted to cover as much as possible of the functioning of intercropping, in all contexts and crops, in order to address the question of intercropping in market gardening with sufficient knowledge.

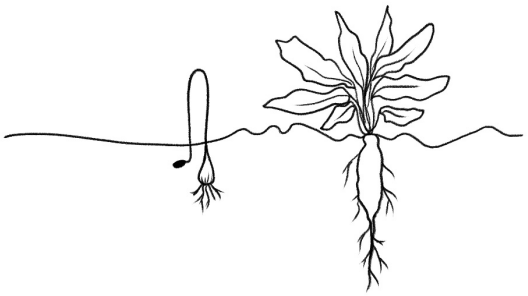
This allowed us to highlight the complexity of intercropping and the diversity of elements that influence its outcome as well as to describe some key concepts linked to intercropping – complementarity, competition, facilitation – which will be mobilised in the rest of this thesis. Besides, we

used its results to define relevant hypotheses for the experimental trials conducted during the thesis and explained in the subsequent chapters.

In addition to laying the foundation for understanding the following chapters of this thesis, our literature review also contributes to the scientific knowledge about intercropping. The networks we created are a map of the interactions between component crops and between these crops and their environments that have already been observed in studies about intercropping. They may serve as a basis for subsequent research by providing a comprehensive vision of intercropping and by facilitating the choice of the variables and the hypotheses to be taken into account in a study. Besides, the networks might also be used as a basis for modelling intercropping, with a quantification of the interactions.

Furthermore, this work may also be useful for farmers interested in intercropping. It gives them a glimpse of the complexity of the practice, but can also provide them with some of the theoretical knowledge needed to help them design effective intercropping themselves. We are however aware that (i) the networks should be simplified in order to be fully understandable by farmers and (ii) even if simplified, they mainly serve an intellectual purpose and remain difficult to use as such as a decision-making tool.

Chapter 3 |
A quest for a complementarity model



The concept of complementarity, which refers to the fact that two crops will not use the same resources or remove them from the same part of the environment, thanks to architectural and physiological differences (Andersen et al., 2007; Hooper, 1998; Loreau & Hector, 2001; Trenbath, 1974) is key in intercropping. It is often put as the rationale of why some intercrops may produce more biomass on the same piece of land than pure crops. Therefore, intercrops between theoretically complementary crops, whether temporally or spatially, are associated with productivity.

In mainstream market gardening books – the main source of information for professional market gardeners regarding intercropping – complementarity is often used to formulate intercropping recommendations, e.g. associate a short crop in rosette with a higher and straight crop. If these suggestions do not lack logic, to our knowledge, their veracity has never been proven. This is why we designed an on-field trial, set up in agricultural experiment station, dedicated at exploring the explanatory and predictive value of intercropping guidelines based on complementarity and found in market gardening books.

In this chapter, we first introduce the development of a complementarity model based on pieces of advice related to intercropping found in market gardening books and/or used by market gardeners (section 3.2). We then present the material and methods of the trial (section 3.3) and its results (section 3.4). We analyse first the effect on the land equivalent ratio of the intercrops (section 3.4.1) and second the effect on various ecophysiological variables (section 3.4.2) and we finish by discussing our findings (section 3.5).

The “Introduction” and the “Development of the complementarity model” sections are derived from “Chevalier, C., Baret, P., Draye, X. (2021). Reliability of growth cycle and architectural characteristics as criteria for intercropping design in market gardening: Strategies to cluster vegetable crops according to their architecture. *Aspects of Applied Biology*, 146”, with some changes.

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3.1. INTRODUCTION

Intercropping is a frequent topic in mainstream market gardening books. In fact, the sector of vegetable production is a good candidate for the adoption of intercropping. At least in Wallonia (Belgium): (i) the majority of market gardeners are settled on less than two hectares of cultivated land (Dumont & Baret, 2017) and are thus concerned by the efficient use of space across the season that can be provided by intercropping (Lin, 2011; Malézieux et al., 2009; Mommer et al., 2010); (ii) small market gardeners are usually highly diversified (from 20 up to 45 different vegetables (Dumont & Baret, 2017)), which means intercropping would not lead to a complete reorientation of their farm; (iii) small market gardeners are usually poorly mechanised and are therefore unlikely to face the mechanisation difficulties often linked to intercropping (Anil et al., 1998; Lithourgidis, Dordas, et al., 2011; Singh et al., 2013).

Despite the growing interest for this cultivation method, choosing efficient intercropping designs remains challenging. On the one hand, the large number of crops cultivated in market gardening entails an even larger number of possible pairwise combinations. On the other hand, many interactions, ranging from facilitation (Li et al., 2007, 2014; Mommer et al., 2016; Pierik et al., 2012; Zhang & Li, 2003) to competition (Schenk et al., 1999; Schenk, 2006), can take place between two associated crops and influence their growth (cf. Chapter 2) and the effect of any change in the design remains hard to predict.

So far, information and guidelines regarding intercropping between vegetables mainly include recommendations found in mainstream market gardening books, which are usually poorly explained or not explained at all (cf. 1.2.2) and are sometimes inconsistent from one book to another (cf. Appendix A). These recommendations are mainly based on claims about the protective power of one crop against the pests of another (e.g. Wagner, 2004) or on differences in the architecture and growth length of crops (e.g. Riotte, 2010), i.e. complementarity. They usually come from empirical observations rather than resulting from scientific studies, their reliability is therefore not guaranteed.

In this study, we deliberately chose to disregard the aspect of pest protection of intercropping to focus on investigating the reliability of growth cycle and architectural characteristics, *viz.* temporal and spatial complementarities, as

criteria for intercropping design in market gardening. Growth cycle and architectural characteristics are in fact easily accessible information in the field and market gardeners use them as guidelines to select intercrops.

We conducted a field trial to test the relevance of the complementarity criteria as indicators of an intercrop success. We assembled several intercrops according to architecture and growth cycle and compared their outcome against their theoretical complementarity. We deliberately chose a scanning approach – i.e. screening a high number of intercrops at the same time – different from what is usually done in intercropping studies, in order to draw up generalisations to help market gardeners in intercropping design. This chapter presents the methodology and results of this field trial. It will focus on a global analysis of the reliability of the complementarity criteria we used as indicators of intercropping productivity but will not go into detail about the results of each of one of the intercrops grown in the corresponding field trial, as this will be addressed in Chapter 5.

3.2. DEVELOPMENT OF THE COMPLEMENTARITY MODEL

We based our strategy on references used by market gardeners. It ranged from mainstream books to popularisation websites, seed retailers' websites and technical sheets for professionals, from which we extracted data for seventy-three different crops – and their varieties when available and relevant – about (i) the duration of the growth cycle, (ii) sowing, plantation and harvest dates, (iii) the type of vegetables (fruit, leaf, root, flower), (iv) shoot system characteristics (mean height at maturity, growth habit), (v) root system characteristics (tap-root *vs* fasciculate root system, lateral spread and depth of root system) and (vi) irrigation, fertilisation and weeding needs.

We defined five complementarity criteria, based on (i) what is currently used by farmers (pers comm, 2018; 2019), (ii) the results of the Master's thesis of de Liedekerke de Pailhe (2014), who investigated intercropping in a renowned French permaculture farm as well as through interviews with professional market gardeners, market gardening advisors and researchers and provided advice for intercropping, and (iii) advice available in market gardening books (among others, the one from Hervé-Gruyer and Hervé-Gruyer (2019)). The five criteria are the following : (i) there should be a difference of growth cycle duration of at least three months between associated crops; (ii) there should be a height difference of at least 30 cm between plants; (iii) intercropping should be between a spreading plant and a plant with upright growth habit; (iv) intercropping should be between a

plant with a tap-root system and a plant with a fasciculate root system; (v) intercropping should be between a root vegetable, i.e. a vegetable whose harvested part grows underground, and a vegetable of another type (fruit, leaf, flower, bulb). Each criterion was associated to one of three types of complementarity: temporal complementarity for criterion (i), shoot spatial complementarity for criteria (ii) and (iii) and root spatial complementarity for criteria (iv) and (v).

Each complementarity type was linked to assumptions regarding its effect on intercropping outcome, based on the results of our literature review (cf. Chapter 2):

- The temporal complementarity should allow a higher biomass production thanks to (i) a development of the faster-growing crop as if it was in pure crop and (ii) a decrease in the yield loss of the crop with a longer cycle thanks to a compensatory growth, after the harvest of the crop with a shorter cycle (Awal et al., 2006; Hinsinger et al., 2011; Huang et al., 2017; Zhang & Li, 2003; Zhang et al., 2017). It may also alleviate the competition between crops thanks to a spreading over time of their resource requirements (Duchene et al., 2017; Trenbath, 1974; Willey, 1990; Willey 1996) (Figure 9A);
- The shoot spatial complementarity should favour the development of a two-tier canopy with minimum shade and high soil-coverage with tall and upright plants above and short and wide plants below. This should enhance the light interception (Gebru, 2015; Zhang et al., 2008) and/or the light use of the intercrop (Reddy & Willey, 1981; Willey, 1990) (Figure 9B);
- The root spatial complementarity should favour the biomass production of both crops by increasing the volume of soil explored and the amount of exploitable resources (Gao et al., 2010; Gebru, 2015; Hauggaard-Nielsen & Jensen, 2005; Hinsinger et al., 2011; Li et al., 2006) (Figure 9C).

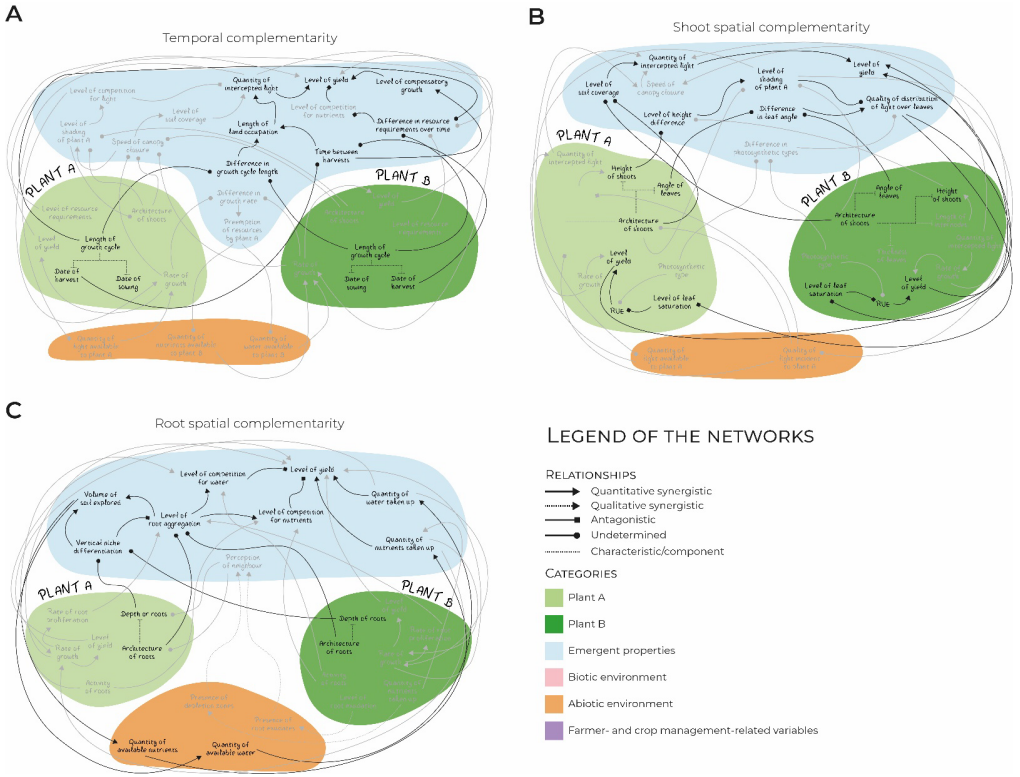


Figure 9 - Illustration of the interactions justifying the choice of the criteria linked to temporal complementarity (A), shoot spatial complementarity (B) and root spatial complementarity (C). Interactions used as rationale are shown in black. Links and variables shown in grey are other interactions linked to the three types of complementarity that were not directly considered in the choice criteria but might happen as well.

We began by sorting and selecting crops based on (i) the possibility of growing them outside of greenhouses in Belgium climate, (ii) their ease of cultivation and (iii) the availability of seeds. Perennial crops and legumes were excluded. Then, we attributed to each pairwise combination between crops of distinct botanical families an overall complementarity score depending on whether it met all or none of the above criteria. Pairwise combinations for which only one of the two criteria regarding shoot or root complementarity was met were not considered in the model. Different varieties of the same crop were seen as separate crops in the model. For each complementarity type, each intercrop was attributed either a "+" – if all the criteria linked to this complementarity type were met – or a "-" – if none of the criteria associated to this complementarity type was met –. Each pairwise combination was characterised by a score made up of three signs, each sign representing one of the complementarity types. In total, there were eight possible scores – "+ + +", "+ + -", "+ - +", "- + +", "+ - -", "- + -", "- - +", "- - -" – . The first term represented the temporal complementarity, the second the shoot spatial complementarity and the third the root spatial complementarity (Figure 10). For our field trial, we chose sixteen intercrops (cf. 3.3) – two per complementarity score – based on the sowing dates of the crops while trying to minimise the number of different crops.

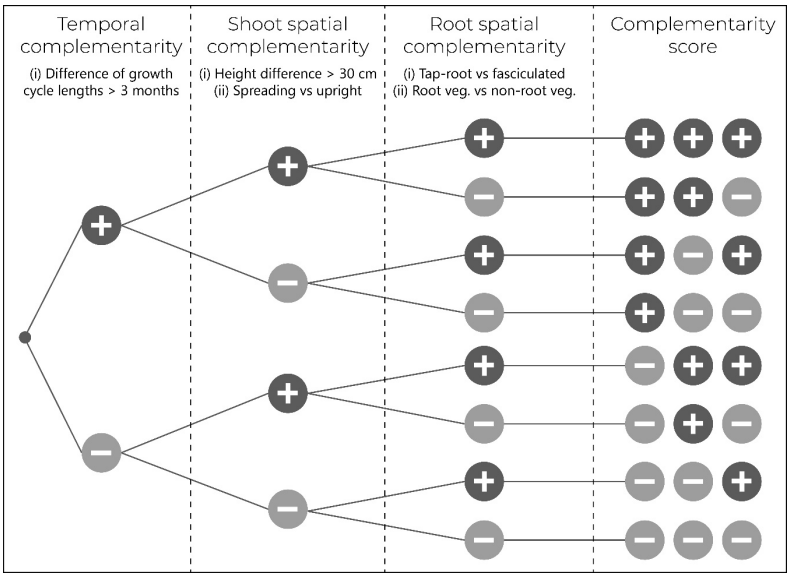


Figure 10 - Components of the complementarity score and related criteria. The quantitative criteria are derived from the work of de Liedekerke de Pailhe (2014), in agreement with principles used by market gardeners and stated in market gardening books. The three other criteria are derived from discussion with market gardeners and from mainstream gardening books.

3.3. Material & Methods

3.3.1. Study zone and crop management

The experimental field trial was conducted in 2019 in the market gardening farm of the UCLouvain, located at Louvain-la-Neuve, Belgium. The study zone is characterised by an average annual temperature of 10.6°C, with 15°C and 6.2°C as average maximal and minimal temperature (IRM, 2021). Average annual rainfall is 849.4 mm, with an average of 134.8 rainy days[2], and the average incident radiation is 3.6GJ.m-1.yr-1 (IRM, 2021). The soil is sandy-silty with moderate to imperfect drainage (SPW, 2018) and a hydraulic conductivity between 6 and 10 mS/m in the plots. The trial plots were located at an altitude between 136.5 and 137.5 m and were characterised by a slope of 3.33% in the direction of the crop rows.

Plots were irrigated when needed, following the advice of the professional market gardener working at the UCLouvain farm, and weeded once a week. No fertilisation was used during the trial. As the plots were a centuries-old grassland that was turned over one year before the start of the trial, they were supposed to be rich in mineral nitrogen (De Toffoli et al., 2013). The analysis of soil samples taken from one of the cropping beds of the farm revealed a nitrate concentration of 9.27 mg/kg of dry soil in April 2019 and 81.92 mg/kg of dry soil in June 2020. Besides, the same plot had a good humus (8.56%) and potassium (26.12mg/100g) contents and was rich in magnesium (15.19mg/100g) and phosphorus (16.77mg/100g). The calcium content was 169.84mg/100g, the oxydisable carbon content 2.80% and the cation exchange capacity was 10.81cmol/kg. The soil was slightly acid (pH H_2O=6.2, pH KCl=5.45). Plots were temporarily covered by dead leaves before the grassland was turned over. All plots were covered with anti-insect veils. Finally, all plants of a given crop were harvested at the same time in all modalities containing that crop.

3.3.2. Experimental design

The trial took place on five crop beds of 1.20 m wide and 30 m long, divided in 21 plots of 1.20 m long (Figure 11A). We studied sixteen intercrops (Figure 11B), each corresponding to one complementarity score (Figure 11C) and associating two of the following fifteen crops: beetroot, Brussels sprout, carrot, Chinese cabbage, fennel, kohlrabi, lamb's lettuce, parsnip, radish,

[2] A day is considered as rainy if rainfall is a least 1 mm (IRM, 2021).

rutabaga, savory, spinach, scorsonera, white onion and yellow onion. Two different varieties were used for beetroots, scorsoneras, white onions and yellow onions, which brings the total number of studied crops to nineteen.

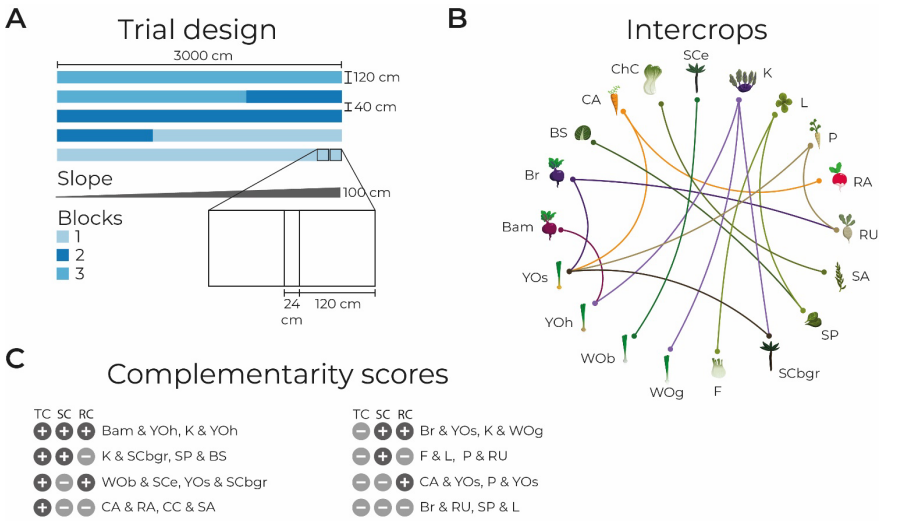


Figure 11 - Dimensions of the plots and organisation of the blocks (A), intercrops studied (B) and intercrops corresponding to each complementarity score (C) in the first field trial set up in agricultural experiment station. Bam=Beetroot Alvro-Mono, Br=Beetroot Rhonda F1, BS=Brussels sprout, CA=Carrot, ChC=Chinese cabbage, F=Fennel, K=Kohlrabi, L=Lamb's lettuce, P=Parsnip, RA=Radish, RC=Root spatial complementarity, RU=Rutabaga, SA=Savory,SC=Shoot spatial complementarity, SCbgr=Scorsonera Noir Géant de Russie, SCe=Scorsonera Enorma, SP=Spinach, TC=Temporal complementarity, WOb=White onion Barletta, WOg=White onion de Gladstone, YOh=Yellow onion Hylander F1, YOs=Yellow onion Sturon.

Information related to crop varieties, planting distances, planting densities and sowing/plantation and harvest dates is listed in Appendix C and growth cycle length and architectural characteristcs of the crops in Appendix D. Densities and planting distances in pure crop were chosen based on recommendations found in market gardening books and were confirmed by a market gardener. Regarding the intercrops, in an objective of maximising the biomass production per square meter, each crop was sown at a density equal to 75% of its density in pure crop. This ratio was however adapted to the specific case of each crop, in order to obtain natural number of rows for the two densities. If the pure crop of a crop only included two rows, we kept its pure crop density in intercrop rather than lowering it down to 50%. The densities of the crops in the intercrops are expressed based on the area of a plot and not on the area allocated to each crop within a plot. Rows of the two crops were alternated in the intercrops. The mean survival rate, i.e. actual density at harvest/expected density, was 78% for pure crops and 93%

for intercrops. We used a randomised complete bock design. The five crop beds were divided into three blocks, into which the organisation of the modalities was defined randomly.

3.3.3. GROWTH MONITORING

We monitored the growth of crops by taking one picture of the profile of each plot every week. As scale, a meter was placed vertically, with the "0" on the ground. The resulting images were treated manually (using image J) and the height of each crop whose top was visible on the picture was measured. For practical reasons, this method could not be conducted late in the season.

3.3.4. SOIL COVERAGE

We took one nadir picture[3] of the canopy of each modality in each block every week (cf. Appendix E). We used a regular RGB camera for this measurement. We analysed all the resulting pictures with ImageJ in order to segment soil pixels from plant pixels and we calculated the mean percentage of soil coverage for each modality in each block and at each measurement date.

3.3.5. LIGHT INTERCEPTION

We measured the incident, reflected and transmitted photosynthetically active radiation (PAR) in each repetition of each modality. The incident PAR was measured by placing a ceptometer above the canopy, captors facing the sky; the reflected PAR by placing it above the canopy, captors facing the ground; and the transmitted PAR by placing it on the ground, below the plants, captors facing the sky. Every time, the ceptometer was positioned perpendicularly to the lines of plants. We used the data from the ceptometer to calculate the intercepted PAR, in percent, using the following formula:

$$iPAR = \frac{PARinc - (PARr + PARt)}{PARinc} * 100 \text{ (eq.1)}$$

Where iPAR is the intercepted PAR, in percent, PARinc the incident PAR, PARr the reflected PAR and PARt the transmitted PAR.

In addition to the intercepted PAR obtained thanks to the data of the ceptometer, we estimated the cumulative PAR intercepted during the whole trial, based on the soil coverage. Firstly, we retrieved the incident PAR during

[3] Picture taken above the canopy, with the vertical axis joining the center of the camera lens and the ground being perpendicular to the ground.

each day of the trial using the data from the Pameseb[4] weather station installed in Louvain-la-Neuve. Secondly, we computed a linear interpolation of the data of soil coverage to estimate the percentage of soil coverage for every day, repetition and modality. Thirdly, we estimated the daily PAR interception by multiplying, for every day, repetition and modality, the amount of incident PAR by the percentage of soil coverage. Finally, we summed the daily intercepted PAR between sowing and harvest to estimate the cumulative PAR interception. We also calculated the cumulative PAR intercepted by each plot in percent, by dividing the cumulative PAR of each modality in each block by the cumulative incident PAR for this modality.

Using the yield data and the cumulative intercepted PAR, we calculated the radiation use efficiency (RUE) of the modalities, by dividing the yield (in g/m²) by the cumulative intercepted PAR (in MJ/m²). The RUE was calculated based on fresh weight, whereas it is usually expressed as dry weight (Monteith et al., 1977). The obtained values were then ca. 10 times larger than the usual range of RUE values. To express this distinction, we named our RUE calculation "RUE_{fw}" instead of "RUE". This way of calculating RUE does not allow us to compare the values we obtained with the ones obtained by other authors. However, it should not affect the interpretation of our results, as we worked mainly on a relative scale, comparing the results of the crops in intercropping and those of the same crops in pure crop (cf. 3.3.8).

Besides, we also calculated the energy share between component crops in each intercrop plot, i.e. the percentage of the total amount of PAR intercepted by the whole intercrop plot that was intercepted by each one of the component crops. The energy share was based on an estimation of the PAR each crop should theoretically have intercepted to produce the biomass it actually produced in intercropping based on the RUE_{fw} of its corresponding pure crop.

3.3.6. YIELD DATA

For each one of the crops, we weighed the total harvested biomass, the marketable harvested biomass, the foliar harvested biomass and, when possible – i.e. for beetroot, carrot, parsnip, radish, rutabaga and scorsonera

[4] Pameseb is a Belgian nonprofit organisation dedicated to the promotion of agrometeorology. It owns a network of 30 weather stations in Wallonia, whose data are used to advice farmers about integrated pest management and irrigation (https://www.pameseb.be/).

– the root harvested biomass. Each crop was weighed separately. The number of harvested plants in each modality in each block was counted.

Since the actual yields were subject to variability due to differences in germination and survival rate (cf. Appendix C), we computed adjusted yields by multiplying the mean weight per plant and the mean marketable weight per plant by the expected density of the corresponding crops. This calculation was based on the assumption that missing plants would have grown in the same way as the other ones and that the level of competition would have been the same if all plants had germinated. The fact that, for 18 out of 19 crops, the yield *vs* density relationship was similar in the pure and intercropped modalities suggests that this assumption is valid. Based on this data, we calculated (i) the adjusted yield, adjusted shoot yield and adjusted root yield by dividing the corresponding adjusted biomass by the surface of the plot, (ii) the root-shoot ratio by dividing the root biomass, when available, by the foliar biomass, (iii) the mean weight per plant by dividing the total harvested biomass by the number of harvested plants and (iv) the harvest index, by dividing the marketable harvested biomass by the total harvested biomass. In all our results, the yields are expressed based on the area of a plot and not on the area allocated to each crop within a plot.

Besides the yield data, we calculated the land equivalent ratio (LER) of each intercrop. LER indicates the surface needed in pure crops to obtain the same yield of each crop as in an intercrop of these two crops. A LER higher than one means that the pure crops require more land than the intercrop to reach the same yield of each crop. The LER was calculated as follows (Mead & Willey, 1980):

$$LER = \frac{Y_A}{S_A} + \frac{Y_B}{S_B} \quad \text{(eq.2)}$$

where Y_A and Y_B are respectively the yield of crop A and crop B in the intercrop and S_A and S_B are respectively the yield of crop A and crop B in pure crop.

We also calculated a yield ratio (YR) per crop, i.e. the ratio between the yield of a crop in an intercrop and its yield in pure crop. Both the LERs and the YRs were calculated using the total adjusted yields.

Finally, we calculated for each crop the gain of yield, in percent, by dividing each yield ratio by the expected density ratio, i.e. the ratio between the expected density of the crop in the intercrop and its expected density in pure

crop. To evaluate the total gain of each intercrop, we summed the yield gain, in percent, of each component crop. To evaluate the yield asymmetry between component crops in each intercrop, we calculated the absolute value of the subtraction of the yield gains of the two component crops. The lower the absolute value, the lower the asymmetry between the crops, i.e. both crops gained/lost as much yield compared to their expected yield. The formulas of the indicators derived from yield data are listed in Table 1.

Table 1 - Indicators derived from yield data. We consider an intercrop between a crop A and a crop B. The first two indicators are calculated for each crop in each intercrop and the last two for the intercrop as a whole. All indicators are based on total adjusted yields. Y_A=Yield of crop A in the intercrop, Y_B=Yield of crop B in the intercrop, S_A=Yield of crop A in pure crop, S_B=Yield of crop B in pure crop, dr=ratio of expected densities between a crop in intercrop and the same crop in pure crop.

NAME	ABBREVIATION	FORMULA
Yield ratio of crop A	YR	$YR_A = \frac{Y_A}{S_A}$
Yield gain of crop A (%)	YG	$YG_A = ((YR_A/dr) - 1) * 100$
Yield gain of the intercrop (%)	YG	$YG_{IC} = YG_A + YG_B$
Asymmetry of yield gain (%)	AYG	$AYG = \lvert YG_A - YG_B \rvert$
Land equivalent ratio	LER	$LER = \frac{Y_A}{S_A} + \frac{Y_B}{S_B}$

3.3.7. LEAF AREA

We predicted the total leaf area from the total leaf biomass, using a linear model of area *vs* mass estimated for each crop using a random sample of 10 leaves.

3.3.8. DATA PROCESSING AND STATISTICAL ANALYSIS

Quality check led to removal of outliers (cf. Appendix F.1). Consequently, although the trial was initially designed to include two intercrops for each one of the eight complementarity scores, the final dataset only included one intercrop for the "+ + -" and the "- - -" scores and no intercrop for the "+ - -" score. Yield data of some of the plots from the 2019 trial were corrected to take into account differences in sowing date (cf. Appendix F.2).

We analysed our datasets at three different levels: at the crop level, i.e. the effect of intercropping on a given crop, at the intercrop level, i.e. the outcome of an intercrop compared to the corresponding pure crops, and at

the global level, i.e. the reliability of the complementarity model as a tool to explain differences in intercrop outcomes. Results at the crop and the intercrop levels are reported in Chapter 5.

We make the distinction between data measured or estimated once per plot, i.e. yield gain, asymmetry of yield gain, shoot biomass yield, root biomass yield, root-shoot ratio, mean weight per plant, leaf area, LER, cumulative iPAR in percent, maximum soil coverage, radiation use efficiency and absolute difference in energy share between crops, and the time-series data measured or estimated along the season, i.e. soil coverage, percentage of iPAR and height of plants (Figure 12).

We evaluated the link between the estimated or measured variables and the discrete factor that is the complementarity score. The analysis was carried out in two steps.

Firstly, we analysed the impact of the complementarity score and its components on the LER of the intercrops using two linear mixed models, one with each component of the score – temporal complementarity, shoot complementarity, root complementarity – individually and every two-way interaction – temporal+shoot, temporal+root, root+shoot – as fixed factors and a second with the number of "+" signs in the score – ranging from zero to three – as fixed factor. The random factor was the block in both models.

Secondly, we evaluated the correlation between the complementarity score and the other estimated or measured variables. This analysis was performed using a linear mixed model with the three components of the score and the three two-way interactions as fixed factors for all the variables measured or estimated once, i.e. yield gain, shoot biomass, root biomass, mean weight per plant, root-shoot ratio, leaf area and slope of height *vs* time linear regression for per crop variables, asymmetry of yield gain, yield gain, maximum soil coverage, cumulative percentage of iPAR, RUE_{fw} and absolute difference in energy share between crops for intercrop variables. The random factor was again the block. As data related to one out of the eight complementarity scores was not available due to the removal of outliers, the three-way interaction between the three components of the score was not included in the model. To allow comparison between data from different crops, we calculated, for each of these variables except for the yield gains, the asymmetry of yield gain and the absolute difference in energy share between crops – which were already relative variables – the ratio between the value of the variable – either per crop or per intercrop – in an intercrop

and either the value of the same crop in pure crop (for per crop variables) or the mean or sum of the values of the corresponding pure crops (for per intercrop variables). Ratios were estimated per block. When relevant, a corrective factor was used to take into account the differences in density between the crops in intercropping and in pure crop. As we were not able to simplify the time-series data using simple regression due to non-linear shapes and differences between shapes of the temporal evolutions across modalities, they were analysed using a contingency table method (cf. Appendix F.3), by testing the independence between the complementarity score components (rows) and the ranks of the intercrop curve for the variable of interest (columns), using a chi-square test.

All the variables available for this trial are summarised in Figure 12.

All statistical analyses were performed on R v.3.4.1. We used the *lmer* function for all linear mixed models, the *lm* function for the height *vs* time linear regression, the *anova* function to the test the significance of the fixed factors of the linear mixed models, the *chisq.test* function to run the chi-square test on the contingency tables of the time-series data and the *emmeans* function to perform mean comparisons.

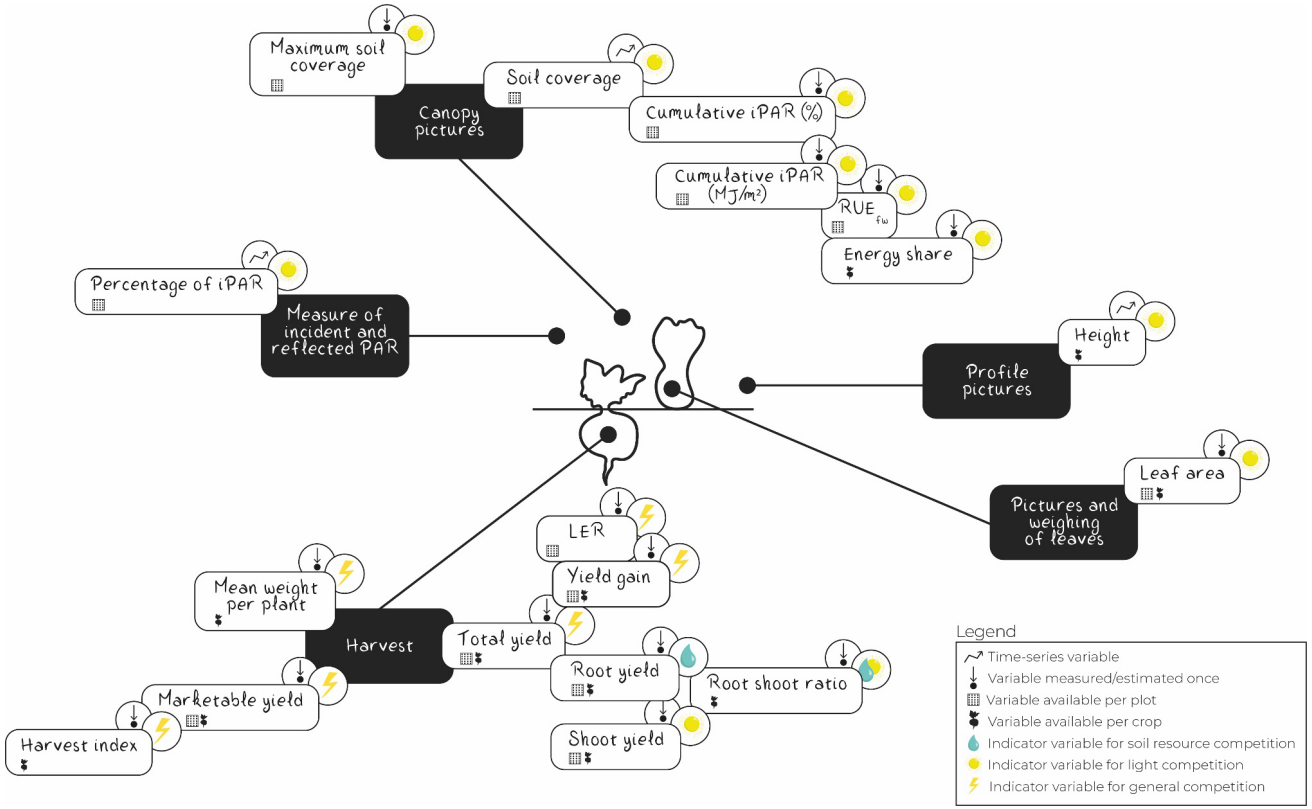


Figure 12 - Summary of the measurements taken and variables estimated in the first trial set in agricultural experiment station. Black boxes are the measurements we took, white boxes the variables we derived from these measurements. Variables that are next to each other are linked to each other. iPAR=Intercepted photosynthetically active radiation, LER=Land equivalent ratio, RUE_{fw}=Radiation use efficiency based on fresh weight.

3.4. RESULTS

3.4.1. COMPLEMENTARITY AS A DRIVER OF INTERCROPPING PERFORMANCE?

As the plots were irrigated and the soil was still rich from the many years spent in grassland, the radiation was probably the most limiting resource. Therefore, we expected that the root spatial complementarity would have a minor effect and that the temporal and shoot spatial complementarities would influence positively the LER of the intercrops. Surprisingly, the shoot spatial complementarity as defined by our criteria did not have any main-effect impact on the LER of the intercrops (p-value=0.97) whereas the temporal complementarity as defined by our criterion had a strong positive impact (p-values<0.001) and the root spatial complementarity as defined by our criteria had a weak negative impact (p-value=0.002) (Figure 13A). Interactions between the components of the complementarity score were only significant between the root spatial and the temporal complementarities (p-value=0.043). As shown on Figure 13B, the temporal complementarity effect was consistently positive, while the effect of the shoot and root spatial complementarities differ according to the signs of the other score components.

If the complementarity scores were a good indicator of performance of an intercrop, the LER of the intercrops should increase with the increase of the number of positive signs in the score. This is in fact what we observe, with a significant and positive slope (Figure 13C, p-value<0.001) between the LER of the studied intercrops and the number of positive signs (Adjusted R^2=0.191), meaning that our complementarity criteria help, at least in part, for the selection of productive intercrops. The R^2 is however low.

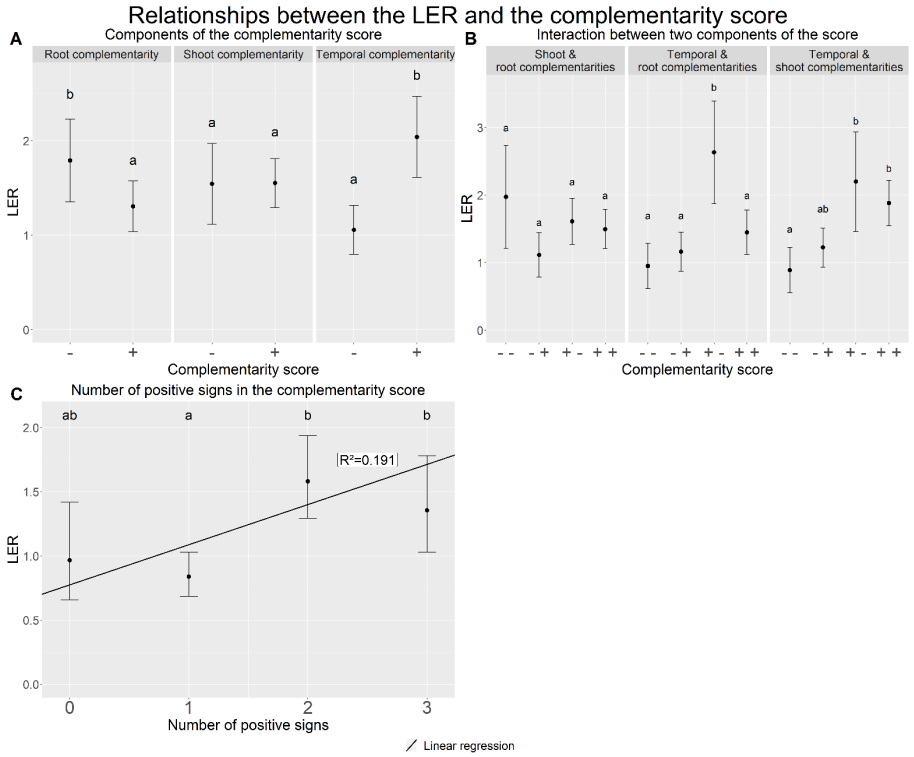


Figure 13 - Relationship between the complementarity score and its components and the LER of the intercrops. (A) link between the LER and each score component, (B) link between the LER and each two-ways interaction between score components, (C) link between the LER and the number of positive signs in the score. (A) and (B) are based on the results of a linear mixed model with the three components of the score and the three two-way interactions between these components as fixed factors. (C) is based on the results of a linear mixed model with the number of positive signs in the score as fixed factor. Block was used as random factor in both models. In (B), the first sign of each pair of signs refers to the first complementarity type cited in the title of the subgraph. LER=Land Equivalent Ratio.

3.4.2. Dissecting LER into ecophysiological components to understand the effect of complementarity components

To understand better the potential link between the classification of the intercrops and the performance of the intercrops, we conducted the same analysis that we carried on the LER on the other variables. For the sake of simplicity, we used for each variable the ratio between its value in intercropping – either per crop of for the whole intercrop – and its value in pure crop – either the corresponding pure crop, the mean of the corresponding pure crops or the sum of the corresponding pure crops – (cf. 3.3.8). Therefore, when we write that a variable is positively influenced, we refer to the ratio between intercrop and pure crop.

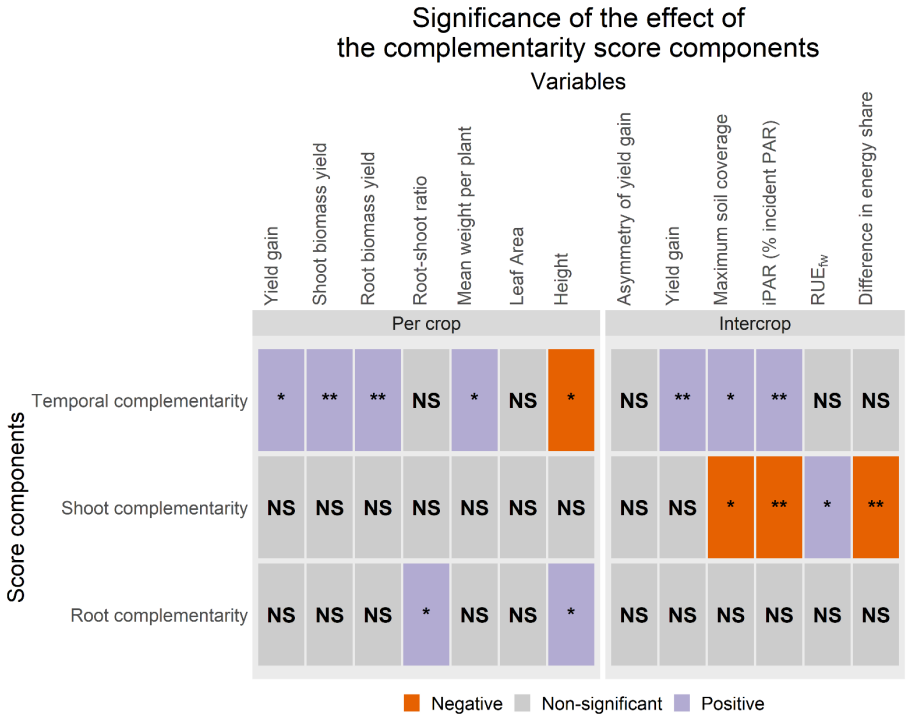


Figure 14 - Significance of each score component on crop and intercrop variables. The effect of the score components was analysed by using a linear mixed model where they were the fixed factors and the block was the random factor. In order to compare data from different crops, we calculated, for each variable except the yield gain, the asymmetry of yield gain and the difference in energy share, which were already on a relative scale, the ratio between its value for each component crop in each intercrop and its value for the corresponding pure crop. When per crop data were not available for the intercrops, e.g. iPAR, RUE_{fw}, Maximum soil coverage, the ratio was calculated using either the sum of the corresponding pure crops (iPAR, Maximum soil coverage) or the mean of the corresponding pure crops (RUE_{fw}). Regarding energy share, the absolute difference in energy share between the component crops of the intercrops was used, i.e. a positive effect on the energy share means that the energy share was less equal. To analyse height difference, we calculated the ratio between intercrop and pure crop of the slope of the height vs time linear regression. iPAR=intercepted photosynthetically active radiation, RUE_{fw}=Radiation use efficiency based on fresh weight.

3.4.2.1. Temporal complementarity

The temporal complementarity was the component that had the highest impact. It influenced positively the yield gain (p-value=0.016), the shoot biomass yield (p-value=0.006), the root biomass yield (p-value=0.006) of the crops, the mean weight per plant (p-value=0.013) and the maximum soil coverage (p-value=0.018), the iPAR (p-value=0.003) and the yield gain of the intercrop (p-value<0.001) (Figure 14). In general, the compliance with our

temporal complementarity criterion led to an increase in the average value of the variables it influenced without changing the distribution of the points.

These effects of the temporal complementarity are all consistent with one another and suggest that the crops had a higher relative biomass production in the intercrops from the temporal "+" group than in the intercrops from the temporal "-" group, without any significant changes in the allocation of biomass between root and shoot. When comparing the growth of the crops with a longer or a shorter growth cycle[5] from the temporal "+" and temporal "-", we saw that the average yield gain of the crops with a shorter cycle was significantly higher than that of the crops with a longer cycle in both groups (p-values: 0.001 (group "-"), 0.039 (group "+"), data not shown). However, the yield gain of the crops with a shorter cycle was not significantly different between the two groups (p-value=0.56, data not shown) whereas that of the crops with a longer cycle was significantly higher in the temporal "+" group than in the temporal "-" group (p-value=0.045, data not shown). Therefore, the compliance with our temporal complementarity criterion seems to have supported a better growth of the crop of the intercrop with the longest cycle without detriment to the the one with the shortest cycle, which is line with our starting hypothesis.

Indeed, one of the phenomena that could explain this is the compensatory growth. When the delay between the harvests of two associated crops is long enough, the crop with a longer cycle may compensate for its loss of growth caused by competition with the crop with a shorter cycle by increasing its growth once the crop with a shorter cycle is harvested (e.g. Awal et al., 2006; Huang et al., 2017; Zhang et al., 2017). In our case, the average compensatory growth period was longer – expressed as a percentage of the longer growth cycle – in the intercrops from the temporal "+" (27%) group than from the temporal "-" group (19%). Nevertheless, there was no significant correlation between the percentage of its cycle a crop spent alone after the harvest of its companion, i.e. the duration of the compensatory growth, and its yield gain (p-value=0.50).

[5] Shorter and longer growth cycles do not correspond here to specific growth cycle lengths but are used in a relative way, "crop with a shorter cycle" and "crop with a longer cycle" referring respectively to the crop with the shortest growth cycle and the one with the longest growth cycle in each intercrop.

Another explanation of the positive effect of the temporal complementarity might come from the height data. There was no height difference between crops with a longer or with a shorter cycle in the temporal "+" group (p-value=0.34) whereas crops with a longer cycle were taller than crops with a shorter cycle in the temporal "-" group (p-value<0.001). Crops with a longer cycle from the temporal "+" group were also significantly smaller than these from the temporal "-" group (p-value<0.001) whereas there was no height difference between the crops with a shorter cycle coming from the two groups (p-value=1.00) (Figure 15). Internodes elongation being a common shade-avoidance reaction (Ballaré, 1999; Holmes & Smith, 1975; Pierik et al., 2012; Smith, 2000), these results suggest that the competition for light was less intense for the crops with a longer cycle in the temporal "+" group than in the temporal "-". This is consistent with the yield results: the increased yield in the temporal "+" group compared to the temporal "-" group was mainly linked to an increase in the yield of the crops with a longer cycle, allowed by a reduced domination of crops with a shorter cycle on crops with a longer cycle.

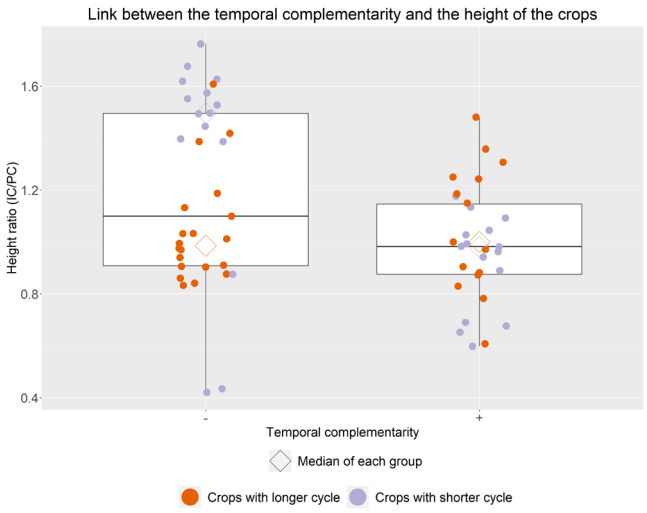


Figure 15 - Ratio between the slope of the height vs time linear regression in intercrop and pure crop in the temporal "+" and temporal "-" groups. Each dot represent one crop in one repetition of one intercrop. In each intercrop, the components crops were differentiated based on their relative growth cycle length (longest one vs shortest one) and colored accordingly (orange vs purple). Diamonds represent the median of the crops with shorter or longer cycle in the temporal "+" and temporal "-" groups. The graph shows a decrease of the relative height for the crops with a longer cycle (purple dots) when going from the temporal "-" group to the temporal "+" group whereas the median height ratio of the crops with a short cycle (orange dots) stays approximately the same when going from the temporal "-" to the temporal "+" group. IC=Intercrop, PC=Pure crop.

Regarding time-series data, temporal complementarity had a significant effect on the soil coverage (p-values: 0.003 (part one, i.e. before the harvest of the crop with the shortest growth cycle of the intercrop), <0.001 (part two, i.e. after the harvest of the crop with the shortest growth cycle of the intercrop)) and the iPAR (p-values: 0.009 (part two)). Before the harvest of the crop with a shorter cycle, the temporal complementarity had a mixed effect on soil coverage. On the one hand, the proportion of cases in which the curve of the intercrop was below the reference line was higher in the temporal "+" group than in the temporal "-" (e.g. 56% *vs* 41%). On the other hand, there was a higher proportion of the cases in which the curve of the intercrop was below all other curves in the temporal "-" group than in the temporal "+" group (17% *vs* 5%). After the harvest of the crop with a shorter cycle, however, the trend was clearer: for soil coverage for example, whereas in 83% of the cases the curve of the intercrop was below all other curves in the temporal "-" group, this happened in only 27% of the cases in the temporal "+" group.

In a nutshell, the compliance with our temporal complementarity allowed better results, both at the crop and at the intercrop level. However, this gain seems to have been more linked to a decrease in competition for light in the intercrop than to a compensatory growth of the crop with the longest cycle of the intercrop. This suggests the importance of growth dynamics in the competition for resources between crops.

3.4.2.2. Shoot spatial complementarity

The aim of our shoot complementarity criteria was to create a canopy with low shading of the short plants and a decrease in the fraction of light reaching the soil. The shading of crops indeed occurred later in the shoot "+" than in the shoot "-" group (loss of visibility of one of the crops after 82% of the cycle of the shaded crop in the "+" group *vs* 64% in the "-" group, p-value=0.017). This observation is consistent with the negative link between the difference of energy share between associated crops and the shoot complementarity (p-value<0.001, Figure 14). This suggests that when the shoot spatial complementarity criteria were respected, the component crops of the intercrop shared the light more evenly that when they were not. However, this result might just reflect the higher proportion of onions – which had a high RUE_{fw} and low biomass, resulting in a low energy share – in the intercrops without shoot spatial complementarity (80%) than with shoot spatial complementarity (57%). The similarity of energy share of the

component crops may also originate from an overestimation of the radiation intercepted by one of the crops since we used the RUE_{fw} of the corresponding pure crop – rather than the RUE_{fw} of the crop in the intercrop – to estimate the energy share.

The shoot spatial complementarity also had a positive influence on the RUE_{fw} (p-value=0.032) but a negative one on the maximum soil coverage (p-value=0.011) and the iPAR (p-value=0.002) of the intercrop (Figure 14). The intercrops from the shoot "+" group were therefore better at converting radiation into biomass than the intercrops from the shoot "-" group. However, as they intercepted less radiation due to a poorer soil coverage, this did not result in an increase in yield gain. The increase in RUE is consistent with our initial hypothesis and may be related to a decrease in the proportion of saturated leaves in the canopy. On the opposite, the decrease in maximum soil coverage and iPAR contradicts the hypothesis of better soil covering canopies.

Time-series data indicated that the compliance with our shoot spatial complementarity criteria had a significant effect on the soil coverage before (p-value=0.036) and after the harvest of the crop with the shortest cycle in each intercrop (p-value<0.001): the intercrop curve tended to be higher in the shoot "+" than in the shoot "-" group. This could mean that the crops with a longer cycle suffered less from the presence of the crops with a shorter cycle in the shoot "+" than in the shoot "-" group, which would be consistent with the more balanced energy share and the later shading. This result is, however, contradictory with the one regarding maximum soil coverage. This suggests that, overall, the compliance with our shoot complementarity criteria allowed to increase the soil coverage throughout the intercrop growth cycle but not the maximum it reached.

The effects of the shoot complementarity were in line with part of the theoretical principles: the compliance with our criteria balanced the distribution of incident light between component crops and improved their use of intercepted light. However, it resulted neither in an increase of iPAR nor in an increase in biomass production. It is noteworthy to see that, for many variables, going from "-" to a "+" in the shoot complementarity changed the range of values of the variables rather than resulting in a net increase – or decrease –, even when the link was not significant (Figure 16). In other words, the compliance with our shoot complementarity criteria increased the attainable maximum – or minimum – of the variables but was

no guarantee of success. Besides, it is also interesting to notice that the intercrops in the upper part of the range also happened to be in the temporal "+" group.

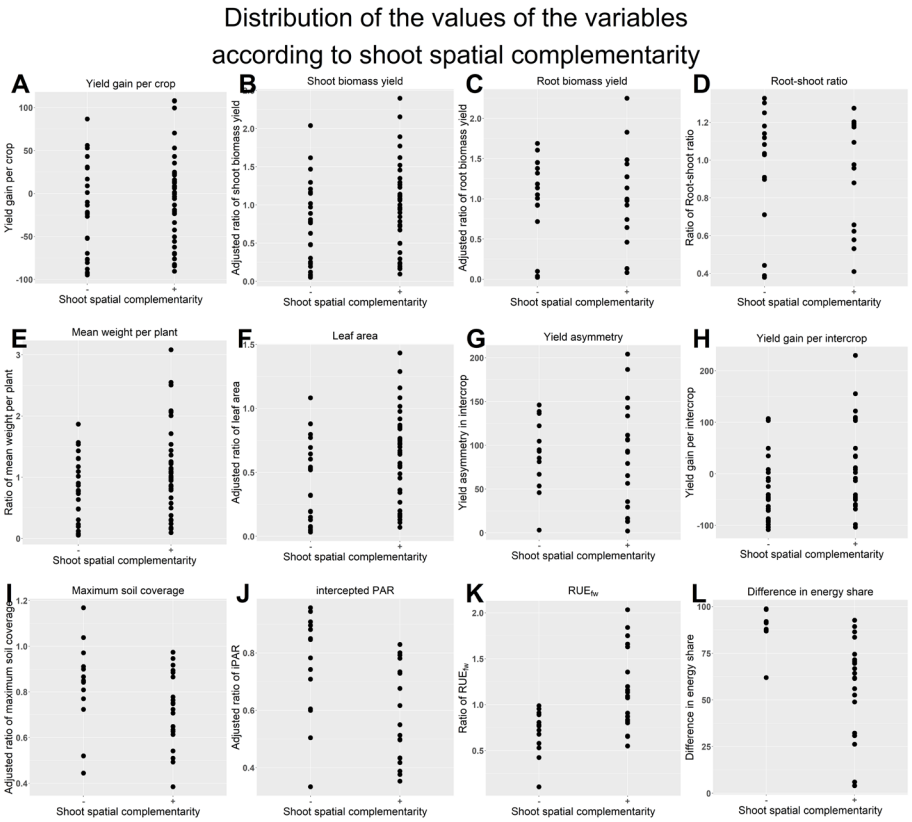


Figure 16 - Distribution of the values of the ecophysiological variables according to the compliance with our shoot complementarity criteria. (A) yield gain per crop, (B) shoot biomass yield, (C) root biomass yield, (D) root-shoot ratio (E) mean weight per plant, (F) leaf area, (G) yield asymmetry, (H) yield gain per intercrop, (I) maximum soil coverage, (J) cumulative intercepted PAR (%), (K) RUE_{fw}, (L) difference in energy share. Variables are presented using their relative values, i.e. the ratio between the value in intercrop and in the corresponding pure crop. When relevant, the values of the pure crops were adjusted to account for density differences between the crops in intercropping and in pure crop. Variables significantly influenced by the shoot complementarity are the maximum soil coverage (I), the iPAR (J), the RUE_{fw} (K) and the difference in energy share (L). Each dot represent one repetition of one intercrop or crop. iPAR=intercepted photosynthetically active radiation, RUE_{fw}=Radiation use efficiency based on fresh weight.

3.4.2.3. Root spatial complementarity

Root complementarity influenced positively the root-shoot ratio (p-value=0.023) but none of the intercrop variables (Figure 14). This effect can be explained by an uneven share of resources between root and non-root vegetables in the intercrops from the root "+" group. The non-root vegetables developed less in the root "+" group than in the root "-" group. On the opposite, the root vegetables developed better in the root "+" group than in the root "-" group. All the non-root vegetables from the root "+" group were onions, a crop that develops slowly and with a superficial root system[6] and probably became shaded rapidly by the root vegetable crops, while root vegetable crops developed as if they were in pure crop, or even better thanks to their lower densities in intercropping than in pure crop.

This hypothesis is supported by time-series data. Firstly, the root complementarity had a positive impact on the height of the crops (p-value=0.020). This effect was mostly linked to an increase in the height of onions, which is an indicator of competition for light and shade-avoidance response from the onions. Secondly, the root complementarity had a positive impact on iPAR (p-value<0.001) and soil coverage (p-value<0.001) before the harvest of the crop with the shortest cycle of the intercrop but a negative impact on soil coverage (p-value<0.001) after the harvest of the crop with the shortest cycle in the intercrop. As the crop with the shortest cycle was the root vegetable in six out of the eight intercrops from the root "+" group, these effects further reinforce the hypothesis of the dominance of root vegetables over onions in the intercrops from the root "+" group.

The compliance with our root complementarity criteria, rather than sharing evenly the resources between the component crops, favoured the root vegetables crops over their companions. Unfortunately, these results highlight the low competitive ability of the onions more than they explain the potential effect of intercropping root vegetables with non-root vegetables.

[6] On average, onions have a rooting depth of $50.39^{\pm 26.75}$ cm and a lateral root spreading of $71.86^{\pm 23.66}$ cm (Weaver & Burner, 1927; Kutschera et al., 2009; Nishida, 2011)

3.4.3. LIMITATIONS OF OUR MODEL

Our complementarity model was based on information regarding (i) the growth cycle length, (ii) the height of crops, (iii) the growth habit of crops, (iv) the type of vegetable and (v) the type of root system. This information was retrieved from many sources, ranging from mainstream gardening books to seeds retailers websites, popularisation websites or technical sheets dedicated to producers. In our opinion, it was important to base our complementarity model on this type of data, as this is the one that is available to market gardeners. However, this decision challenged us in a number of ways. Firstly, the information was not always consistent from one source to another, probably because the different sources were not based on the same contexts, crop varieties, etc. but this information was rarely specified. Secondly, it was hard to find relevant quantitative data, e.g. for the height of crops. Crops were usually classified between categories of height, whose range was sometimes pretty large, sometimes not indicated at all. Thirdly, the quantity and the quality of information available varied from one crop to another. In order to base our model on the most accurate data possible, we had to cross-reference the sources and calculate means when relevant. On the one hand, this process allowed us to take into account some variability. On the other hand, as the context from which the data came was rarely specified, it may be that we used data that were not representative of our situation. The lack of precision of the starting information probably led to misclassifications of at least some of the intercrops and it is likely that, for these intercrops, the ex-post complementarity score, i.e. the complementarity score we would assign based on the observations and measurements we made during the trial, would not be the same than their starting score, i.e. the score we attributed to each intercrop before the trial.

Besides the problem of information quality, our complementarity model may also be criticised for its dualistic perception of complementarity. Our idea was to develop a simple complementarity model, easily usable by market gardeners. This has inevitably led to some simplifications. For the two quantitative criteria – i.e. the difference in growth cycle length and the difference in height – we had to set thresholds to define which intercrops complied with them and which did not. If these thresholds were based on advice found in the literature, they are nonetheless open to criticism, as a single week/centimetre of difference could tip the balance one way or the other. The criterion of height difference particularly may have smoothed the impact of the shoot spatial complementarity as the differences between the

"+" and the "-" groups may have been lesser than expected. The use of ranges with a buffer zone in between may have been more appropriate to perceive the effect of these criteria. The same criticism may apply for the criterion of shoot growth habit, which was quite subjective for some of the crops.

3.5. DISCUSSION

Our field trial emphasised (i) the strong positive impact of our temporal complementarity criterion on the performance of the intercrops, (ii) the absence of impact of our shoot spatial complementarity criteria on the performance of the intercrops and (iii) the slightly negative impact of our root spatial complementarity criteria on the performance of the intercrops, which could be decomposed on a positive effect on the growth of root-vegetables and a negative effect on the growth of the non-root vegetables.

The significant and positive effect of the temporal complementarity as defined by our criterion on the light interception and the biomass production of the intercrops is in line with other results. Keating & Carberry (1993), in their review about radiation interception and use in intercropping, emphasised the possibility of improving the temporal capture of radiation by associating a crop with a short growth cycle with one with a longer growth cycle. This was for example observed in an intercrop between sorghum and pigeonpea (Willey et al., 1983). Other studies also showed a greater productivity for intercrops between crops with larger differences in growth cycle length (e.g. Adbel-Galil et al., 2014; Ezumah & Lawson, 1990; Guvene et al., 2006; Rao et al., 1987). It is interesting to note that, contrary to what has already been observed in other intercrops combining an early-maturing and a late-maturing crops (e.g. Awal et al., 2006; Li et al., 2011; Xia et al., 2013), the higher LER of the intercrops from the temporal "+" group in our trial did not seem to have been linked to a compensatory growth. In fact, there was no correlation between the time – in proportion to its total growth cycle length – a late-maturing crop spent alone after the harvest of its early-maturing companion and its yield gain. Besides, the analysis of the time-series data revealed that, in about 75% of the cases, the crop with a longer growth cycle developed at least as expected based on its density in intercrop and its growth in pure crop. This suggests that there was no competition between the crop with a shorter cycle and the one with a longer cycle in the temporal "+" group and supports the hypothesis that the temporal

complementarity allows a spreading over time of the use of resources of the associated crops (Willey, 1990).

The shoot complementarity as defined by our criteria did not have any significant effect on the LER of the intercrops. When dissecting the LER into ecophysiological variables, we saw that going from the shoot "-" to the shoot "+" group had two consequences. Firstly, it increased the radiation use efficiency of the intercrop. This effect has already been observed in other intercrops (e.g. groundnut + sorghum (Harris et al., 1987) millet + groundnut (Marshall & Willey, 1983; Reddy & Willey, 1981), wheat + maize (Gou et al., 2017b), canola + wheat (Karimian et al., 2015)) and is usually explained by a decrease in leaf saturation thanks to a better distribution of light in intercrop canopies (Willey, 1990). Secondly, in our trial, the increase in RUE did not imply an increase in LER as it was counterbalanced by a decrease in light interception compared to what was expected. This may have been caused by the shading of the shorter crop by the taller crop, as already seen in other intercrops (e.g. Ezumah & Lawson, 1990; Mandal & Mahapatra, 1990; Thole, 2012). Therefore, it seems that the shoot spatial complementarity criteria had antagonistic effects: the shading of the shorter plant by the taller plant limited leaf saturation but increased competition for light. In order to avoid this problem, it should probably be interesting to use more objective characteristics to define the growth habit of the crops. Using the leaf angle as a parameter of the complementarity model might be a good choice, as Abdel-Galil et al. (2014) showed, in a trial comparing cultivars of maize and soybean for maize + soybean intercropping, that the maize cultivar with the most erected leaves was the one with the least negative effect on soybean growth.

Finally, the root complementarity as defined by our criteria seems to have led to greater competition, with an uneven share of resources between root and non-root vegetables. Following our definition of the root spatial complementarity, we expected that two crops should compete less if their root system architectures are different, as shown in the experiment of Fargione & Tilman (2005). Two hypotheses could explain our result. Firstly, our root complementarity criteria were based on the supposed root architecture of the crops. However, due to the plasticity of root systems, their architecture in the field might be very different from what was expected, as it is influenced by the characteristics of the soil, e.g. the availability and distribution of nutrients (Huang & Zhang, 2020; Paz, 2003; Yu et al., 2014). Besides, the transplantation of some of the crops may have

prevented the growth of their taproot (NeSmith & Duval, 1998; Peterson et al., 1991). Secondly, other studies suggest that the extent of the root system of a crop (Egbe et al., 2010) and its rate of growth (Hauggaard-Nielsen et al., 2001; Tofinga et al., 1993; Xia et al., 2013) confer a competitive advantage to this crop over the crop with which it is associated. It may be that, by selecting crops with different root systems, we unintentionnally selected crops with major differences in their rate of root growth. The global extent of the root systems and their growth dynamics should probably be better criteria.

The results of the temporal complementarity were what we expected: going from a "-" to a "+" for the temporal complementarity increased the average value of the variables it influenced without changing their distribution. On the opposite, going from a "-" to a "+" for the shoot spatial complementarity changed the distribution of the points in many variables and increased – sometimes significantly – their reachable maximum or minimum. This suggests that our criteria regarding shoot spatial complementarity, by increasing the probability of having higher values, are somewhat relevant regarding intercropping design. Nevertheless, our results also show that their effects were not guaranteed: if there were more well-performing intercrops in the "+" group than in the "-" group, not all intercrops from the "+" group were more productive than these from the "-" group. We are aware that these more unclear than expected results might come from the conception of our model (cf. 3.4.3). However, they may also suggest that our criteria were able to capture part of the reality but that their effect was dependent on other variables. It would therefore be interesting to analyse the results of our intercrops outside the frame of the complementarity criteria in order to identify these modulating variables, as they may be more appropriate for intercropping guidelines than the current criteria. This will be the objective of Chapter 5.

*

* *

In this chapter, we developed a complementarity model attributing to intercrops a complementarity score based on their compliance with predefined complementarity criteria.

This first on-field trial set up in agricultural experiment station highlighted the influence of the temporal, the shoot spatial and the root spatial complementarities, as defined by our criteria, on the productivity of the

intercrops and on some ecophysiological variables. Its results show the positive effect of the temporal complementarity on biomass production. This effect was attributed to an increase in light interception permitted by a spreading over time of the use of resources between component crops but not to a compensatory growth of the later-maturing crop. Our trial also emphasises the increase in the range of likely values of some of the studied ecophysiological variables with shoot spatial complementarity, indicating that shoot spatial complementarity increased the probability of having productive intercrops. Moreover, it shows two contrasting effects of the shoot spatial complementarity: an increase in the radiation use efficiency but a decrease in light interception, both being attributed to the shading of the shorter crop by the taller one. Finally, regarding root complementarity, our results suggest that theoretical differences in root architecture (i) may not be actually present or (ii) may lead to a larger asymmetry between the competitive abilities of crops.

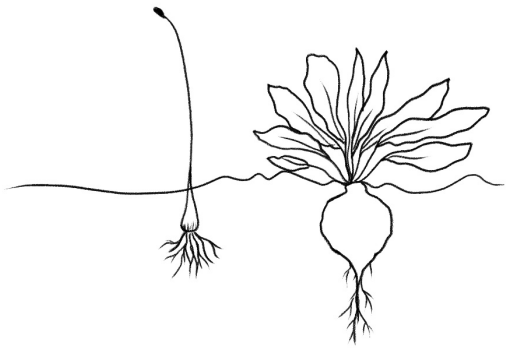
Overall, the results of this trial regarding the effects of the three complementarity types as defined by our criteria are in agreement with a series of previous studies about intercropping. The originality of our work lies in the fact that (i) we investigated all three complementarity types at the same time and on a range of intercrops and (ii) we used the concept of complementarity from a predictive perspective to design experiments rather than to explain the results. This design allows us to contribute to the scientific knowledge about intercropping by providing an assessment of the suitability of certain intercropping design criteria over a range of different situations rather than just providing an explanation of why the performance of a particular intercrop was observed.

We think that the results of this trial also contribute to the operationalisation of intercropping by market gardeners. We based this trial on intercropping criteria usually used by market gardeners and/or found in market gardening books. The results show that market gardeners must use the criteria investigated in our trial carefully as they do not always guarantee a higher productivity. More specifically, the negative effect of the root spatial complementarity as well as the decrease in radiation interception with shoot spatial complementarity as defined by our criteria underline the fact that one must be cautious when selecting crops with contrasted architecture, as this may lead to greater competition due to the dominance of one crop over the other. Nevertheless, our results also indicate that it is beneficial to favour intercrops between crops with differences in their growth cycle lengths. It is

however important to note that the trial was conducted in a context in which light was probably the most limiting resource. The results regarding the relevance of the criteria used in the trial for market gardeners might therefore vary if the soil resources were more limited.

We are aware that our complementarity model had various flaws, including the subjectivity of some our complementarity criteria. It would therefore be interesting to investigate the question of the importance of architectural differences between companion crops in the outcome of intercrops using quantitative data. This will be the subject of the next chapter.

Chapter 4 |
Root and shoot architecture differences are not the main driver of intercropping outcome



In Chapter 2, we identified the main interactions taking place in intercropping and explained the concepts of complementarity, competition and facilitation.

In Chapter 3, we evaluated the explanatory and predictive value of a complementarity model we developed based on recommendations found in market gardening books, inspired by the concept of complementarity. We found (i) an increase in intercropping outcome with the compliance with the temporal complementarity as defined by our criterion, (ii) an increase in the probability of higher productivity when associating crops with different shoot architecture and (iii) an increase in the unevenness of resource sharing between component crops when combining crops with different root architecture, mainly caused by the low competitive ability of onions. We also underlined some difficulties we had when developing the model and pinpointed, among others, the subjectivity of some criteria.

Based on this observation and the assumption that part of our unclear results may come from the flaws in our complementarity model, we decided to explore further the issue of shoot and root architectural complementarities in intercropping. We based ourselves on the same hypotheses regarding the potential effect of complementarities as in Chapter 3 to design a second model, based on quantitative data, and we tested its relevance in a second on-field trial set up in agricultural experiment station.

In this chapter, we introduce first the second model we developed, based on the drawings of Kutschera et al. (2009) and on a principal component analysis (PCA), classifying the crops according to the form and size of their root and shoot architectures (section 4.2). Then, we describe the design of the trial (section 4.3), which differed from the design of the trial described in Chapter 3, and we present its results by analysing first the link between the distance between two associated crops in the PCA and the LER of the intercrops (section 4.4.1) and second the link between the distance between two associated crops in the PCA and various ecophysiological variables (section 4.4.2.1). We also explore the impact of temporal complementarity (section 4.4.2.2). Finally, we discuss the validity of our model (section 4.5).

The “Development of the complementarity model” section is derived from “Chevalier, C., Baret, P., Draye, X. (2021). Reliability of growth cycle and architectural characteristics as criteria for intercropping design in market gardening: Strategies to cluster vegetable crops according to their architecture. *Aspects of Applied Biology*, 146”, with some changes.

CHAPTER 4 | ROOT AND SHOOT ARCHITECTURE DIFFERENCES ARE NOT THE MAIN DRIVER OF INTERCROPPING OUTCOME

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4.1. INTRODUCTION

Intercropping is a frequent topic in market gardening books and many different tips exist today on how to select successful intercrops, making it look relatively simple. However, choosing productive intercrops, in which competition for resources is low, is not an easy task, firstly because of the large number of crops cultivated in market gardening and the resulting number of possible combinations and secondly because of the complexity of the interactions that can take place in intercropping (cf. Chapter 2).

Nowadays, market gardeners only have at their disposal the recommendations from mainstream market gardening books, which are usually poorly explained, sometimes inconsistent from one book to another (cf. Appendix A) and that seem to overlook the complexity of the intercropping system. Moreover, these pieces of advices are generally linked to qualitative criteria, whose interpretation may vary from one person to another. We believe that intercropping management would benefit from objective, robust and trustworthy criteria for intercropping design, derived from statistical design and based on relevant and quantifiable variables.

The limitations and drawbacks of our first strategy (cf. Chapter 3) led us to develop a second methodology based on quantitative data. In this study, we investigated the reliability of differences in architectural characteristics, *viz.* spatial complementarities, as criteria for intercropping design in market gardening. We developed a classification of crops based on quantitative data on shoot and root architectures using a principal component analysis (PCA). We tested the relevance of this classification regarding intercropping outcome by conducting a field trial in which we monitored the growth of various intercrops in the same trial, i.e. scanning and exploratory approach, which combined crops more or less distant from each other in the PCA. This chapter presents the development of this model and the results of the corresponding field trial. It will focus on a global analysis of the reliability of the relative distance between crops in the PCA as an indicator of intercropping productivity. Details on the results of each intercrop grown in the corresponding field trial will be addressed in Chapter 5.

4.2. DEVELOPMENT OF THE COMPLEMENTARITY MODEL

We developed a complementarity model based on the concept of spatial complementarity, i.e. the fact that differences between plant architecture of the component crops lead to resource uptake taking place at different locations (Duchene et al., 2017; Malézieux et al., 2009; Trenbath, 1974; Willey, 1990; Willey, 1996), using quantitative data regarding the architecture of vegetable crops.

We collected drawings of vegetable plants available in the Wurzelatlas (Kutschera et al. 2009) – over 70 drawings for more than 40 different crops –. From these drawings, we extracted data of height (H) and width (W) of shoot system as well as depth (D) and spread (S) of root system (Figure 17). In addition, we computed (i) the ratios between width and height of shoot system (W/H) and between spread and depth of root system (S/D), which are indicators of the global shape of the systems (square, more horizontal, more vertical); (ii) the cross of width and height of shoot system (W*H) and of depth and spread of root system (D*S), which are indicators of the total area covered, in 2D, by the plant.

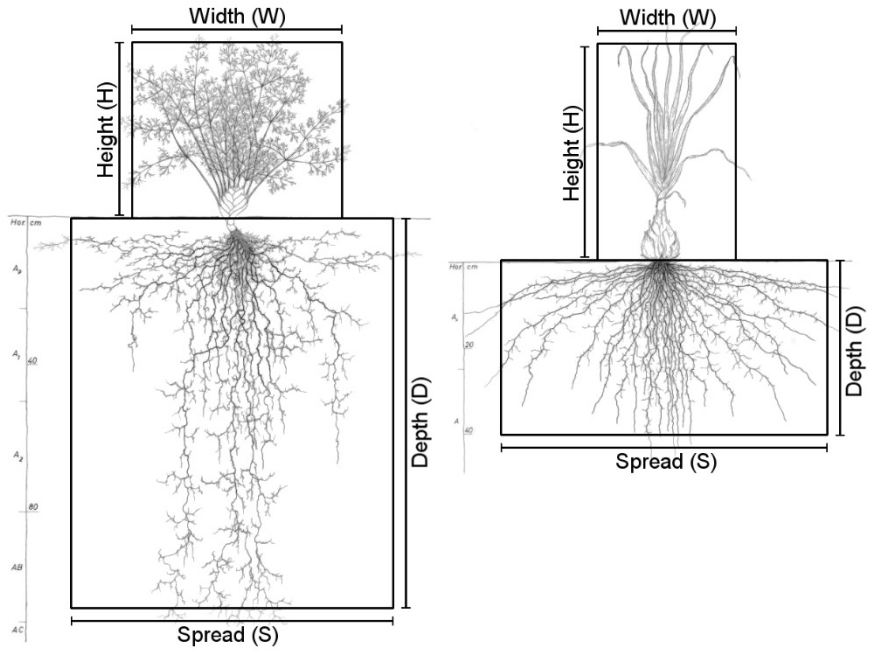


Figure 17 - Extraction of data of height (H) and width (W) of shoot system and depth (D) and spread (S) of root system from Kutschera et al's drawings (2009) for fennel (left) and onion (right).

We then conducted a PCA (performed on R v.3.4.1 using the *pca* function) with these eight variables to assemble groups of vegetable crops based on architectural characteristics. We performed the PCA on a reduced number of crops (eleven), as we took into account only the vegetables that we might grow in our field trials on the basis of (i) the availability of seeds, (ii) the sowing/plantation time, (iii) the possibility to grow them outside greenhouses under the Belgian climate and (iv) their ease of cultivation.

The first three dimensions of the PCA explained more than 90% of the variability of the data. In the first three dimensions, shoot width (W) and root spread (S) appeared together, which means that we could not differentiate plants that have a high W and a small S and vice-versa. The first dimension was mainly accounting for the global size of the plants (highest contribution from W*H and D*S). As our aim was to classify crops based on the form of their root and shoot systems rather than their size, dimensions 2 and 3, which were mainly influenced by S/D and W/H, were therefore more interesting (Figure 18). Along dimension 2, plants ranged from tall and shallow to short and deep. Along axis 3, plants ranged from tall and deep to short and shallow but wide. Even if dimensions 2 and 3 helped us to define morphological categories, the PCA showed that there was a continuous distribution of plants along the first three dimensions. It was therefore hard to make a unique objective classification of plants based on their root and shoot architectures, even from quantitative data.

For the field trial, we decided to take the five crops located at the extreme points of the 2-3 plane of the PCA: white onion, broccoli, fennel, collard cabbage and kale. We chose broccoli over Chinese cabbage because of the latter's sensitivity to pests. In addition to these five crops, we selected the two legumes – dwarf bean and string bean – that were both neighbours of one of the other five crops selected in the 2-3 PCA design. This allowed us to add another dimension to our field trial: the study of the impact of legumes on intercrop performance. As the second and third dimensions of the PCA capture differences in root and shoot architecture, our hypothesis was that an intercrop of two crops that are far apart in the PCA graph (second and third dimensions, Figure 18) should exploit spatial complementarity effects better than an intercrop of crops that are close to one another (cf. Appendix B.2, Appendix B.3).

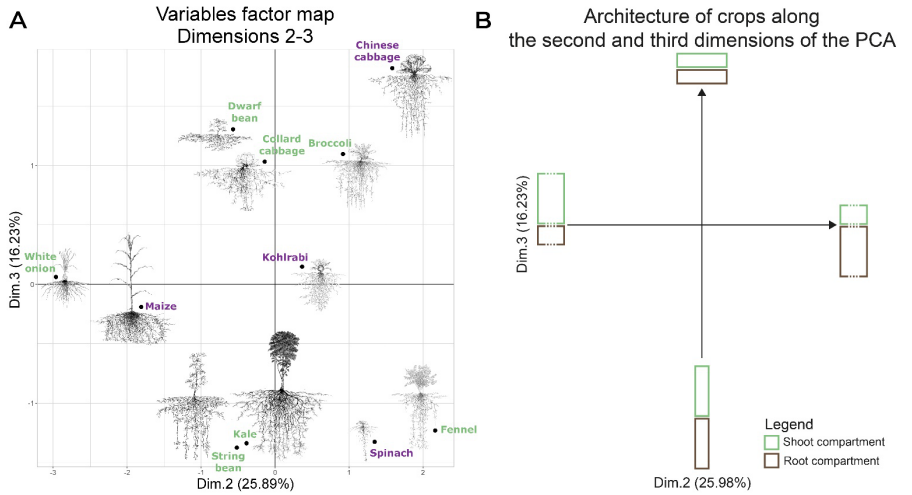


Figure 18 - Distribution of the vegetable crops used for the PCA analysis along dimensions 2 (x axis) and 3 (y axis) of the PCA performed on quantitative data extracted from Kutschera et al's drawings (2009) (A) and schematic representations of the shoot (green) and root (brown) architecture of the crops along the second and third dimensions of the PCA (B). Plants ranged from tall and shallow to short and deep along dimension 2 (x axis) and from tall and deep to short and shallow but wide along dimension 3 (y axis). Crops with light green names (A) have been selected and crops with purple names have been set aside for the field trial. PCA=Principal component analysis.

4.3. Material & Methods

4.3.1. Study zone and crop management

The field trial was conducted in 2020 in the market gardening farm of the UCLouvain, located at Louvain-la-Neuve, Belgium. The study zone is characterised by an average annual temperature of 10.6°C, with 15°C and 6.2°C as average maximal and minimal temperature (IRM, 2021). Average annual rainfall is 849.4 mm, with an average of 134.8 rainy days[7], and the average incident radiation is 3.6GJ.m-1.yr-1 (IRM, 2021). The soil is sandy-silty with moderate to imperfect drainage (SPW, 2018) and a hydraulic conductivity between 6 and 10 mS/m in the plots. The trials plots were located at an altitude between 136.5 and 137.5 m and were characterised by a slope of 3.33% in the direction of the crop rows.

Plots were irrigated when needed, following the advice of the professional market gardener working at the UCLouvain farm, and weeded once a week. As the experiment took place on a field converted from centuries-old

[7] A day is considered as rainy if rainfall is a least 1 mm (IRM, 2021).

grassland two years before the trial, plots were supposed to be rich in mineral nitrogen (De Toffoli et al., 2013). The analysis of soil samples taken from one of the cropping beds of the farm revealed a nitrate concentration of 9.27 mg/kg of dry soil in April 2019 and 81.92 mg/kg of dry soil in June 2020. Besides, the same plot had a good humus (8.56%) and potassium (26.12mg/100g) contents and was rich in magnesium (15.19mg/100g) and phosphorus (16.77mg/100g). The calcium content was 169.84mg/100g, the oxydisable carbon content 2.80% and the cation exchange capacity was 10.81cmol/kg. The soil was slightly acid (pH H_2O=6.2, pH KCl=5.45). Plots were temporarily covered by dead leaves before the grassland was turned over. All plots were covered with anti-insect veils. Finally, all plants of a given crop were harvested at the same time in all modalities containing that crop.

4.3.2. Experimental design

The trial took place on five crop beds of 1.20 m wide and 30 m long, divided in 18 plots of 1.40 m long (Figure 19A). We studied all pairings between the following seven crops: broccoli, collard cabbage, dwarf bean, fennel, kale, string bean and white onion (Figure 19B). Information related to crop varieties, planting distances, planting densities and sowing/plantation and harvest dates is listed in Appendix G and growth cycle length and architectural characteristics of the crops in Appendix H. Densities and planting distances in pure crop were chosen based on recommendations found in market gardening books and were confirmed by a market gardener. Regarding the intercrops, in an objective of maximising the biomass production per square meter, each crop was sown at a density equal to 75% of its density in pure crop. This ratio was however adapted to the specific case of each crop, in order to obtain natural numbers of rows for the two densities. If the pure crop of a crop only included two rows, we kept its pure crop density in intercropping rather than lowering it down to 50%. The densities of the crops in the intercrops are expressed based on the area of a plot and not on the area allocated to each crop within a plot. Rows of the two crops were alterned in the intercrops. The mean survival rate, i.e. actual density at harvest/expected density, was 90% for pure crops and 89% for intercrops.

The experiment followed a randomised complete bock design. The five crop beds were divided into three blocks, into which the organisation of the modalities was defined randomly.

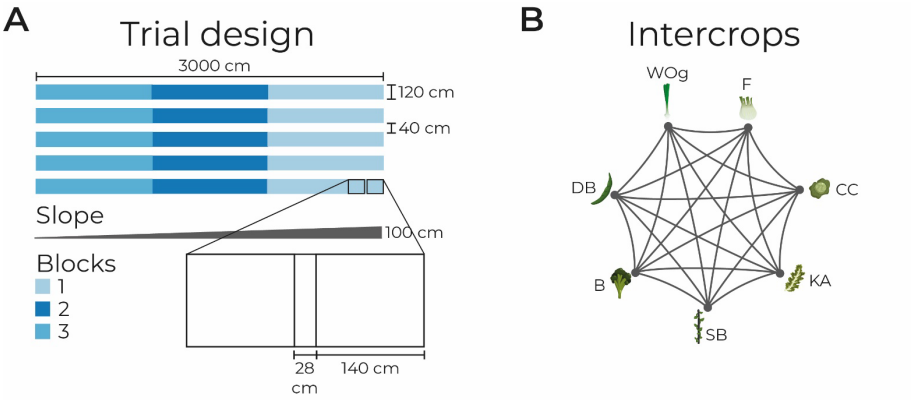


Figure 19 - Dimensions of the plots and organisation of the blocks (A) and intercrops studied (B) in the second field trial set up in agricultural experiment station. B=Broccoli, CC=Collard cabbage, DB=Dwarf bean, F=Fennel, KA=Kale, SB=String bean, WOg=White onion de Gladstone.

The intercrops were designed using a combining ability approach, where each crop was combined with each one the six other crops. This design allowed us to differentiate between (i) the general (average) impact of intercropping on each one of the crops, (ii) the general impact of each crop on its associated crops and (iii) the specific impact of each intercrop on each one of its component crops.

4.3.3. Soil coverage

The soil coverage was obtained using the pictures from a multi-spectral camera. This imaging equipment was composed of a vertical metallic stand attached to a scooter, allowing us to move the device easily, and a horizontal metallic bar, fixed to the vertical bar at a 90° angle, whose height was adjustable. The horizontal bar carried eight cameras (ESP32-Cam modules), facing downwards and located over the canopy : two RGB cameras, located 50 cm apart along the bar and six cameras closely packed equipped with bandpass filters (445-455 nm, 563-573 nm, 671-681 nm, 687.5-712.5 nm, 725-735 nm, 837.5-862.5 nm). The eight cameras were triggered almost instantaneously by a Raspberry Pi, although a time lag of a few seconds sometimes occurred between two cameras. A small white target was placed in the plot to estimate the incident radiation. At each passage, we captured one set of eight pictures for each modality in each block. In total, we collected 1161 sets of eight pictures during the trial. An example of one set of eight pictures is available in Appendix I.

Firstly, we delimitated manually the zone occupied by each crop in each picture, excluding the weeds, in order to estimate the percentage of the soil covered by each crop and to be able to work on each crop separately. Secondly, thanks to a deep-learning process developed by a master's student (Charles Rongione, ongoing master's thesis), each pixel of each scene, i.e. the picture resulting from the overlap of the six non-RGB images, was attributed a probability to be a plant. Finally, we discriminated between soil pixels and vegetation pixels by choosing a minimum probability threshold of 81.25% (which corresponded to 95% of plants pixels recognised as plants and 76% of ground pixels recognised as ground) and calculated the soil coverage for each crop at each measurement date by dividing the number of pixels above the threshold of the corresponding zone by the total number of pixels of the scene. When more than one zone were delimited for the same crop, the number of pixels in each zone was summed to get the total percentage of soil coverage of the crop.

4.3.4. LIGHT INTERCEPTION

The acquisition of the cumulative iPAR and RUE_{fw} data was done as described in Chapter 3, except that (i) no ceptometer was used in 2020, i.e. iPAR was approximated based on canopy pictures and meteorological data, as explained in Chapter 3 (cf. 3.3.5), and (ii) thanks to the delimitation of the zones occupied by each crop in the estimation of soil coverage (cf. 4.3.3), the cumulative iPAR, percentage of iPAR and RUE_{fw} could by estimated both for the plot and for each crop.

The variables derived from this data and used in the present trials are listed hereunder:

- Evolution of the percentage of soil coverage for the plot and for each crop;
- Cumulative amount of intercepted photosynthetically active radiation (iPAR) for the plot and for each crop;
- Percentage of photosynthetically active radiation intercepted during the whole season by the plot and by each crop, i.e. cumulative iPAR expressed as a percentage of the cumulative incident radiation;
- Radiation use efficiency based on fresh weight (RUE_{fw}) for the plot and for each crop.

In addition to these variables, we calculated the energy share between component crops in each intercrop plot, i.e. the percentage of the total amount of iPAR of the whole intercrop plot that was intercepted by each one of the component crops, by dividing the iPAR of each component crop by the iPAR of the whole intercrop plot.

4.3.5. YIELD DATA

Adjusted yield, mean weight per plant, land equivalent ratio (LER) yield ratio (YR), yield gain per crop, total yield gain of intercrops and asymmetry of yield gain in intercrops were measured/calculated in the same way as in the field trial described in Chapter 3 (cf. 3.3.6, Table 1).

The root biomass was not weighed in this field trail. Accordingly, the root biomass yield and shoot-root ratio are not available. Plots of string beans were harvested five times and plots of dwarf beans four times. Except for the first harvest, all the plots containing dwarf beans or string beans were harvested the same day. Accordingly, only the marketable harvested biomass, i.e. the biomass of the fruits, was available for beans and was the sum of the marketable harvested biomass of all consecutive harvests for each plot. The total yield gain of intercrops combining one bean with another crop was based on total yield gain for the non-bean crop and marketable yield gain for the bean crop. In all our results, the yields are expressed based on the area of a plot and not on the area allocated to each crop within a plot.

4.3.6. DATA PROCESSING AND STATISTICAL ANALYSIS

Marketable yield data of beans were corrected to take into account differences in harvest dates. These corrected data were used in the subsequent analyses (cf. Appendix J.1).

We analysed our datasets at three different levels: at the crop level, i.e. the effect of intercropping on a given crop, at the intercrop level, i.e. the outcome of an intercrop compared to the corresponding pure crops, and at the global level, i.e. the reliability of the relative positions of the crops in the PCA as a tool to explain differences in intercrop outcomes. The present chapter will focus on the global level. Results at the crop and intercrop levels are reported in Chapter 5.

We make the distinction between data measured or estimated once per plot, i.e. shoot biomass yield, yield gain, asymmetry of yield gain, mean weight per plant, LER, cumulative iPAR in percent, maximum soil coverage, radiation use efficiency and absolute difference in energy share between crops and the time-series data measured or estimated along the season, i.e. soil coverage.

We evaluated the link between the variables we estimated or measured and a continuous factor, the position of the crops in the second and third dimensions of the PCA (Figure 18). We used three different linear mixed models on the following variables: LER, shoot biomass yield, asymmetry of yield gain per intercrop, yield gain per crop and per intercrop, mean weight per plant, maximum soil coverage per crop, cumulative iPAR in percent per crop and per intercrop, absolute difference in energy share between crops and RUE_{fw} per crop. To allow comparison between data from different crops, we calculated, for each per crop variable except for the yield gain, the ratio between the value of the variable for each crop in an intercrop and its value for the same crop in pure crop. For the iPAR on the intercrop level, we summed the ratios of both component crops in each intercrop. Ratios were estimated per block. When relevant, a corrective factor was used to take into account the differences in density between the crops in intercropping and in pure crop.

The three models that were applied to our variables used either (i) the absolute value of the distance between crops on the second dimension, i.e. |Dim2A-Dim2B|, (ii) the absolute value of the distance between crops on the third dimension, i.e. |Dim3A-Dim3B|, or (iii) the Euclidian distance between crops on second and third dimensions, i.e. $\sqrt{(\mathrm{Dim2A}-\mathrm{Dim2B})^2+(\mathrm{Dim3A}-\mathrm{Dim3B})^2}$, as fixed factor. The random factor was the block in all three models.

In addition to evaluate the impact of the position of the crops in the 2-3 plane of the PCA, we evaluated the impact of temporal complementarity-related variables, namely the time between the harvests of the two crops in each intercrop and the time really spent in intercrop, i.e. during which the two crops were growing together. We calculated (i) the percentage of its cycle each crop with the longest cycle in each intercrop spent alone after the harvest of the other crop of the intercrop, (ii) the percentage of its cycle each crop spent in intercropping and (iii) the percentage of the intercrop cycle actually spent in intercropping. The length of the growth cycle of an intercrop

was considered as the duration between the setting up of the first crop on the plot and the harvest of the last crop.

We analysed the impact of these three temporal characteristics on the per crop and intercrop variables using three variance analysis models. Each model had one of the three temporal characteristics as fixed factor and the block as random factor. The effect of the percentage of its cycle each crop with the longest cycle in each intercrop spent alone after the harvest of the crop it was combined with was analysed on the per crop variables – with the data of the crops with the longest cycle in each intercrop only – and the intercrop variables. The effect of the percentage of its cycle each crop spent in intercropping was analysed on per crop variable only and the percentage of the intercrop cycle actually spent in intercropping on the intercrop variables only.

All statistical analyses were performed on R v.3.4.1. We used the *lmer* function for all linear mixed models, the *anova* function to the test the significance of the fixed factors of the linear mixed models and the *emmeans* function to perform mean comparisons.

All the variables available for this trial are summarised in Figure 20.

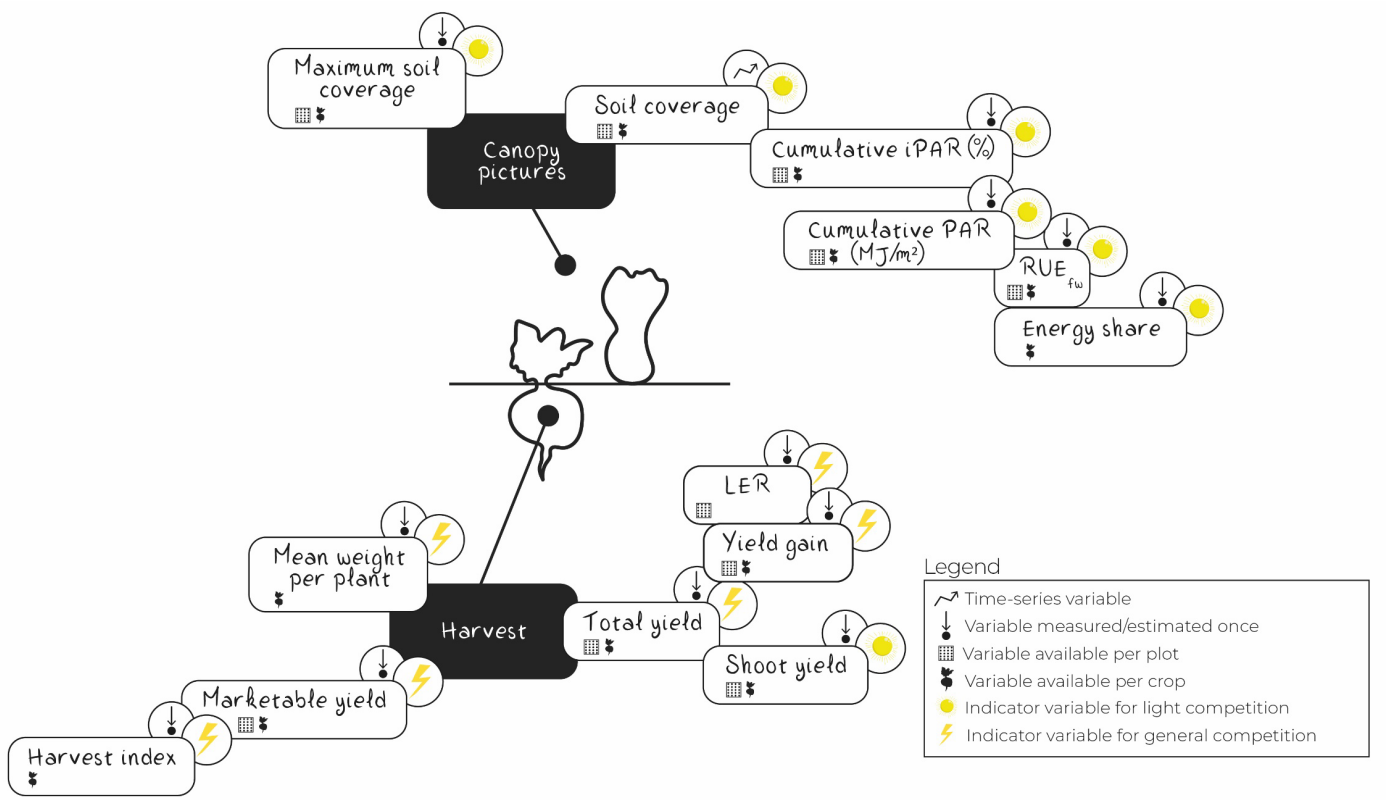


Figure 20 - Summary of the measurements taken and variables estimated in the second trial set in agricultural experiment station. Black boxes are the measurements we took, white boxes the variables we derived from these measurements. Variables that are next to each other are linked to each other. iPAR=Intercepted photosynthetically active radiation, LER=Land equivalent ratio, RUE_{fw}=Radiation use efficiency based on fresh weight.

4.4. RESULTS

4.4.1. COMPLEMENTARITY AS A DRIVER OF INTERCROPPING PERFORMANCE?

The white onion, which was the crop with the largest yield loss in intercropping, influenced our global results in a very marked way. Therefore, we decided to consider it as an outlier for the following of the result section and to remove it from our dataset. This also made the distribution of the six remaining crops more balanced in the PCA (Figure 18).

As the second and third dimensions of the PCA reflected differences regarding root and shoot architectures between crops, we would expect intercrops between two distant crops on the PCA graph (Figure 18) to perform better than intercrops combining nearer crops. However, the results of our global analysis (Figure 21) clearly show that there was no influence of the distance between the component crops of an intercrop – neither along the second dimension, nor along the third, nor along both dimensions – and its LER. There was an important range of possible values for LER (Figure 21). However, 87% of the points – each one representing one repetition of one intercrop – are between 1 and 1.8 and 60% are between 1 and 1.5 for the LER, which corresponds to usual LER values (Yu et al., 2015). The points that have a LER above 2 (6.5%) represent cases in which the crops developed particularly well in the corresponding repetition of the intercrop and/or particularly poorly in the corresponding repetition of the pure crops. In contrast, the points that have a LER below unity (6.5%) represent cases in which the crops grew particularly poorly in the corresponding repetition of the intercrop and/or particularly well in the corresponding repetition of the pure crops.

Moreover, the LER was not influenced by the percentage of the total growth cycle during which both crops grew together (p-value=0.37), nor by the percentage of its cycle the crop with longest cycle in each intercrop spent alone after the harvest of the crop it was associated with, i.e. the relative length of the potential compensatory growth (p-value=0.17) nor by the relative difference between the sowing/plantation dates of the component crops of the intercrop (p-value=0.87).

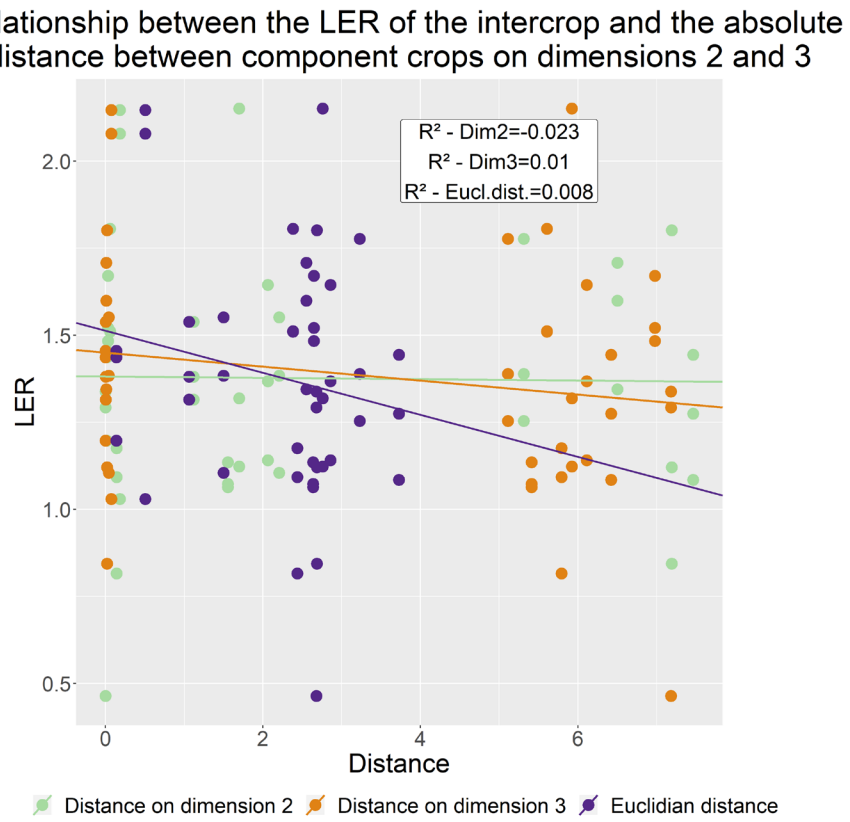


Figure 21 - Relationship between the LER of the intercrops and the absolute value of the distance between component crops on dimension 2 (light green), the absolute value of the distance between component crops on dimension 3 (orange) and the Euclidian distance between component crops on dimension 2 and 3 (dark purple). Regression lines were obtained using a linear model with the corresponding distance as fixed factor. Each point in the graph represents one repetition of one intercrop. Each repetition of each intercrop is present three times in the graph, once in green, once in orange and once in purple. LER=Land Equivalent Ratio.

4.4.2. Dissecting LER into ecophysiological components to understand the effect of PCA dimensions

4.4.2.1. Link with PCA dimensions

To understand better the potential link between the relative position of the component crops of the intercrops in the PCA graph (Figure 18) and the performance of the intercrops, we conducted the same analysis that we carried on the LER on the other variables. For the sake of simplicity, we used for each variable and each crop the ratio between its value in intercropping and its value in pure crop (cf. 4.3.6). For the intercrop variables, we used the

sum or the difference of the ratios of the two component crops. When we write that a variable is positively influenced, we refer to the ratio between intercrop and pure crop.

The second dimension had a significant effect on a few variables (Figure 22). At the crop level, being associated with a crop far from itself on the second dimension increased the shoot biomass of a crop (p-value=0.033). At the intercrop level, the inequality of the share of incident light between these crops increased with the distance between companion crops on the second dimension (p-value=0.016), therefore showing the increased dominance of one of the crops over the other for light interception. As the crops ranged from tall to short along the second dimension, this result was not unexpected: the taller crop shaded the shorter one. However, this dominance did not lead to an increase in the yield asymmetry. This suggests that the crop that had a lower share of incident radiation was able to use successfully the diffuse light, which was not considered in our estimation of iPAR.

In contrast, the third dimension had no significant effect on the studied variables (Figure 22). Consistently, the significance of the effects of the second dimension decreased when considering the Euclidian distance, i.e. the distance between crops on both the second and third dimension, as shown by the absence of significant effect of the Euclidian distance (Figure 22). The addition of the third dimension reduced the effects of the second dimension. As our crops were either very close or far away from each other along dimension 3, this was not really surprising (Figure 18).

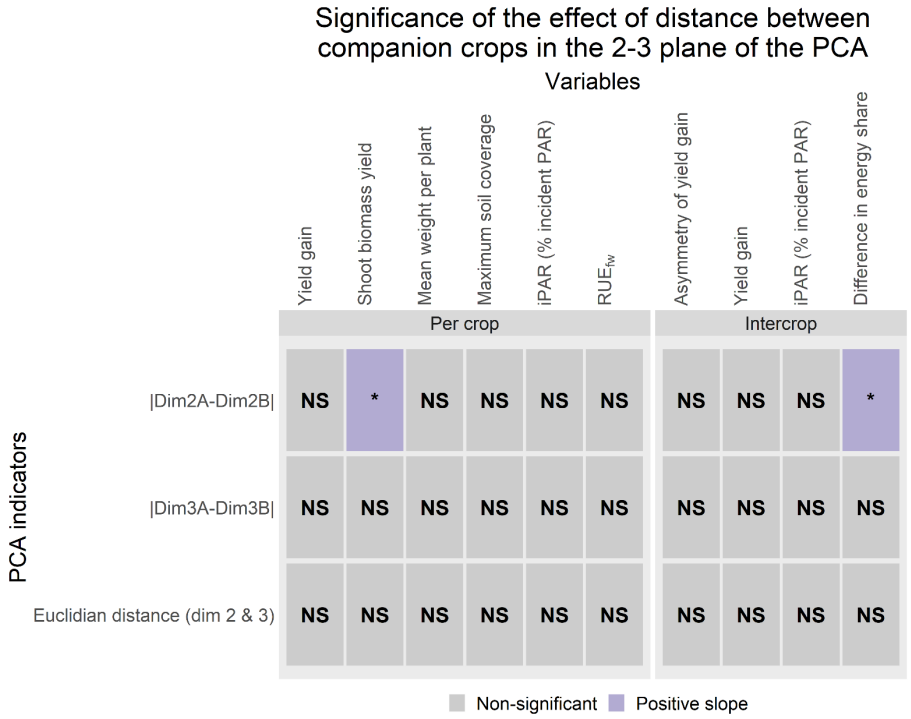


Figure 22 - Effect of the distance between component crops in the 2-3 plane of the PCA on per crop and intercrop variables. The effect of each distance was evaluated by using a linear mixed model in which the distance of interest was the fixed factor and the block was the random factor. In order to compare data from different crops, we calculated, for each variable except the yield gain, the asymmetry of yield gain and the difference in energy share, which were already on a relative scale, the ratio between its value for each component crop in each intercrop and its value for the corresponding pure crop. For the iPAR of the intercrop, the sum of the ratios of the two crops was used. Regarding energy share, the absolute difference in energy share between the component crops of the intercrops was used, i.e. a positive effect on the energy share means that the energy share was less equal. iPAR=intercepted photosynthetically active radiation, RUE_{fw}=Radiation use efficiency based on fresh weight.

4.4.2.2. Link with temporal complementarity-related characteristics

According to the theory of temporal complementarity, the longer the time between the harvests of the two companion crops, the higher the yield, thanks to a compensatory growth of the crop with a longer cycle during this time.

This is consistent with our results, as the percentage of its cycle each crop with a longer cycle[8] spent alone after the harvest of the crop with a shorter cycle, influenced positively its shoot biomass yield (p-value<0.001), its maximum soil coverage (p-value=0.042) and its yield gain (p-value=0.015) (Figure 23). Interestingly however, the increase in yield gain of the crop with a longer cycle when associated with a crop whose cycle was shorter than its own did not result in an increased yield at the intercrop level. This suggests that the yield gain of the crop with a longer cycle was counterbalanced by a yield loss of the crop with a shorter cycle.

The percentage of the total intercrop growth cycle during which both crops actually grew together had a negative link with the asymmetry of yield gain (p-value=0.005, Figure 23). This suggests that the dominance of one crop on the other was lower when crops spent more time growing together. Intercrops in which the crops spent the most time together were, by definition, the ones in which both crops were setup in the field at the same time and harvested more or less at the same date. In these intercrops, no component crop had the advantage of either being setup before the other or developing faster than the other did, which explains the less marked dominant-dominated relationship. This resulted in a decrease in the yield gain (p-value=0.004) and the maximum soil coverage (p-value=0.013) per crop but not at the intercrop level. Intercropping crops with similar growth dynamics, i.e. in our case, crops that developed their soil coverage at the same pace and attained their maximum soil coverage more or less at the same time, therefore seems to be a way to balance the distribution of the produced biomass between component crops without reducing the total biomass production of the intercrop.

[8] Shorter and longer growth cycles do not correspond here to specific growth cycle lengths but are used in a relative way, “crop with a shorter cycle” and “crop with a longer cycle” referring respectively to the crop with the shortest growth cycle and the one with the longest growth cycle in each intercrop.

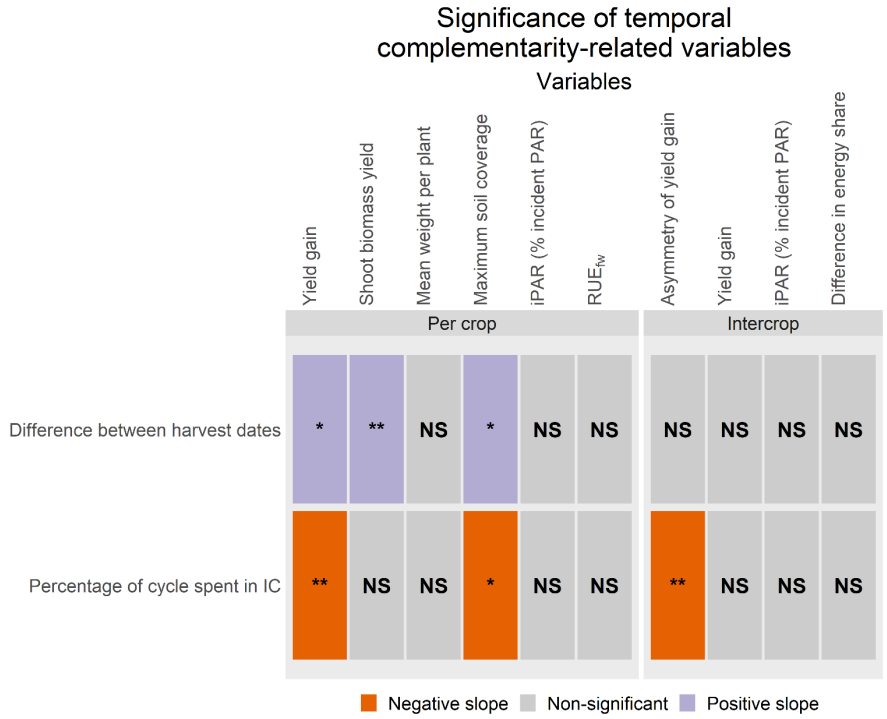


Figure 23 - Effect of temporal complementarity-related variables on per crop and intercrop variables. The effect of each temporal variable was evaluated by using a linear mixed model in which the temporal variable of interest was the fixed factor and the block the random factor. In order to compare data from different crops, we calculated, for each variable except the yield gain, the asymmetry of yield gain and the difference in energy share, which were already on a relative scale, the ratio between its value for each component crop in each intercrop and its value for the corresponding pure crop. For the iPAR of the intercrop, the sum of the ratios of the two crops was used. Regarding energy share, the absolute difference in energy share between the component crops of the intercrops was used, i.e. a positive effect on the energy share means that the energy share was less equal. For the difference between harvest dates, we calculated the percentage of its cycle the crop with the longest cycle in each intercrop spent alone after the harvest of the crop with which it was combined. The percentage of cycle spent in IC was calculated based on the cycle length of each crop for the per crop variables and on the total growth cycle of each intercrop (difference between first sowing/plantation and last harvest) for intercrop variables. IC=Intercropping, iPAR=Intercepted photosynthetically active radiation, RUE_{fw}=Radiation use efficiency based on fresh weight.

4.5. Discussion

The results of our trial showed (i) an absence of significant link between either the Euclidian distance between component crops in the 2-3 plane of the PCA or the distance between component crops on the second and third dimensions and the LER of the intercrops, (ii) an increase of the inequality of incident radiation interception between component crops with the increase

in the distance between the crops on second dimension but no increase in the asymmetry of yield gain, and (iii) no significant effect of either the distance between crops on dimension 3 or the Euclidian distance between crops on the ecophysiological variables. Besides, our results also showed a significant link between the time interval between the harvests of the crops and the yield of the crop with a longer growth cycle and a more even distribution of the produced biomass between the crops when intercropping crops with similar growth cycle lengths.

The objective of this trial was to assess the role of architectural differences between the crops, as revealed by a PCA, to explain – and hopefully predict – the differences in outcome between our intercrops, on the basis of spatial complementarity principles. However, our results did not show any clear link between the relative positions of the crops in the PCA and the outcome of the intercrops. Only the second dimension had a significant effect, suggesting that associating crops with contrasted shoot architecture (tall *vs* short) increased the interception of direct light by the tall crop. This has already been observed in many cases: the taller crop shades the shorter one and prevents it from intercepting direct light (e.g. wheat + rapeseed (Khan et al., 2005), cowpea + maize (Wahua et al., 1981), soybean + maize (Abdel-Galil et al., 2014), groundnut + millet (Reddy & Willey, 1981)). However, the increase in the difference in energy share did not lead to a decrease in LER or an increase in the asymmetry of yield gain. This suggests that the shorter crops were able to use the diffuse light that reached them and that they maybe used it in a more efficient way, as observed by Marshall & Willey (1983) in an intercrop between millet and groundnut or by Gou et al. (2017b) in a maize + wheat intercrop.

Regarding roots, we expected some positive effects on the LER when combining crops with contrasted root architecture, i.e. crops that were far apart either on the second or on the third dimension of the PCA. In fact, Li et al. (2006) showed that maize was able to explore a larger portion of the soil when intercropped with faba bean than when combined with wheat, thanks to the shallower root system of faba bean and the ability of maize roots to grow deeper than and under those of faba bean. Similarly, Xia et al. (2013) observed that the root length, growth and distribution of maize was less impeded when intercropped with faba bean, chickpea and soybean than when associated with turnip, which had a more extended root system than all three other crops. It may be that the root length density and the root distribution of the crops were modified in presence of the companion crop.

However, we noticed no positive effect on the LER. It is possible that the positive effect of combining crops with different root architectures would be greater in soil resource-limited conditions. Allen & Obura (1983), for example, observed better results for a corn + cowpea intercrop than for a corn + soybean intercrop but argue that, in dry conditions, the corn + soybean one might be more suitable thanks to the deeper root system of soybean compared to corn and cowpea. It may also be that, in some cases, the combination of root systems with contrasted architecture may favour the crop with the more extended root system over the other (e.g. cowpea + maize, Egbe et al., 2010).

According to us, the absence of clear link between the relative position of the crops in the PCA and the productivity of the crop may come from two elements. Firstly, our PCA was based on an average of two drawings per species grown in unknown conditions drawn when the crops were mature, with no systematic indication regarding the variety of the crop. Consequently, it did not capture the variability that exists between individuals of the same crop (e.g. Mishra et al., 2012) due to phenotypic plasticity, i.e. the modification of the expression of a genotype according to the environment (Bradshaw, 1965), and the crops may not have developed in the same way in our trial as represented in the images used to determine the inputs of the PCA. This is all the more true when talking about intercropping: the competition for resources between associated crops can provoke further changes in the architecture of the crops (e.g. change in the root distribution of maize in intercropping (Xia et al., 2013), increase in height of cassava intercropped with maize (Ezumah & Lawson, 1990)). A way of improving the model would probably be to take into account more quantitative data about the extent of the root and shoot compartments of vegetable crops but there is no data of this type available at the moment. Secondly, the PCA was based on the assumption that it is the spatial complementarity between mature crops that may influence the performance of intercrops and does no take into account the growth rate of the crops. The effect of spatial complementarity may actually be adjusted by the effect of temporal complementarity.

Our results were more promising regarding temporal complementarity. They showed a clear link between the yield of a crop with a longer cycle and the time it spent alone after the harvest of its companion crop. This was probably linked to a compensatory growth phenomenon, as has already been observed in other studies (e.g. Awal et al., 2006; Huang et al., 2017; Zhang et

al., 2017). According to this observation, it seems beneficial to intercrop plants with difference in growth cycle length, which is consistent with what we observed in Chapter 3. The increased yield gain of the crop with a longer cycle, however, was not reflected at the intercrop level, which supposes that it may have been counterbalanced by a lower yield gain for the crop with a shorter cycle. On the other hand, our results also showed that intercropping two crops with similar growth cycle lengths, set in place at the same time, led to a more even distribution of the produced biomass between component crops but not to an increase in the global yield gain compared to other intercrops.

Our results highlight the fact that working with intercrop implies working with complexity and underline the difficulty of drawing general trends from data of a range of intercrops using a pre-defined analytical framework, even if based on quantitative and objective data. This calls for a more exploratory approach to understand intercropping, i.e. analysing the pattern of resource sharing between companion crops without relying on preconceived theoretical concepts.

*

* *

In this fourth chapter – and the second one dedicated to our second research question, related to criteria for intercrop selection – we differentiated market gardening crops according to the size and the form of their shoot and root systems using a PCA. Our assumption was that an intercrop between two crops far apart in the PCA should be more productive, thanks to spatial complementarity, than a combination of two crops close together in the PCA.

Overall, this hypothesis was disproved in the context of our trial, as no clear link was found between the distance between companion crops along the second and third dimensions of the PCA and the productivity of the intercrops. The non-verification of our starting hypothesis is interesting on both practical and theoretical levels. On the one hand, no matter if our results come from the fact that the PCA did not take enough into account the architectural variability of each crop or from the fact that architectural differences are not decisive for intercrop productivity, they highlight the fact that it is hazardous to base the choice of an intercrop on architectural criteria only. On the other hand, our results suggest that other characteristics are probably more important than architecture in determining the pattern of

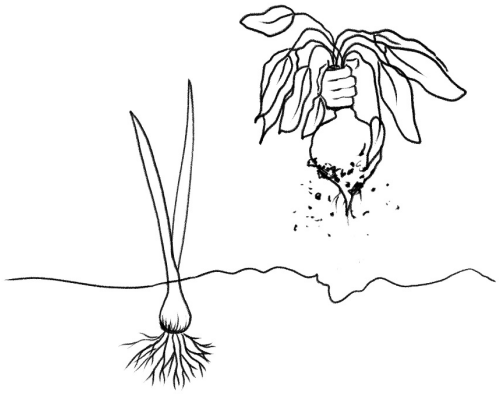
resource sharing and the outcome of an intercrop. This requires further exploratory analysis of our results to identifiy these characteristics, which might have a better predictive value. This will be the subject of our next chapter (cf. Chapter 5). These results are in line with those of Chapter 3, in which we showed that (i) differences in architecture may not always lead to better complementarity between crops and (ii) the effect of the shoot spatial complementarity as defined in Chapter 3 was probably modulated by other variables.

This trial also shows that the temporal complementarity between crops, i.e. the time lag between their harvests, had a positive impact on the yield of the later-maturing crops, suggesting an effect of compensatory growth. However, the yield gain of the later-maturing crops was not reflected in the total yield gain of the intercrops. Besides, we showed that when two crops had similar growth cycle lengths, the asymmetry between their yield gains was lower, suggesting that they had more equal competitive abilities. These findings allow to qualify the result regarding temporal complementarity from Chapter 3.

Both trials agree that temporal differences between the growth of crops seem to be prevailing in the outcome of the intercrops. However, this second trial emphasises the fact that (i) increasing the time-lag between the harvests of associated crops does not always lead to a greater LER and (ii) combining crops with similar growth cycle lengths may decrease the asymmetry in resource sharing between the crops. On a practical point of view, this suggests that a market gardener combining crops with differences in growth cycle lengths exposes himself to the risk of greater yield gain asymmetry between the associated crops, which is not necessarily negative but is important to anticipate.

It is important to note that our results were observed in a context where light was probably the most limiting resource and that the conclusions might change in other contexts.

Chapter 5 |
Growth dynamics and resource capture and not efficiency determine the outcome of intercrops



In the two previous chapters, we presented the results of the two on-field trials we set up in agricultural experiment station (AES), designed to address our second research question, i.e. “Which criteria use to choose productive intercrops?”.

If we were able to identify some interesting links between some components of our complementarity models and some of the studied ecophysiological variables, it was overall difficult to interprete the differences in outcome we observed between the intercrops by sticking to our initial assumptions and crop/intercrop classification. Moreover, we saw in Chapter 3 that if the complementarity criteria we defined seemed to capture part of the reality, their effect was modulated by other variables, which it would be interesting to identify.

In this chapter, we will analyse further the results of the two on-field trials presented in Chapter 3 and Chapter 4 by using a more exploratory approach and try to identify, based on the data from the second on-field trial (cf. Chapter 4), common characteristics between the intercrops that performed in the same way.

We begin by briefly reminding the organisation of the two trials and the intercrops that we studied as well as the statistical analyses we performed (section 5.2). Afterwards, we dive into the results (section 5.3) by presenting first the conceptual model on which our analysis is based (section 5.3.1), then the results regarding radiation use efficiency (section 5.3.2), intercepted radiation (section 5.3.3) and growth dynamics and soil coverage (section 5.3.4). Finally, we validate our findings based on the data from the second field trial in AES (cf. Chapter 4) against the data of the first field trial in AES (cf. Chapter 3) (section 5.3.5) and discuss these findings (section 5.4).

CHAPTER 5 | GROWTH DYNAMICS AND RESOURCE CAPTURE AND NOT EFFICIENCY DETERMINE THE OUTCOME OF INTERCROPS

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5.1. INTRODUCTION

In Chapter 3 and Chapter 4, we analysed the link between two classifications of intercrops – one attributing to each intercrop a complementarity score on the basis of growth cycle length and qualitative architectural data and one based on a principal component analysis (PCA) on quantitative architectural data – and the performance of the intercrops. We evaluated the link between our classifications and the land equivalent ratio (LER) and we dissected the LER into various physiological variables to understand better the interactions between crops. Although we found some significant relationships between our classifications and some of the studied variables (cf. Chapter 3 & Chapter 4), it was hard to draw conclusions regarding their explanatory value and, even more, their predictive value. Two assumptions may explain this difficulty: it may be that our classifications did not represent well the reality, because of the poor quality and/or the scarcity of the starting data, as it may be that the criteria used in our classifications were not adequate to explain the differences in productivity between intercrops.

In the present chapter, we decided to address the reverse question: can we, on the basis of a physiological analysis of the growth of the intercrops studied in the trials described in Chapter 3 and Chapter 4**,** reformulate rules that are predictive of the performance of intercrops? This question can be addressed by identifying characteristics or set of characteristics that are common to intercrops that performed in the same way.

5.2. MATERIAL & METHODS

5.2.1. STUDY ZONE, EXPERIMENTAL DESIGN, CROP MANAGEMENT AND MEASUREMENTS TAKEN

The results used in this chapter come from the experimental trials presented in Chapter 3 and Chapter 4. Measurements taken and variables derived from these are summarised in Figure 24. Information regarding the design of the trials can be be found in Chapter 3 and Chapter 4. Variables available in both trials were measured in similar ways (cf. Chapter 3 & Chapter 4). However, the intercepted photosynthetically active radiation (iPAR), the evolution of soil coverage, the maximum soil coverage and the radiation use efficiency based on fresh weight (RUE_{fw}) were estimated at the plot level in the first trial while, in the second trial, their estimation at the plot level was further detailed for each crop.

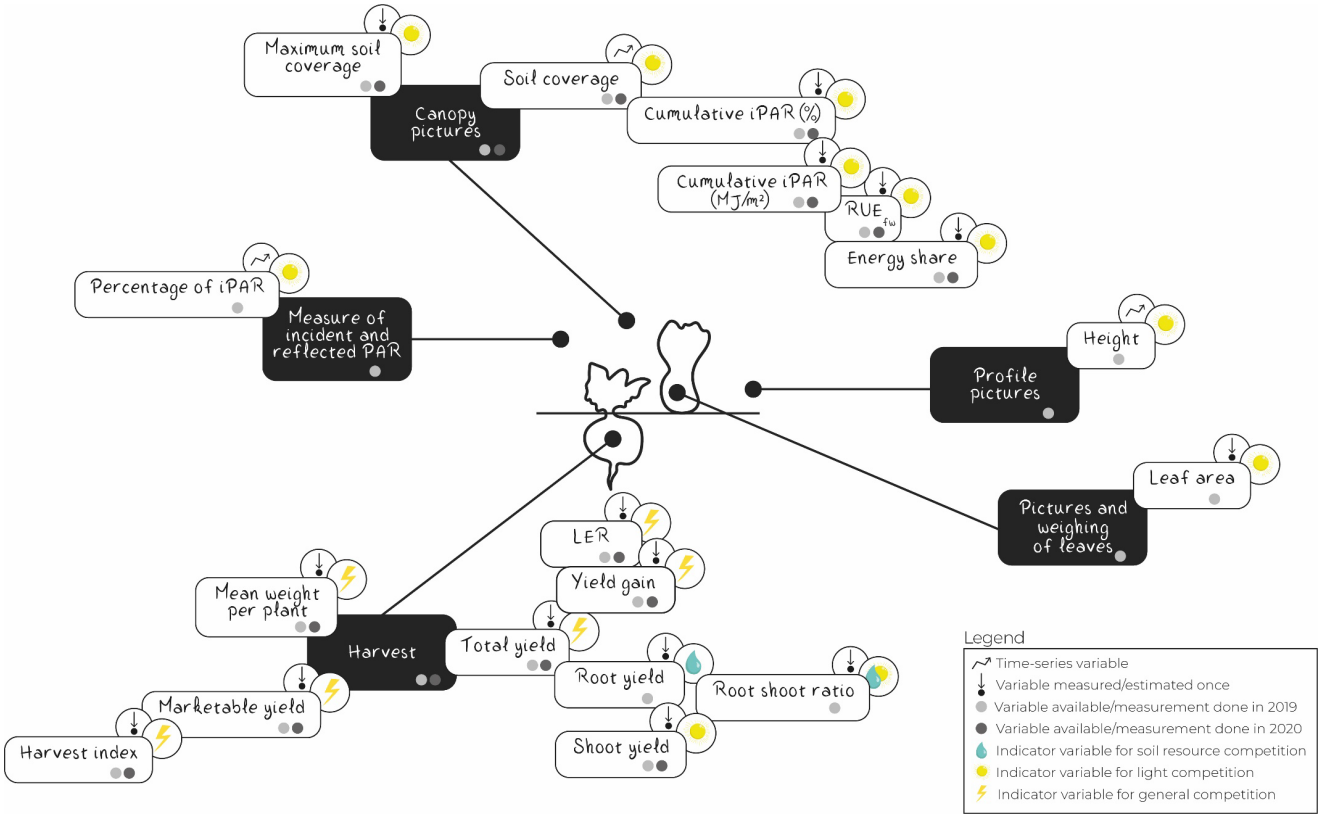


Figure 24 - Summary of the measurements taken and variables estimated in both field trials set in agricultural experiment station. Black boxes are the measurements we took and white boxes the variables we derived from these measurements. Variables that are next to each other are linked to each other. PAR=Photosynthetically active radiation, RUE_{fw}=Radiation use efficiency based on fresh weight.

The 2019 trial, i.e. the first trial set in agricultural experiment station (AES), focused on 16 different intercrops based on 19 crops. Some of these crops were present in various intercrops, the others in only one (Figure 25A). In the 2020 trial, i.e. the second trial set in AES, we studied all pairwise combinations between seven crops (Figure 25B), analog to a diallel design allowing the estimation of general and special combining abilities. The 2020 trial also included two legumes (dwarf bean and string bean).

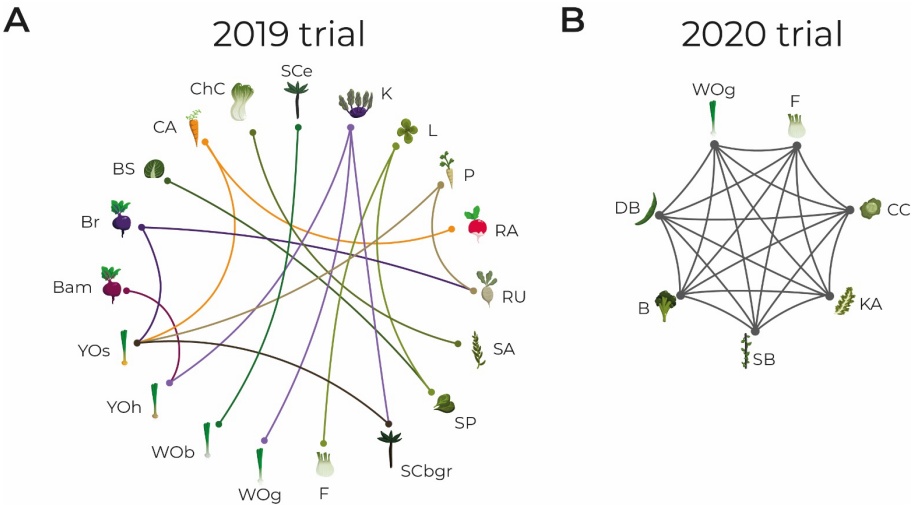


Figure 25 - Intercrops studied in the first (A) and second (B) on-field trial set in agricultural experiment station. B=Broccoli, Bam=Beetroot Alvro-Mono, Br=Beetroot Rhonda F1, BS=Brussels sprout, CA=Carrot, CC=Collard cabbage, ChC=Chinese cabbage, DB=Dwarf bean, F=Fennel, K=Kohlrabi, KA=Kale, L=Lamb's lettuce, P=Parsnip, RA=Radish, RU=Rutabaga, SA=Savory, SB=String bean, SCbgr=Scorsonera Noir Géant de Russie, SCe=Scorsonera Enorma, SP=Spinach, WOb=White onion Barletta, WOg=White onion de Gladstone, YOh=Yellow onion Hylander F1, YOs=Yellow onion Sturon.

5.2.2. STATISTICAL ANALYSIS

5.2.2.1. Analysis at the level of individual crops

In both trials, the variables measured/estimated once in the trial (e.g. harvest related variables) were analysed using a linear mixed model with "Modality" as fixed factor and "Block" as random factor. For each crop and each variable, we performed comparisons of means between each component crop of the intercrops and the corresponding pure crop (Tukey). For density dependent variables, e.g. maximum soil coverage, density-adjusted pure crop data were computed by multiplying the raw data by the density ratio between intercrop and pure crop.

In 2020, we analysed the impact of the presence and identity of a legume in the intercrop on the yield gain of each crop using two linear mixed models: one with the presence of legume as a fixed factor, the other with the identity of the legume, either dwarf bean, string bean or none, as a fixed factor. Block was the random factor in both models.

In 2020, we also estimated (i) the general combining ability of a crop, computed as its mean yield gain (compared to the pure crop) across all intercrops where it is included, (ii) the mean effect of a crop on its associated crops, expressed as mean yield gain across all intercrops were it is included and (iii) the difference between the yield gain of a crop in a given intercrop and its mean yield gain across all intercrops where it is included, which can be seen as its special combining ability. These values were estimated based on the means obtained from a linear mixed model using “Crop”, “Modality” and their interaction as fixed factors.

The previous analyses were also performed on the cumulative iPAR value at the end of the season (in percent compared to the cumulative incident radiation over the season) and on soil coverage time series. For cumulative iPAR, the combining abilities were computed using relative intercrop:pure crop ratios. The ratio was also adjusted for density differences between intercropping and pure crop by dividing it by the density ratio of the crop in the two modalities.

Because the shape of the temporal evolution of soil coverage was not linear and differed across modalities, the soil coverage time series were analysed using a score method. For each measurement date, we assigned a score to the soil coverage of each crop in each repetition of each intercrop. This score had a value of “1” if the soil coverage of the crop in the intercrop was higher than its expected soil coverage and a value of “2” otherwise. The expected soil coverage was computed as the soil coverage of the corresponding pure crop at the same date multiplied by the density ratio between the crop in the intercop plot and in the pure crop plot in the same block. Therefore, the lowest the mean soil coverage score of a crop in intercropping, the higher the frequency with which its soil coverage was higher than expected. For the calculation of the specific combining abilities, we substracted the mean soil coverage score of a crop across all intercrops to its mean soil coverage score in each intercrop.

5.2.2.2. Analysis at the level of the intercrop

The yield data, RUE_{fw}, maximum soil coverage and cumulative iPAR were analysed for each intercrop using a linear mixed model with "Type" as fixed factor – pure crop 1, pure crop 2, intercrop – and "Block" as random factor. We used custom mean comparisons (contrasts) to compare (i) the intercrop to each pure crop, and (ii) the intercrop to the sum (yield data, maximum soil coverage, iPAR) or the mean (RUE_{fw}) of the two corresponding pure crops. When relevant, data of the pure crops were corrected by multiplying them by the density ratio between intercrop and pure crop.

All statistical analyses were performed in R v.3.4.1 with the *lmer* and *anova* functions for the linear mixed models, the *contrasts* function to perform custom mean comparisons and the *emmeans* function to perform other mean comparisons. For the comparison of means of per crop variables between each intercrop and the corresponding pure crop, we used the *DunnettTest* function.

5.3. RESULTS

In the previous chapter (cf. Chapter 4), onions were removed from the data of the 2020 trial as they outweighed the global message. In this chapter, onions were maintained in the dataset, as per crop and per intercrop analyses allow us to distinguish the effect of the onions from the effect of the other crops.

In Chapter 3 and Chapter 4, results were interpreted with reference to theoretical criteria or PCA descriptors that had been established prior to the experiment. Given the limits encountered in interpreting results in this manner, we decided to interpret the results using actual ecophysiological data collected in the trials.

Since the combining ability design of the 2020 trial allows to study the average effect of intercropping on each crop and the average effect of each crop on its companion crops, we used the results of the 2020 trial (cf.Chapter 4) as the basis of our analysis and confronted the general trends with the results of the 2019 trial (cf. Chapter 3).

5.3.1. CONCEPTUAL MODEL

The LER is the primary indicator of intercropping success. Out of the 33 intercrops we studied in the two trials in AES, thirteen had an average LER significantly higher than unity and only one had an average LER significantly lower than unity. This means that nearly all intercrops used the land as well or better than the corresponding pure crops. It also suggests that it would be beneficial for a market gardener, in terms of biomass production, to grow two plots of an intercrop rather than one plot of each of the corresponding pure crops. The fact that the results regarding LER are so consistent across a variety of intercrops argues in favour of this cropping practice, at least if one disregards the complexity of crop management that it entails.

Although all the intercrops we studied had a LER either not different from or significantly higher than unity, about 30% of the individual crops had a yield significantly lower than expected. This means that there was, in at least some of the intercrops, some competition for resources that prevented some crops to develop as well in intercropping as in pure crop.

Considering the conditions under which our field trials were conducted – rich soil and irrigation (cf. 3.3.1 & 4.3.1) – solar radiation is likely the key resource to analyse the results of the intercrops. The biomass a plant produces depends on the quantity of PAR it intercepts and the efficiency with which it converts radiation into biomass (Figure 26). The two factors can be affected by intercropping. On the one side, the capture of solar radiation depends on the incident PAR, the length of the growth cycle and the crop architecture, which determines the fraction of light intercepted by the crop. On the other side, the efficiency of conversion of photons to biomass (RUE) is a characteristic of each crop and is expected to decrease when a stress condition occurs that reduces net photosynthesis more than light interception. The various forms of interaction between the component crops of an intercrop (cf. Chapter 2) are therefore likely to influence each crop, potentially in different ways.

Using the soil coverage, which is a reasonable proxy for radiation interception, and the RUE, we will analyse (i) why some intercrops produced less biomass than expected and (ii) what were the common characteristics between the intercrops with the highest LERs.

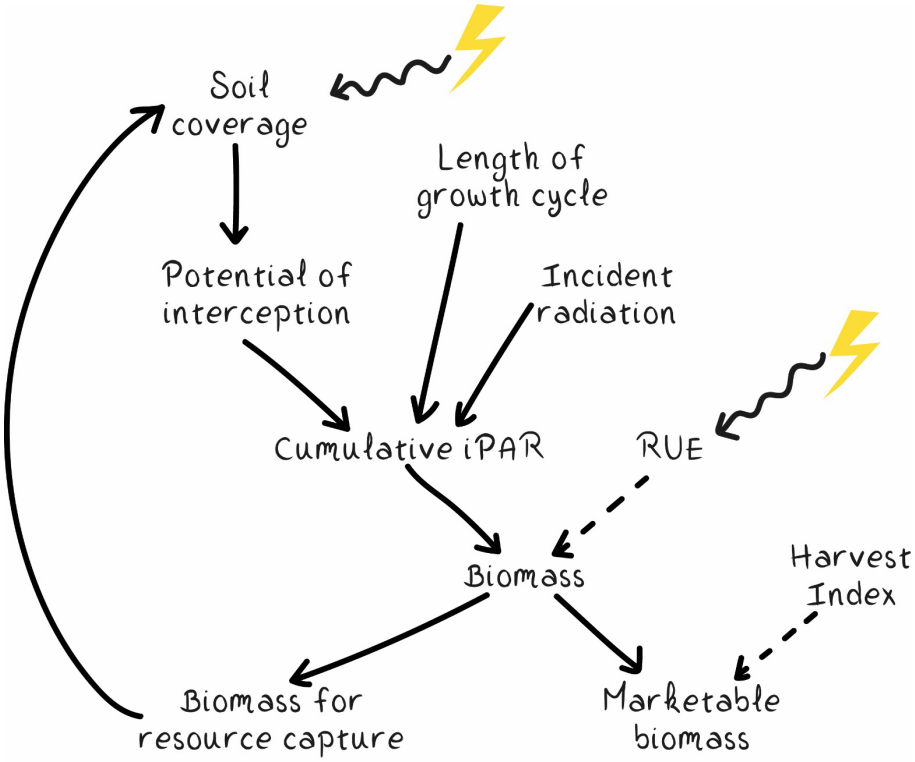


Figure 26 - Conceptual links between the light-related variables. Lightnings and wavy arrows show the variables on which the competition with a companion crop can have an impact and hence affect the biomass production.

5.3.2. RADIATION USE EFFICIENCY

The RUE is a characteristic proper to each crop. The higher it is, the more efficient the plants are at using the intercepted light, i.e. the more biomass they produce for a given quantity of photons. Some environmental conditions can modulate the RUE value. In intercropping, two main modifications can be expected: the RUE can be lowered due to a competition for nutrients and/or for water, while it can be increased via a better distribution of the radiation among the leaves, as we could expect that the likelihood of leaves being radiation saturated might decrease in certain intercrop canopies.

Our results showed no modification of the RUE_{fw} when comparing pure crop to intercropping (p-values: 0.28 (type of cropping), 0.054 (type of cropping*crop)) (Figure 27). According to this result, the differences between the yield of each crop in intercropping and in pure crop was linked to a

difference in the quantity of intercepted light rather than to a difference in the efficiency with which crops converted the radiation to biomass.

There was however one particular case: the broccoli had, in all intercrops but one, a RUE_{fw} significantly lower than in pure crop (p-values<0.05). The fact that this decrease was observed with nearly all crops it was associated with lead us to think that these observations were no outliers but that intercropping had a particularly negative effect on broccoli. This shows that some crops seem to be unsuited for intercropping. Unfortunately, our data do not allow us to explain the causes of this effect.

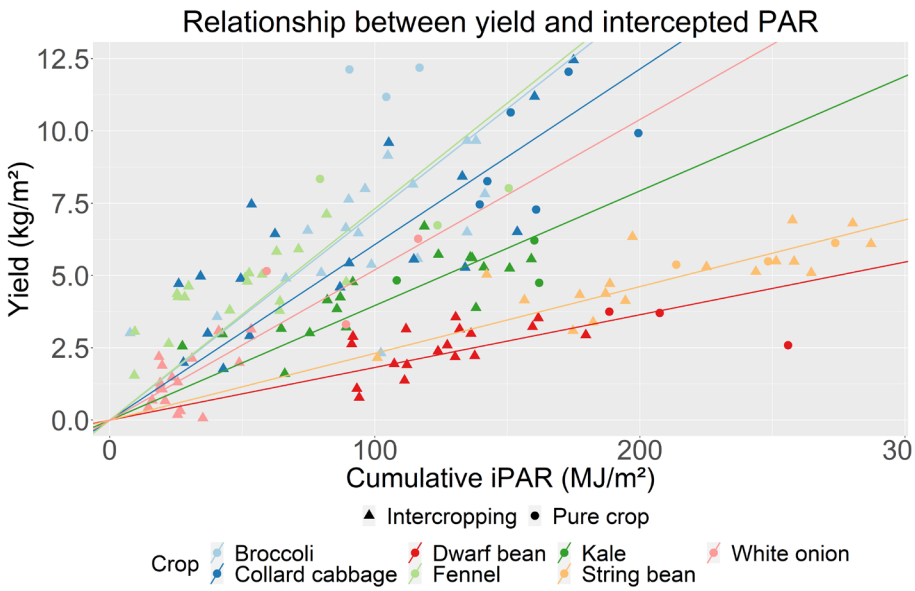


Figure 27 - Relationship between the yield and the cumulative intercepted PAR for each crop from the second on-field trial in agricultural experiment station. For each crop, the values in intercropping are represented as triangles and these in pure crop as circles. The linear regressions were calculated using the lm function in R with the interaction between cumulative iPAR and the crop as fixed factor. The regressions were forced by (0,0). iPAR=intercepted photosynthetically active radiation.

5.3.3. Intercepted radiation

As the RUE_{fw} of a crop was not significantly different in pure crop and in intercrop, we would expect that biomass production in the intercrop depended mainly on the quantity of intercepted radiation (iPAR), which was related to its soil coverage. We observed, indeed, that the loss of iPAR of a crop in an intercrop was negatively correlated to its mean soil coverage score over the season in this intercrop (-0.79, p-value<0.001), i.e. the more the soil coverage of a crop in an intercrop exceeded its expected coverage, the lower

was its loss of iPAR. The loss of iPAR of a crop in an intercrop was also positively correlated to its yield loss in the same intercrop (0.56, p-value<0.001), i.e. the higher the loss of iPAR, the higher the yield loss.

The analysis of the soil coverage score (Figure 28A), iPAR (Figure 28B) and yield (Figure 28C) can help to draw few general trends. Firstly, all seven crops intercepted less PAR than expected and six of them produced less yield than expected. This reflects the fact that, on average, the crops suffered from a higher level of competition when intercropped than when grown alone. This may have been caused either by the dominance of the companion crop or by a density effect, since the total density of the intercrop plot was higher than that of pure crop. In the same way, all the seven crops prevented their associated crops from intercepting as much PAR as expected and prevented them from reaching their expected yield. On average, both crops lost something by being in an intercrop.

Secondly, the average loss of iPAR was negatively correlated with the average loss of iPAR of its associated crops (-0.38, p-value<0.001). Besides, there usually was a difference between the mean soil coverage score of a crop and this of its associated crops, one of the average score being higher than the other (correlation=-0.28, p-value=0.072) This indicates that the crops, when intercropped, competed for space and that a better capture of radiation by one crop was accompanied by a decreased capture by the companion crop. There was, in all intercrops, a winner crop – which was either less or not impacted by the intercrop – and a loser crop. Interestingly, the correlation between the average loss of a crop and the average loss it caused to its associated crops was not significant when it comes to yield (-0.092, p-value=0.30). The overall pattern of yield losses (Figure 28C) was consistent with the one of iPAR losses (Figure 28B): the crops that lost the most iPAR were the ones that lost the most yield. However, the extent of the loss varied between yield and iPAR. This may have been caused by (i) an over/underestimation of the soil coverage leading to an over/underestimation of the iPAR or (ii) the use of diffuse light, which was not accounted for in our estimation of iPAR. A loss of yield lower than the corresponding loss of iPAR might therefore be an indicator of the use of diffuse light and, hence, an indicator of a form of shoot complementarity between crops.

The analysis of these general trends brings to light the fact that, although not all intercrops performed in the same way and despite the diversity of the intercrops we studied, there were some constants: (i) as the soil resources were probably not limiting, the light, linked to the occupation of space in the aerial strata, was the key resource in all intercrops and (ii) overall, both crops tended to suffer from being in an intercrop but one of the component crops was usually less affected than the other.

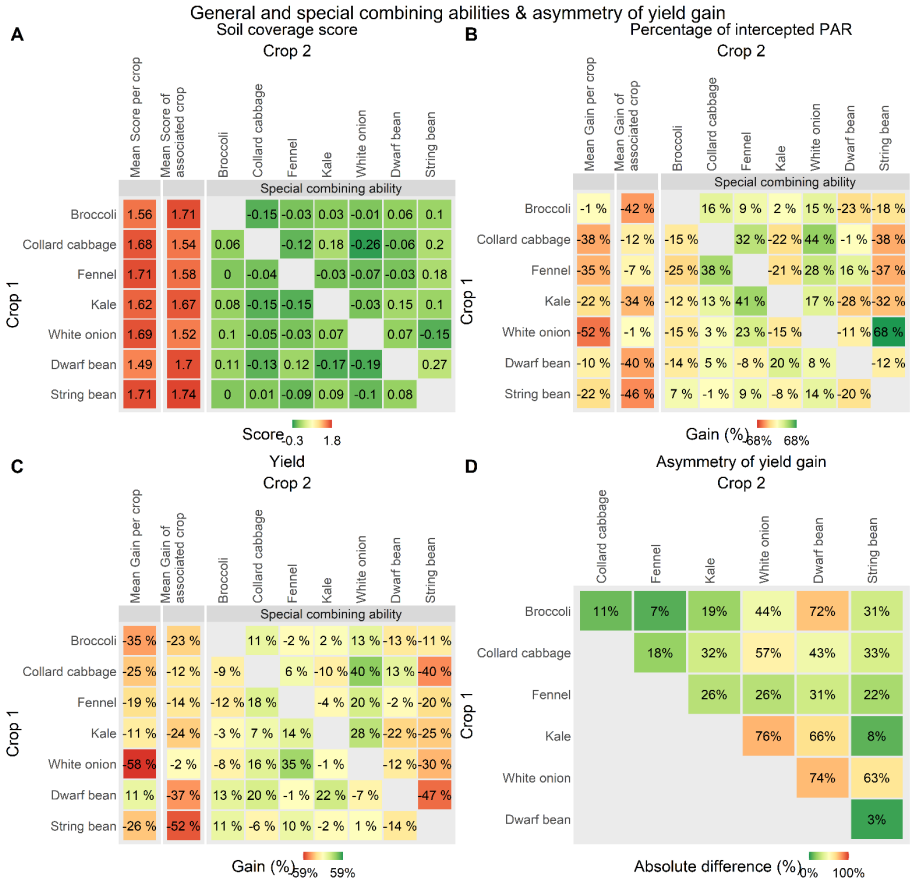


Figure 28 - Mean soil coverage score (A), mean gain of cumulative intercepted PAR (in percent) (B) and mean gain of yield (C) on average for each crop and on average for the crops associated to each crop and special combining ability for each crop in each intercrop for soil coverage score (A), cumulative intercepted PAR (in percent) (B) and yield (C). Asymmetry between yield loss in the intercrops (D). In (A), a positive number in the special combining ability is linked to a decrease in the frequency at which the soil coverage of a crop in intercropping was higher than expected whereas a negative number is linked to an increase in the frequency at which the soil coverage of a crop in intercropping was higher than expected. The positive effects regarding soil coverage and iPAR at the intersection between "White onion" row and "String bean" column are probably largely overestimated due to harvesting difficulties.

5.3.4. GROWTH DYNAMICS AND SOIL COVERAGE

The analysis of the intercrops from the 2020 trial led us to classify them into the three following groups:

Intercrops between two crops with similar soil coverage – maximum of soil coverage reached and time needed to reach the peak (Figure 29A) – and similar date of establishment on the plot (e.g. all intercrops between broccoli, collard cabbage, fennel and kale and the intercrop between dwarf bean and string bean) had lower yield loss asymmetry than the other intercrops of the trial. In other words, the biomass produced by these intercrops was distributed more evenly between the component crops than in the other intercrops of the trial. This suggests that the dominance of one crop on the other was less pronounced in these intercrops that in the others: as both crops developed at the same rhythm, it was probably more difficult for one crop to take the lead on the other (Figure 29B). Following on this hypothesis, they were both bothered by the presence of the other crop and this resulted in losses of yield for both crops. Interestingly, these intercrops were, on average, the ones with the highest LER (mean=1.44).

On the opposite, intercrops combining a fast-growing crop with a high soil coverage potential and sown before a slower-growing crop led to the most pronounced yield asymmetry between the two crops. In these intercrops, the former crop lost less yield than the latter. This is the case of the intercrops between either beans and broccoli, collard cabbage fennel or kale. In these intercrops, the beans developed faster than their companion crops and occupied the aerial space first, hence preventing their companion crops from intercepting as much light as expected (Figure 29C). The beans developed nearly as if they were in pure crops. This phenomenon of dominance of one crop over the other was more pronounced in intercrops with dwarf bean than in intercrops with string bean, which was probably more impacted by the intercrops because of its slightly slower development compared to dwarf bean (Figure 29A). Apparently, the intercrops combining a legume and a non-legume did not take advantage of the nutritive complementarity. However, this effect could have been more pronounced under nutrient-limited conditions (e.g. increase in P availability for maize thanks to the presence of beans especially under P deficient soil (Latati et al., 2016)) or if the beans were associated with more competitive crops (e.g. competition with barley increased the proportion of N from pea derived from atmospheric fixation (Corre-Hellou et al., 2006)). The average LER of the intercrops from this group

(mean=1.25) was lower than in the previous, consistent with the more pronounced asymmetry. Surprisingly, LER was higher (mean=1.31) for intercrops with dwarf bean (that were more asymmetric) than for intercrops with string bean (mean=1.17). The intercrops combining bean and onions are discussed in the next paragraph because the effect of onion outweighed all other factors.

The six intercrops that did not fall in any of these two categories were the ones involving white onion. White onion had a low soil coverage and a slow development (Figure 29A). Consequently, despite being implemented first on the plot, it was rapidly shaded by its companion crop (Figure 29D) and was therefore the crop that had the highest yield losses when intercropped. It was also the crop that affected the least its companion crops. The intercrops from this group had a mean LER lower than the first group (mean=1.20). In particular, the two intercrops combining onion with any of the two bean crops were the ones with the lowest LER (mean=0.89).

The foliar architecture also seems to have played a role in the level of competition between crops. For instance, broccoli and kale had similar growth dynamics and soil coverage as collard cabbage and fennel, yet with a more negative impact on their associated crop. This difference may come from differences in architecture. Broccoli and kale are tall plants (>60cm) and have large full leaves whereas collard cabbage is a rosette plant and fennel grows in height but has a very indented foliage, i.e. leaves with cuts. Consequently, broccoli and kale shaded their companion crops more than fennel and collard cabbage. The same difference in foliar architecture may explain the more negative impact of string bean compared to dwarf bean. Nonetheless, the architecture of the crops seems to come second in determining the performance of intercrops, the main differences being explained by differences in growth dynamics and soil cover. It may be suprising to differentiate soil coverage from shoot architecture but it is justified by the fact that a similar soil coverage may be reached by two crops with distinct architecture.

Finally, when designing this trial, we decided to select two leguminous crops that were near non-leguminous crops (dwarf bean near collard cabbage, string bean near kale) in the PCA (cf. Chapter 4), to be able to isolate the effect of the legume itself from an effect linked to its architecture. However, the analysis above show that the difference in the outcome of intercrops combining dwarf bean/string bean with another crop and the intercrops

combining collard cabbage/kale with another crop was more linked to differences in growth dynamics than to the fact that they were legume or non-legume.

This classification allowed us to identify three main factors that could explain the differences in yield between the 21 intercrops we studied in 2020: (i) the difference in date of establishment on the plot (cf. Appendix G.2), (ii) the difference in growth dynamics (Figure 29A) and (iii) the difference in soil coverage (Figure 29A) between the component crops. Besides these three factors, we also identified an influence of the shoot architecture that, however, came second in determining the yield of the intercrop.

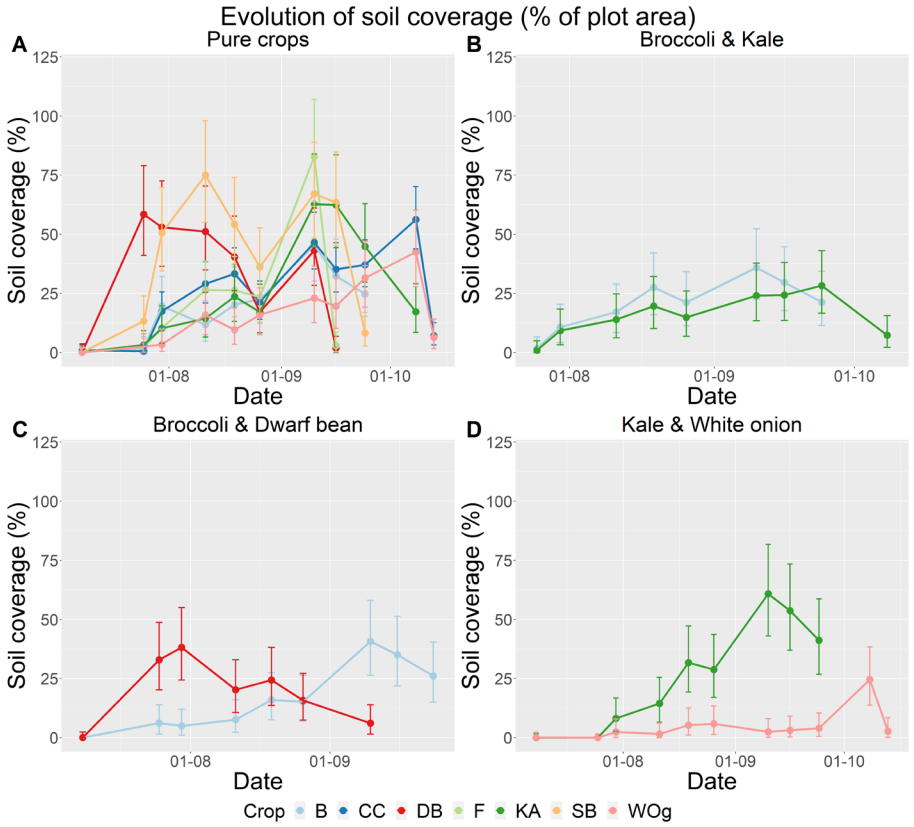


Figure 29 - Average evolution of the soil coverage for the seven pure crops of the second trial set in agricultural experiment station (A), the broccoli-kale intercrop (B), the broccoli-dwarf bean intercrop (C) and the kale-white onion intercrop (D). Graphs B, C and D are situations representative of each of the three groups of intercrops presented in the text. B=Broccoli, CC=Collard cabbage, DB=Dwarf bean, F=Fennel, KA=Kale, SB=String bean, WOg=White onion.

5.3.5. VALIDATION AGAINST 2019 TRIAL DATA

In the previous sections, we identified ecophysiological hypotheses accounting for the differences in biomass production between intercrops based on the 2020 trial (cf. Chapter 4). Here, we will focus on the validation of these hypotheses using the results from the 2019 trial (cf. Chapter 3). Figure 30 represents the adjusted yield ratios (see legend) of the component crops of each intercrop in the first trial. These twelve intercrops can be classified using similar reasoning as for the 2020 trial (cf. 5.3.4).

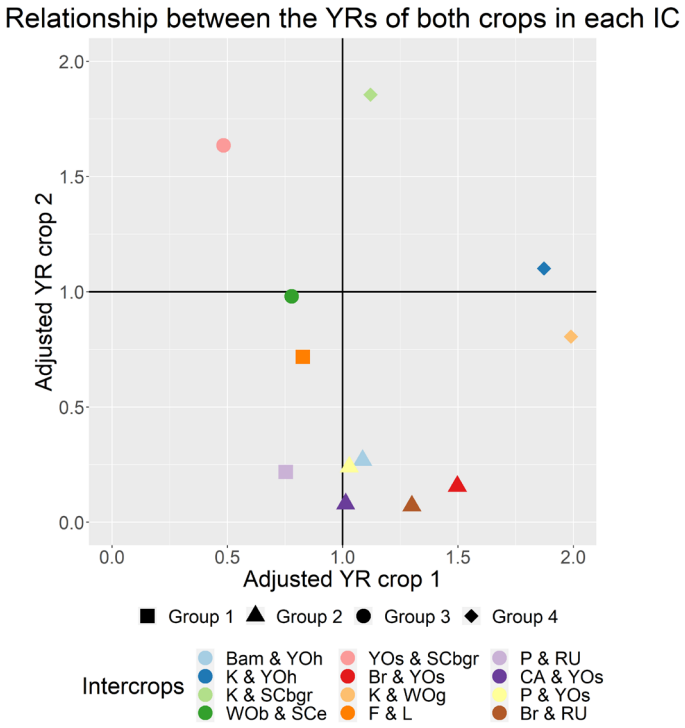


Figure 30 - Adjusted yield ratios of the component crops of the intercrops from the first trial set in agricultural experiment station (2019). The adjusted yield ratio was obtained by dividing the yield ratio of each crop by the density ratio of this crop between intercropping and pure crop, to take into account density differences. An adjusted yield ratio of one means that the crop produced as much biomass in the intercrop as expected based on its yield in pure crop and its density in intercropping. The groups correspond to different dynamics of competition and dominance between component crops and are described in the text. The "Crop 1" is the one with the shortest cycle in each intercrop. IC=Intercrop, YR=Yield ratio, i.e. the ratio between the yield of each crop in an intercrop and in pure crop. Bam=Beetroot Alvro-Mono, Br=Beetroot Rhonda F1, CA=Carrot, F=Fennel, K=Kohlrabi, L=Lamb's lettuce, P=Parsnip, RU=Rutabaga, SCbgr=Scorsonera Noir Géant de Russie, SCe=Scorsonera Enorma, WOb=White onion Barletta, WOg=White onion de Gladstone, YOh=Yellow onion Hylander F1, YOs=Yellow onion Sturon.

In a first group, we find the intercrops between fennel and lamb's lettuce (F & L) and between parsnip and rutabaga (P & RU). In these two intercrops, the two component crops developed more or less at the same pace (Figure 31) and prevented one another from reaching its expected yield (Figure 30) but none of the crops largely outperformed the other. There was a co-dominance between the associated crops, as was the case when intercropping crops with similar growth dynamics in 2020. Interestingly, this group had one of the lowest LER (mean=0.93) whereas the similar intercrops in 2020 had the highest average LER (cf. 5.3.4).

A second group brings together a series of intercrops where a slow-growing crop (RU, YOh and YOs) was shaded by a fast-growing and highly soil-covering crop (Bam, Br, CA and P) (Figure 31). This is the same situation as in the intercrops between legumes and white onion in 2020: because of its very low soil coverage and its very slow development, the onion was shaded by its companion despite being installed first on the plot. In these intercrops, the faster-growing crops developed as expected and they impacted negatively the yield ratio of the slower-growing crops with which they were associated (Figure 30). The intercrops from this group had the lowest LER, as was the case in 2020, except that in 2019, the mean LER was lower than unity (mean=0.92).

A third group comprised the two intercrops combining scorsonera and onions (WOb & SCe, YOs & SCbgr). It had similar dynamics to the one of the intercrops between white onion and broccoli, collard cabbage, fennel or kale in 2020: the higher soil-covering companion crop shaded the onion, which developed less than expected (Figure 30). However, the yield loss of onion was lower in 2019 than in 2020 as the crops it was associated with in 2019, i.e. scorsoneras, had a slower development (Figure 31) than the crops it was associated with in 2020. This slower development enabled the onions to grow better at the beginning of their cycle, hence reducing the yield gap. The LER of these intercrops was significantly higher than unity (mean=1.42).

Finally, a fourth group was present in the 2019, comprised of the intercrops combining kohlrabi with scorsonera or onions (K & SCbgr, K & YOh, K & WOg). In this group, crops with a longer cycle were associated with a crop with a shorter cycle. However, as the crop with a shorter cycle had a low soil coverage and a slow development (Figure 31), it did not shade the ones with a longer cycle and slow development and both crops yielded nearly as much or more than expected (mean LER=1.95, Figure 30).

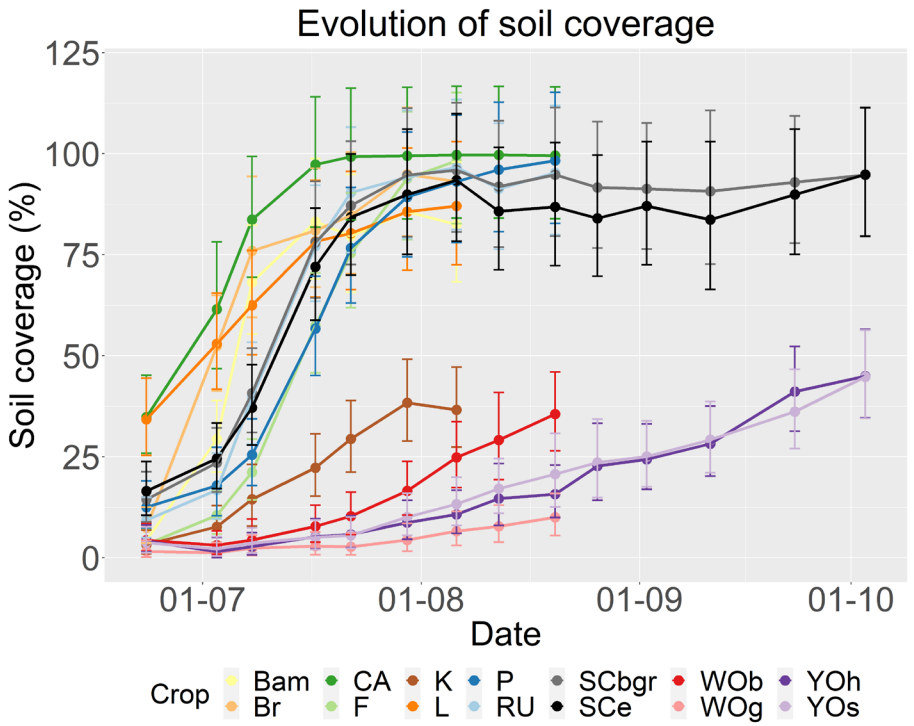


Figure 31 - Average evolution of soil coverage of the pure crops from the first trial set in agricultural experiment station. Bam=Beetroot Alvro-Mono, Br=Beetroot Rhonda F1, CA=Carrot, F=Fennel, K=Kohlrabi, L=Lamb's lettuce, P=Parsnip, RU=Rutabaga, SCbgr=Scorsonera Noir Géant de Russie, SCe=Scorsonera Enorma, WOb=White onion Barletta, WOg=White onion de Gladstone, YOh=Yellow onion Hylander F1, YOs=Yellow onion Sturon.

Overall, the results of the 2019 trial follow the lines of what was observed in 2020: differences in performance of the intercrops in 2019 can also be related to (i) differences in growth dynamics and (ii) differences in soil coverage. This reinforces the idea that the principles identified thanks to these trials could be generalised and used as a guide for the choice of crop associations, at least when solar radiation is the limiting resource. Overall, the rankings of the LERs of the different groups we distinguished were consistent between 2019 and 2020, except for the intercrops combining crops with similar growth dynamics.

5.4. Discussion

To begin with, our results showed the overall benefit of intercropping regarding biomass production. We studied a variety of intercrops – 33 intercrops mixing 19 different crops – among which only one had a LER significantly lower than unity and more than one third had a LER significantly

higher than unity. Moreover, over our 33 intercrops, 16 had a transgressive overyield, i.e. produced more biomass than the most productive corresponding pure crop (Trenbath, 1974). These results show that overall, the intercrops made use of resources at least as well as pure crops and even better sometimes. This is consistent with the concept of complementarity, namely that thanks to physiological and architectural differences, two different crops will not use the same resources or take them from the same place (Andersen et al., 2007; Hooper, 1998; Loreau & Hector, 2001; Trenbath, 1974). This suggests that the overall optimal density could be greater in an intercrop than in the corresponding pure crops (Hauggaard-Nielsen et al., 2006; Natarajan & Willey, 1980a; Willey & Osiru, 1972). Our results are also in line with the numerous studies proving the yield advantage of intercropping (Allen & Obura, 1983; Olowe & Adeyemo, 2009; Reddy & Willey, 1981; Thole, 2012; Zhang & Li, 2003) – although they also show that the yield advantage of intercropping is not 100% guaranteed – and argue in favour of growing two plots of an intercrop instead of one plot of each one of its component crops as pure crop.

We are nonetheless aware that managing intercropping is more complicated than managing pure crops (Malézieux et al., 2009; Morel et al., 2020; Theunissen, 1997a; Trenbath, 1999), e.g. market gardener may injure one crop while harvesting the other, and that if a market gardener spends more time on the intercrop than he would on the corresponding pure crops, the use of intercropping may not be followed by an increase in financial yield (Gebru, 2015; Theunissen, 1997a). Furthermore, as the overall density of the intercrops was higher than the density of the pure crops, we cannot determine whether the greater use of resources in intercropping resulted from a complementarity effect between companion crops or simply from a density effect, a problem already raised by Keating & Carberry (1993). In the latter case, the yield could also be increased by raising the density in pure crop. Keating & Carberry (1993) argue that the increased light interception per square meter reached in intercropping often reflects sub-optimal densities in the corresponding pure crops. It would be interesting, in order to solve this issue, to perform the same trial using an equal density in both pure crops and intercrops. Nevertheless, we think that it was relevant, as a first step, to compare the productivity of intercrops with the productivity of the pure crops as they are set up in the field by a majority of market gardeners. Moreover, similar density in both pure crops and intercrops may

be less straightforward to design than one might think, as different crops do not exploit the space in the same way.

Even though the intercrops used the resources at least as well as the corresponding pure crops, 35% of the crops produced, individually, significantly less biomass than expected based on their yield in pure crop and only 4.5% of the crops produced significantly more biomass than expected based on their yield in pure crop. Intercropping negatively affected the biomass production of nearly all crops, probably because of some competition for resources between component crops. In our trials, all data converge to light being the limiting resource. It was particularly the decrease in the amount of light intercepted by the crops that explained their lower biomass production rather than a decrease in the use efficiency of the intercepted light. This result is not particularly surprising, as an increase (e.g. Reddy & Willey, 1981), a decrease (e.g. Azam-Ali et al., 1990) or a maintenance (e.g. Coll et al., 2012) of RUE in intercropping compared to pure crops have all already been observed. A decrease in the per crop radiation interception is not surprising either, as it has already been observed in other intercrops (e.g. Harris et al., 1987; Liu et al., 2017; Marshall & Willey, 1983).

Interestingly, some patterns were consistent across most intercrops. Although the two companion crops lost yield in most intercrops, there was usually an asymmetry between the yield losses of both crops, i.e. one crop lost more yield than the other, and this asymmetry in yield gain was linked to an asymmetry in the occupation of the aerial space by the companion crops. Our results therefore emphasise the fact that, when controlling the soil variables – which is usually done in market gardening farm using fertilisation and irrigation – the light is the resource for which companion crops compete the most and the growth of the aboveground parts of the crops – both in time and space – shapes the likely superiority of one crop over the other. This is consistent with the observations of market gardeners, who told us that the main issue of intercropping usually was the shading of one crop by its companion (personal communication 2018, 2019, Hervé-Gruyer & Hervé-Gruyer, 2019).

Further analysis of the development of the 21 intercrops in the 2020 trial revealed three main characteristics that influenced the total biomass production of the intercrops and their asymmetry in biomass production: (i) the difference in establishment dates, (ii) the difference in growth dynamics, i.e. the time each crop took to attain its maximum soil coverage, and (iii) the

difference in maximum soil coverage between associated crops. This finding agrees with other studies. For example, in a study comparing different intercrop between rice and legumes, Mandal et al. (1990) observed that rice was less competitive than legumes when planted simultaneously whereas it became more competitive than some legumes when legume sowing was deferred by 30 days. Similarly, Wekesa et al. (2015) showed that soybean had better performance when sown at the same time as maize than when sown two weeks later and attributed their observation to a decrease in the intensity of shading by the companion crop. Huang et al. (2018) also observed a positive effect of an earlier sowing date on the growth of maize intercropped with watermelon. Another example is the high competitivity of sesame in intercropping thanks to its fast growth at the beginning of its cycle (Khan et al., 2001; Olowe & Adeyemo, 2009).

In our trial, the difference in shoot architecture between companion crops seems to have played only a secondary role. The three characteristics listed above allowed to classify the associations into different major groups, while the architectural differences allowed to explain smaller differences in performance between the intercrops of the same group. This result emphasises the interplay between temporal complementarity and shoot spatial complementarities when light is the limiting resource. The performance of the intercrops did not only depend on which crop occupied the aerial stratum the most but also on which crop occupied it first and on which crop developed the fastest. This finding is in agreement with the study of Wahua et al. (1981) about maize + cowpea intercrops, in which they stated that “relative growth rates of the maize cultivars must be considered along with canopy structure”.

As a consequence of this complexity, one cannot assert that the three characteristics we identified have any predictive value regarding the performance of an intercrop. The fact that we were able to account for differences in biomass production in the intercrops from the 2019 trial using these same characteristics argues in favour of this hypothesis. However, we are still far from a powerful predictive model. Indeed, such a model would require a more comprehensive knowledge of the growth dynamics of the vegetable crops under various environmental conditions and, particularly, would need to take into account the interannual variability.

The classification of the intercrops into groups using the three characteristics listed above also brought to light one of the difficulties of developing guidelines for intercrop selection, *viz.* the diversity of objectives between farmers when setting up an intercrop. In fact, according to the relative importance given to the associated crops, a farmer may prefer an intercrop with a high asymmetry – produce as much biomass as possible of the most valuable crop, the other crop being a bonus – or a low asymmetry – grow two plots of an intercrop instead of one plot of each pure crop and try to even out the biomass production of both companion crops –. According to the farmer's goal, the best choice of intercrop will probably not be the same. In our opinion, one should always accompany intercropping guidelines with an indication of their purpose, so that farmers can make informed choices.

We believe that our results are an interesting lead for the development of intercropping guidelines. We think that it would also be worth exploring further (i) the issue of growth dynamics difference and (ii) the importance of spatial complementarity among intercrops with similar growth dynamics. In this matter, it might be relevant to work with modelling of virtual canopies, which could make it possible to show quantitatively the emergence of complementary or competitive relationships during the development of a complex canopy. Moreover, besides the findings described above, our results also prove the relevance of the exploratory approach we developed, i.e. studying a diversity of intercrops with simple measurements rather than exploring in depth a small number of intercrops, as we showed here that the former approach allows to identify a series of general trends among a diversity of intercrops.

*

* *

In this chapter, we used the data from the two on-field trials set in agricultural experiment station (cf. Chapter 3 & Chapter 4) to identify common characteristics or set of characteristics between the intercrops – among the 33 we studied in these trials – that performed in the same way.

This analysis confirmed the importance of the temporal complementarity shown in the two previous chapters and in various other studies. It did however go one step further (i) by emphasising the interplay between temporal complementarity and shoot spatial complementarity in light-limited conditions and (ii) by allowing us to be more precise regarding which

variables to take into account. We were indeed able to identify, based on the results from the second field trial set in AES (cf. Chapter 4), three main variables influencing the outcome of the intercrops and the asymmetry of yield gain between associated crops: the staggering of establishment date, the growth dynamics and the maximum soil coverage. Architecture differences between crops seem to come only after these three variables in the determination of intercropping outcome. To our knowledge, this is the first study designed to compare a high number of different intercrops, cultivated in similar contexts, in order to identifiy similarities and dissimilarities between these intercrops that could explain the differences in outcome and could potentially be used as choice criteria for intercropping design.

The validation against the data of our first on-field trial in AES (cf. Chapter 3) confirmed the relevance of these three variables to explain differences in outcome and asymmetry between intercrops. While this is a promising result, especially as the crops used and the weather varied between the two trials, we cannot assert that these criteria have an actual predictive value. Moreover, their potential predictive value would probably only be valid in light-limited contexts.

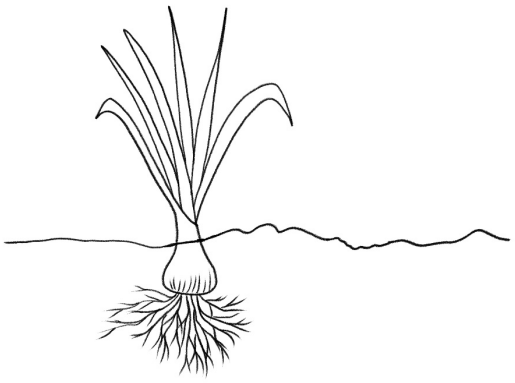
Regarding the practical use of intercropping in market gardening, this study provides some suggestions for market gardeners to follow when experimenting with this cultivation method. Designing participatory on-field trials could be a way to translate the identified criteria into actual intercropping design principles and refine them according to the context and the objective of the market gardener. Meanwhile, the identified variables are some elements that may be useful for market gardeners to pay attention to when choosing and designing intercrops.

This study further confirms the potential benefit of intercropping regarding biomass production, as the majority of the grown intercrops had a LER at least equal to unity. On a scientific point of view, this is no surprise and is in line with many other studies. However, this may be an important result to present to market gardeners, as very few scientific studies about intercropping focused on intercrops between vegetables. This shows objectively that intercropping may help produce more biomass per square meter – although this is not 100% guaranteed either – and that there seems to be a genuine productive interest behind the craze for this practice in market gardening books. This statement should however be further

confirmed by verifying that there was no decrease in harvest index in the intercrops compared to the pure crops.

Finally, our study also underlines the fact that a single LER can hide various situations of competition and asymmetry of yield gain between the crops that are associated. It seems therefore essential to split the LER into the yield ratios of the component crops to be able to assess correctly an intercrop. Moreover, the asymmetry of yield gain between associated crops should be considered when designing intercropping guidelines, as intercrops with a low or high asymmetry of yield gain do not respond to the same objective and may therefore not be used by the same market gardeners.

Chapter 6 |
How to design a participatory trial?



In Chapter 2, we answered our first research question (cf. (A), Chapter 1) by identifying the interactions at play in an intercropping system and we emphasised the complexity of this system.

In Chapter 3, Chapter 4 and Chapter 5 we presented the results of the two on-field trials set up in agricultural experiment station designed to address our second research question (cf. (B), Chapter 1).

This and the next two chapters will tackle the third research question, namely "Is the productivity of an intercrop more dependent on environmental conditions and crop management practices than the productivity of pure crops?".

As explained in Chapter 1, we decided, right from the start, to engage in a participatory process during this thesis. This was done by defining our research questions on the basis of the expectations of market gardeners and following meetings with them, but also by organising participatory trials. Our third research question seemed particularly suitable for the conduct of such trials. Firstly, it arose from contrasted opinions between market gardeners regarding the relevance and productivity of some intercrops, which it would be interesting to objectify by monitoring and comparing intercrop growth in their farms. Secondly, participatory trials offered the possibility of multiplying the number of trial fields, i.e. exploring a higher number of distinct situations, without increasing too much the burden of crop management for researchers, as the day-to-day management of the experimental field would be done by the participating market gardeners.

This first of three chapters dedicated to the participatory part of the thesis focuses on the participatory methodology we developed in this thesis, from the constitution of the network of market gardeners to the implementation and evaluation of the participatory trials. We start by an introduction to participatory research and on-farm trials (section 6.1). We carry on by explaining the course of the developed participatory methology (section 6.2), with an emphasis on the conception of the trials (section 6.2.2). Then, we move on to the results of the methodology, presenting its scientific reliability (section 6.3.1), the evaluation by market gardeners (section 6.3.2), the main challenges we faced (section 6.3.3) and the improvements we made from one trial to another (section 6.3.4). Finally, we provide a general evaluation of the developed methodology (section 6.4.1) and some scope for improvements (section 6.4.2) and we discuss the level of involvement of market gardeners (section 6.4.3).

CHAPTER 6 | HOW TO DESIGN A PARTICIPATORY TRIAL?

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6.1. AN INTRODUCTION TO ON-FARM TRIALS & PARTICIPATORY RESEARCH

On-farm trials and participatory research are usually seen as two forms of applied research, aiming at solving an issue experienced by farmers. On-farm trials usually refer to the test of an innovative technology in real farms, in farmers' conditions and management (Mutsaers, 1997; Tripp, 2008; Tripp et al., 1989) whereas participatory research implies an actual involvement of farmers in the research (Tress et al., 2005). Although they have common traits – e.g. they involve several stages in an iterative process (Chia, 2004; Mackenzie et al., 2012; Méndez et al., 2013; Tripp et al., 1989; Vall et al., 2016), rest on the complementarity of skills and knowledge of farmers and researchers (Franzel & Coe, 2002; Hoffmann et al., 2007) and enable consideration of variability between farmers and evaluation criteria that researchers would not have considered (Haggar et al., 2001; Hoffmann et al., 2007; Schindler et al., 2016) –, on-farm trials and participatory research are two different types of research, with on-farm trials not necessarily implying a participatory approach and vice versa.

Participatory research and on-farm trials are broad terms that encompass a range of different situations, which are largely characterised by the level of involvement of farmers in the research. For example, Riley & Alexander (1997) and Franzel & Coe (2002) distinguish between (i) trials planned and managed by researchers in experimental station but whose design and results are discussed with farmers, (ii) on-farm trials planned and managed by researchers, (iii) on-farm trials planned by researchers but managed by farmers and (iv) on-farm trials planned and managed by farmers. Alternatively, Biggs (1989) proposes a classification based on the nature of the relationship between farmers and researchers, which can be either (i) contractual, i.e. a contract clarifying the roles of each party is signed between farmers and researchers, (ii) consultative, i.e. farmers are consulted by researchers to advise them on their research, (iii) collaborative, i.e. researchers and farmers collaborate but the project remains designed by the researchers or (iv) collegial, i.e. researchers and farmers work as colleagues and develop the research together. Therefore, according to the level of involvement of farmers in the trials, on-farm trials can sometimes be described as "participatory" (e.g. Harris et al., 2001; Riley & Alexander, 1997).

Intercropping in market gardening is a trendy subject in mainstream gardening books but has only been little addressed by scientific research so far. Its adoption rate by professional market gardeners remains low, partly because of a lack of reliable information regarding (i) the design of productive intercrops and (ii) the response of intercrops to their specific abiotic environment. More precisely, we noticed during meetings with market gardeners that their opinions regarding the productivity of a given intercrop were more constrated than regarding the productivity of a pure crop, even though they probably do not grow the pure crops in the same way and with the same performances. The question of the variability of the relative productivity of an intercrop compared to its corresponding pure crops across a range of environmental conditions and crop management practices is worth addressing in order to objectify the differences in opinion between market gardeners. According to us, participatory on-farm trials are a relevant tool in this respect. Indeed, the on-farm trials dimension would allow the study of specific intercrops on a multi-site scale while the participatory dimension would ensure to focus on relevant intercrops with realistic spatial and temporal designs while considering the diversity of farmers' crop management practices. However, until now, participatory research and on-farm trials mainly focused on the appropriation of a technology, e.g. a new crop variety, by farmers (e.g. Burman et al., 2018; Castelli et al., 2018; Etten et al., 2019; Harohau et al., 2016; Le Bellec et al., 2012; Tin et al., 2021; Worku et al., 2020) or on the description of a cropping system (e.g. Agre et al., 2017; Kuivanen et al., 2016; Pelzer et al., 2020; Sinare et al., 2021).

In this chapter, we describe the methodology we developed to tackle a new research question, by mobilising concepts from both participatory research and on-farm trials. Its objectives were to (i) study the outcome and the growth of intercrops and the corresponding pure crops on 11-14 sites, managed by different market gardeners; (ii) compare the outcome of the intercrops, relative to the pure crops, in the different sites and evaluate the impact of environmental and crop management features on this relative outcome; and (iii) develop a methodology of participatory trial. The present chapter describes the methodology we developed during our two seasons of participatory trials, discusses the difficulties we faced and the improvements we made from one season to the other, analyses the satisfaction of participating market gardeners, outlines possible areas for improvement and

highlights the value of such a method. The agronomic results from these participatory trials are reported in Chapter 7 and Chapter 8.

6.2. Applied methodology of participatory research

6.2.1. Network development, meetings and research question definition

The organisation of the participatory part of the thesis is presented in the Figure 32. We describe the different steps of our process, symbolised by letters in Figure 32, hereunder.

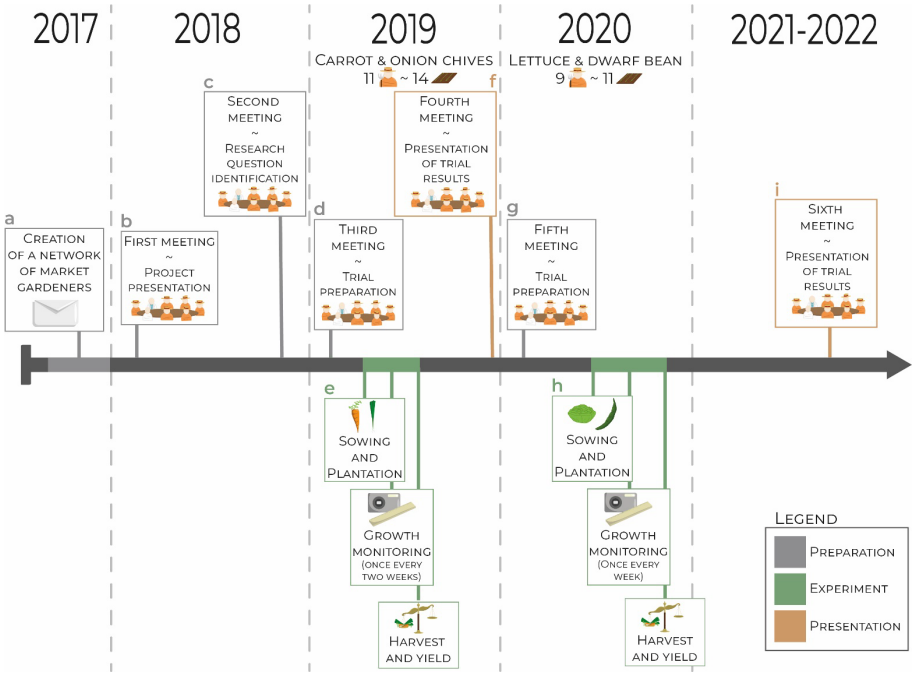


Figure 32 - Organisation of the participatory part of the thesis.

The first step was to create a network (step a) of market gardeners interested and/or experienced in intercropping and willing to take part in our work. We first listed Walloon and Brussels-based market gardeners thanks to the

websites of various associations (C.I.M.[9], GASAP[10], GAL[11], Agricovert[12]). We then set aside the market gardeners who were not (i) French-speaking and (ii) diversified, as we decided to focus on small-scale and diversified market gardening (cf. Chapter 1).

We contacted the remaining market gardeners – 110 in total – and asked them if they were interested in participating in our work, as advisors in the first instance. In addition to market gardeners, we also got in touch with 27 people working in organisations linked to market gardening (CRABE asbl[13], Cynorhodon[14], Biowallonie[15], etc.). Among these 137 people, about twenty answered positively, which was more than what we expected.

Once the network was set up, the next step was to organise group meetings. Two meetings took place in 2018, one in February (step b) and one in November (step c). Their objective was to present more extensively our project to market gardeners and to gather their current knowledge about intercropping and their expectations regarding the thesis.

These meetings allowed us to highlight some of the concerns of market gardeners in relation to intercropping. Based on this information, as well as

[9] Centre Interprofessionnel Maraîcher – Nonprofit organisation whose objective is "to stabilise an extension and service structure for vegetable production in Wallonia" (legumeswallons.be/presentation).

[10] Groupes d'Achat Solidaires de l'Agriculture Paysanne – Groups of consumers buying food directly from local and agroecological farms, without intermediary, in order to support peasant farming (https://gasap.be/).

[11] Groupes d'Action Locale – Groups of partners issued from public and private sectors collaborating to launch a program of local development (LEADER program) whose objective is to promote the economic development of rural areas (http://enrd.ec.europa.eu/enrd-static/leader/leader/leader-tool-kit/the-leader-approach/fr/the-leader-approach_fr.html).

[12] Farming and ecological cooperative of local producers aiming at "selling local products at a fair and sustainable price" (https://www.agricovert.be/?page_id=6).

[13] Nonprofit organisation active in social, cultural and professional reintegration organising, among others, training in market gardening (https://www.crabe.be/content/mission-et-valeurs).

[14] Nonprofit organisation "for socio-professional integration which provides training for adults in organic market gardening, organic agriculture and ecological management of green spaces" (https://www.cynorhodon.be/#).

[15] Organisation whose objective is to accompany all actors, and especially producers, in the organic farming sector by offering personal advice and thematic training (https://www.biowallonie.com/).

the mainstream and scientific literature review we made, we identified the three research questions tackled in this work, presented in Chapter 1.

One of these questions was particularly suitable for a participatory trial approach, namely “Is the productivity of an intercrop more dependent on environmental conditions and crop management practices than the productivity of pure crops?”. Market gardeners seem reluctant to use intercropping partly because they think that its productivity is more variable than that of pure crops. Consequently, even if it was not an issue directly expressed by market gardeners, we thought it would be interesting to verify if the variability of the results of an intercrop is indeed higher from one market gardener to another than the variability of results of the corresponding pure crops. Participatory on-farm trials are a real asset to address this issue, as they bring a multi-local dimension by allowing the trial to be set up in different farms.

6.2.2. TRIAL DESIGN AND MONITORING

6.2.2.1. Distribution of the decision burden

A prerequisite for the development of the participatory trial design was to organise the share of the decision burden between market gardeners and researchers. Our decisions regarding this aspect are gathered in Table 2. As the objective of the trials was to answer a new research question rather than evaluate the adoption of new technology by a group of market gardeners, we had to cope with some some constraints regarding the experimental design. The research team decided some of its aspects alone, in order to ensure proper data collection. This was the case for the minimum number of modalities (one intercrop and the two corresponding pure crops), the distribution of the blocks within the experimental field and the minimum size of the experimental field, taking into account the usual organisation of small-scale market gardening farms in Wallonia and the type of data to be collected. Once these decisions were taken, we organised a meeting with partner market gardeners (steps d, g), during which these decisions were presented, in order to have their opinion, suggestions for improvement and agreement for the general design of the trial.

During these same meetings (steps d, g), the other elements from the trial, i.e. the studied intercrop, the sowing/plantation dates and the plantation distances were chosen by all participating market gardeners, in a consent decision process. We also discussed together how best to manage the

collection of yield data and what material had to be provided for the conduction of the trials. Finally, we explained to market gardeners the main principles of scientific experimental trials and the vocabulary usually used in this context (e.g. modality, repetition) to ensure proper understanding.

At the end of these meetings, all the decisions regarding the design of the trials were taken and summarised into documents. For both trials, we provided each participant with summary documents (Appendix K, Appendix L, Appendix M, Appendix N) and a diagram of the trial design containing the spatial layout of the modalities within the experimental field and the plantation distances for each modality (Appendix O, Appendix P).

Table 2 - Distribution of the decision burden of the participatory trials. R=Decided by researchers, MG=Decided by market gardeners. If both the "R" and "MG" columns are ticked, the decision has been taken commonly between researchers and market gardeners.

ASPECT OF THE TRIAL	**R**	**MG**
Minimum area required for the experiment	X	
Distribution of the blocks and modalities in the experimental field	X	
Number of modalities	X	
Number of repetitions per modality	X	
Studied intercrop		X
Plantation/sowing dates		X
Plantation distances		X
Crop management practices		X
Harvesting method	X	X
Provided material	X	X
Measurements taken	X	
Division of labour between market gardeners and researchers	X	X
Financial compensation	X	X

As we were aware that managing the trial would take them more time than managing their usual crops, market gardeners were offered a financial compensation of €250 for their participation. This compensation was only revealed after the market gardeners had committed in the trial: we wanted to make sure that we were working with people interested in the subject and in our approach more than in the money they would receive. In addition to the financial compensation, market gardeners received all the special equipment required for the trial. This included seeds, seedlings, anti-insect veils, rain gauges and flowmeters. Apart from some sample collection, all

crops cultivated in the trial were at the disposal of the market gardeners and could be sold.

One last decision that we had to make regarding the organisation of the participatory trials was the type of relationship we wanted to create with the partner market gardeners. As our will was to build a relationship based on mutual trust, we decided not to make them sign a contract to formalise their involvement in the trials. We assumed that a good definition and explanation of each party's duties would be sufficient to ensure a smooth running of the trials.

6.2.2.2. Study sites and trial design

The first participatory trial (step e) took place from April 2019 to July 2019 in fourteen sites (Figure 33A), located in thirteen farms, and managed by eleven different market gardeners. In order to be able to relate to the experience of the participating market gardeners and to advise them better, one of the fourteen site was located in the market gardening farm of the UCLouvain and managed by researchers.

The second participatory trial (step h) took place from June 2020 to November 2020 on eleven different sites (Figure 33B), located in ten different farms, managed by nine different market gardeners. Seven out of nine of the partner market gardeners participated in the first participatory trial. As for the 2019 trial, one of the eleven sites was located in the market gardening farm of the UCLouvain and managed by researchers.

In 2019, we focused on an intercrop between carrots (*Daucus carota* subsp. *Sativus*) and onions chives (*Allium cepa* L.) and studied four modalities in each site: (i) a pure crop of carrots, (ii) a pure crop of onions chives, (iii) a replacement intercrop, where the density of carrots and onions chives was equal to half their density in pure crop (Snaydon, 1991), and (iv) an additive intercrop, where the density of carrots and onions chives was equal to their density in pure crop (Snaydon, 1991).

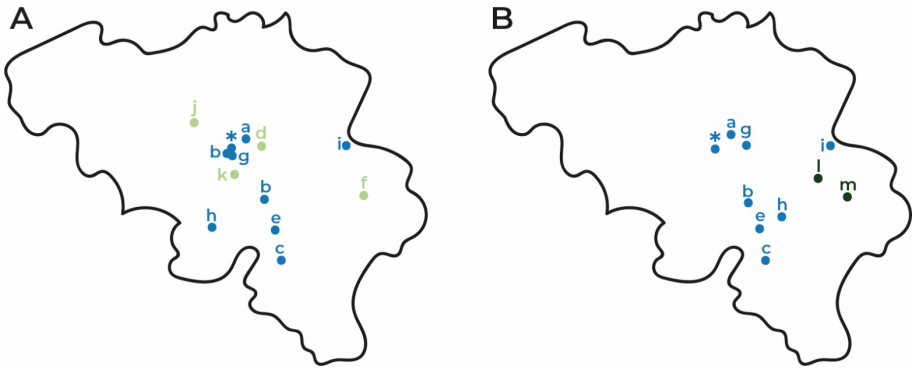


Figure 33 - Location of the fourteen sites of the 2019 (A) and the eleven sites of the 2020 (B) participatory trials. Letters represent the participating market gardeners. The asterisk symbol represents the site of the UCLouvain farm. Only thirteen points are shown on the map for the 2019 trial (A) and ten on the map for the 2020 trial (B), as in both years two out of the fourteen/eleven experimental fields were located at the same place (market gardener c) but managed differently. Market gardeners who participated in both the 2019 and the 2020 trial are shown in blue. Market gardeners who only took part in the 2019 trial are show in light green, market gardeners who only took part in the 2020 trial are shown in dark green.

Although it would have been interesting to redo exactly the same trial in 2020 as in 2019 to have a repetition in time, we decided, based on various problems we faced during the first trial, to focus on another intercrop: the intercrop between lettuces (*Lactuca sativa* var. *longifolia*) and dwarf beans (*Phasoleus vulgaris* L. var. *nanus*). This choice was made by market gardeners, during a meeting dedicated to the preparation of the second participatory trial (step g). We set up three modalities in each of the eleven sites: (i) a pure crop of lettuces, (ii) a pure crop of dwarf beans, (iii) an additive intercrop between lettuces and dwarf beans. For this second trial, we decided to include only one modality of intercropping, in order to alleviate the work for market gardeners as well as for us.

More detailed information regarding the design of the trials is available in Chapter 7.

6.2.2.3. Measurements

All the measurements taken during both participatory trials are gathered into Table 3. The colours in the “2019” and “2020” columns indicate if the measurement was taken for each one of the trial and who was in charge of making it. The most important measurements from Table 3 are explained hereunder.

Firstly, in order to characterise the diversity of sites and market gardeners, we realised a series of pre-trial measurements, focused mainly on soil characterisation, as well as semi-structured interviews with each one of the participating market gardeners. This step was not repeated in 2020 for the market gardeners who participated in the 2019 trial.

Secondly, based on the same objective of characterising diversity, we asked market gardeners to monitor precisely their crop management: soil preparation, fertilisation, pests management, weeding and irrigation. They were also in charge of recording rainfall thanks to a rain gauge we gave them. In 2019, we supplied each market gardener with Excel online sheets to gather this information. In 2020, we changed the system and provided each participant with laminated sheets to be left on the field and to be filled in with the required information. One sheet was for the information about crop management (Appendix Q), one for the recording of irrigation (Appendix R) and one for the recording of rainfall (Appendix S). The rainfall and irrigation sheets were the same for all the trial whereas a new crop management sheet was distributed to each market gardener every week. In 2020, we also attempted to collect data about working time. Intercropping is often criticised by market gardeners for the increase in working time it could cause (communications from market gardeners, 2017) due to the increased complexity it generates (Himanen et al., 2016; Paut et al., 2019; Trenbath, 1999). However very little data is available on this aspect, so we took the opportunity of the participatory trial to objectify this statement. Each market gardener was given plastic pouches with small coloured laminated cards (Figure 34, Appendix T) – each colour corresponding to one repetition of one modality – which we put directly in the field. Each time an operation was made on one plot of the experimental field, they could fill in the corresponding card by ticking the box corresponding to the operation and writing down the start and end time or the total time spent doing this operation on this particular plot. We retrieved the completed cards at each of our visits. As this system required more involvement on the part of market gardeners, the recording of their working time was optional.

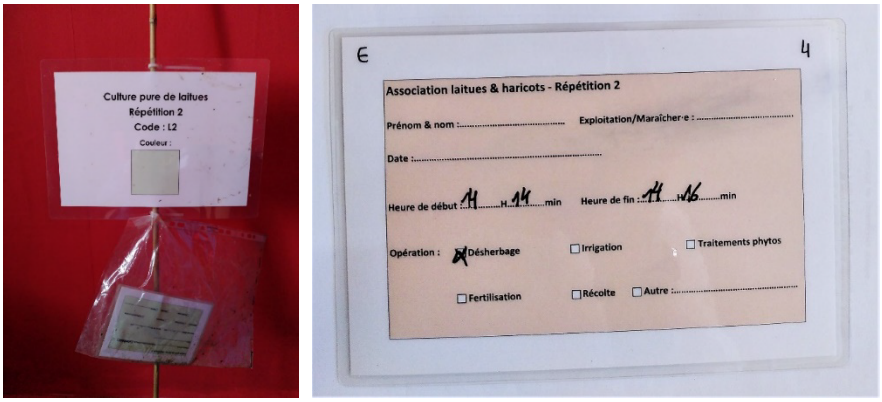


Figure 34 - Example of bamboo stake on which was attached the plastic pouches with the work time cards (left) and example of a filled in laminated card given to the market gardeners to record working time (right).

Thirdly, we approximated meteorological variables other than rainfall thanks to the data collected by the network of meteorological stations of Pameseb, a Belgian nonprofit organisation dedicated to the promotion of agrometeorology that owns a network of thirty weather stations in Wallonia.

Fourthly, we took care of monitoring the growth of plants in each site, visiting them once every fortnight in 2019 and once every week in 2020. Various devices were used in 2019 (Table 3) whereas in 2020, we only used a multi-spectral camera (cf. Chapter 4, 4.3.3), whose advantage was to take quickly and easily a bunch of measurements at the same time for each plot, therefore enabling us to go more frequently in each site.

Finally, regarding harvest, on the one hand, once the crops were ready in more or less half of the sites, we collected samples of the crops in each repetition of each modality in each site. Harvested crops were randomly selected. We picked up the samples from the different sites with as little time difference as possible to ensure a reliable comparison between sites and we calculated “adjusted yields” thanks to them. Market gardeners were in charge of harvesting the remaining crops, to weigh them separately for each repetition of each modality and to enter this data in the Excel file (2019) or on the laminated sheet (2020, Appendix U). This second type of data is the “actual yield”. Having these two types of yield data allowed us to (i) be sure to have reliable and comparable data thanks to the adjusted yield, (ii) have more realistic yield data, taking into account the differences of practices between market gardeners and staggered harvests over time thanks to the actual yield and (iii) test the reliability of the data collected by market gardeners by comparing the two yield types.

Table 3 - Summary of the measurements taken during the 2019 and 2020 participatory trials. An "X" in the "2019" column indicates that the measurement has been made during the 2019 participatory trial. The background colour indicates who was in charge of the measurement: reddish-orange for the research team, purple for the market gardeners, white for a third party. An empty case in the "2019" column means that the measurement was not made during the 2019 trial. The same legend applies to the "2020" column.

MEASUREMENT	TOOL(S)	2019	2020	FREQUENCY	LINKED VARIABLE(S)
Pre-trial & post-trial characterisation of sites					
Farm organisation	Semi-directed interviews	X	X	Once, before the trial	Farm organisation, market gardeners' practices
Soil sampling	Probe, kopeckis	X	X	Once, before the trial	Soil mineral characteristics, soil field capacity and wilting point
Soil compaction	Penetrometer	X		Once, before the trial	Soil compaction
Soil biological activity	Respirometry	X		Once, after the trial	Soil biological activity
Crop management monitoring					
Crop management	Excel files	X		For every action	Fertilisation, irrigation, weeding, pest management
	Laminated sheets		X		
Working time	Laminated sheets		X	For every action	Mean work time per modality and action
Irrigation	Flowmeter		X	For each irrigation	Water quantity

MEASUREMENT	TOOL(S)	2019	2020	FREQUENCY	LINKED VARIABLE(S)
Environmental conditions monitoring					
Rainfall	Rain gauge	X	X	/	Rainfall
Meteorological data	Pameseb stations	X	X	/	Incident light, rainfall, temperature
Crop growth and yield monitoring					
Canopy pictures	RGB camera	X		Every fortnight	Soil coverage
	Multispectral camera		X	Every week	Soil coverage
Profile pictures	RGB camera	X		Every fortnight	Crop height
Crop height	Ruler	X		Every fortnight	Crop height
	Ruler		X	Every week	Crop height
Number of leaves of crops	Manual couting		X	Every week	Number of leaves
Lettuce diameter	Ruler		X	Every week	Diameter
Harvested weight	Weighing scale	X	X	Once, at harvest	Adjusted yield, mean weight per plant
	Weighing scale	X	X	For every harvest	Actual yield
Pictures of vegetables at harvest	RGB camera	X	X	Once, at harvest	Vegetable size

6.2.3. POST-TRIAL PROCESS

6.2.3.1. Data processing

Information relative to data processing are available in Chapter 7.

6.2.3.2. Presentation of the results to market gardeners

At the end of each trial, we organised a meeting dedicated to the presentation of the results to the participating market gardeners (steps f, i). As they played a crucial role in obtaining them, it felt essential for us to share the results directly with them. We provided them with two types of results: anonymous results of all market gardeners, in order to compare the different sites on which the trials were installed, and their personal individual results. Both types of results were gathered in a specific PDF file for each participant.

6.3. RESULTS

6.3.1. AGRONOMIC RESULTS & SCIENTIFIC RELIABILITY

The agronomic results derived from the participatory trials are the topic of Chapter 7 and Chapter 8. Overall, the trials were a success on a scientific point of view. We developed an experimental design that, despite being simple and easily understandable, did not lack scientific rigour and allowed us to collect reliable and interesting information about the growth of the studied intercrops, thanks to a good division of labour between market gardeners and researchers.

All measurements related to plant growth were monitored by the researcher with a major impact in terms of workload. This choice had four major advantages: (i) it allowed to use reliable devices instead of the cheaper equivalents we should have found if we had wanted each market gardener to take the measures on its own, (ii) it saved the need to explain to each market gardener how to properly take the different measures and from requiring more of their time, (iii) it ensured that the measures were taken by the same person and in the same way in all sites, therefore increasing their reliability, and (iv) it strengthened the relationship with the market gardeners as we did not pilot the trial from afar but were physically present in each site at least once a fortnight. On the other hand, we opted to trust market gardeners for data they were used to and that did not require a lot of material, such as crop management and yield. Regarding the yield, as explained before, we collected samples of plants to have, besides the yield

data from market gardeners, an approximation of the yield made by ourselves. This “adjusted yield” was a kind of safety net. Our experience confirmed that it was indeed clever to add this string to our bow, as not all market gardeners sent their yield data to us. A posteriori, we could verify that the adjusted yield based on the samples of crops we took and the actual yield based on the data collected by market gardeners are consistent with one another (Figure 35). In addition, the strong linear relationship between the adjusted yield and the actual yield does not depend on the market gardeners and is present in both years (Figure 35). This means that the yield data collected by market gardeners or estimated by us are both reliable.

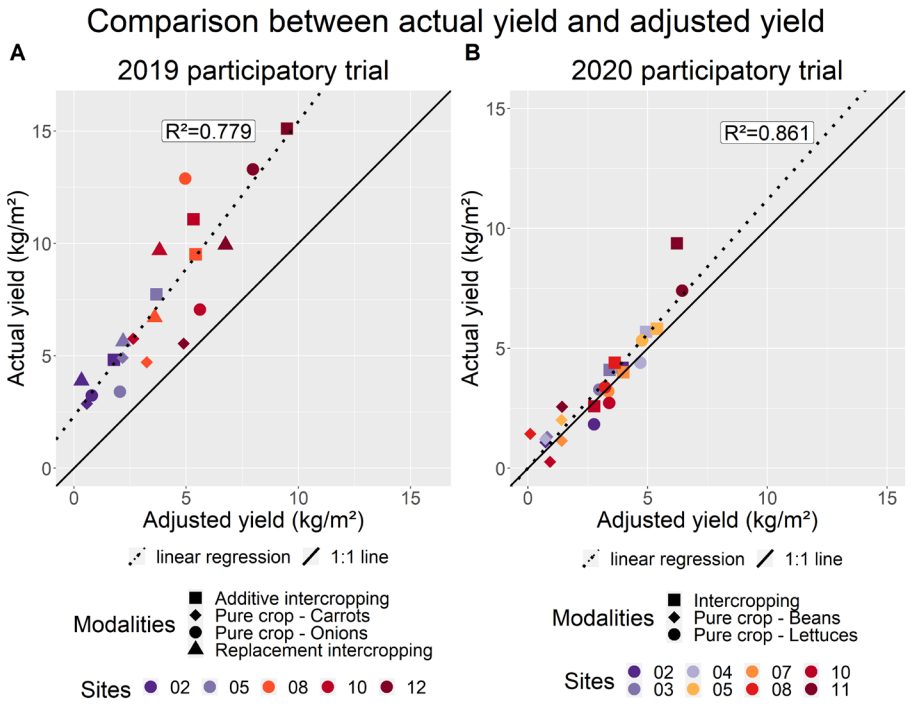


Figure 35 - Comparison between the adjusted yield, calculated on the basis of the plant samples we took from each plot, and the actual yield, based on the yield data collected by market gardeners, for the 2019 (A) and the 2020 (B) participatory trials. The sites presented in the graphs are the ones that were kept for statistical analysis after quality check and for which market gardeners sent us yield data. Site 13 (2019 trial) is a special case as the market gardener specifically told us that he only harvested half of the crops in each plot and is therefore not shown in the graph. Regression lines were calculated using a linear model with the adjusted yield as fixed factor. The UCLouvain site was №12 in 2019 (A) and №11 in 2020 (B).

The trials were characterised by a very low abandonment rate: only one out of eleven market gardeners dropped the trial in 2019 and two out of nine in 2020. Besides, only four sites out of 25 were deleted because of a lack of maintenance by market gardeners, which proves that market gardeners were reliable regarding this aspect. Moreover, even when deleting the sites on which we had problems – too low germination rate, lack of maintenance, abandonment, non-respect of the instructions – the sample size remained sufficient to carry out a multi-site statistical analysis. The repetition of the trials at different locations compensated for the potential lack of accuracy.

6.3.2. EVALUATION OF THE TRIALS BY MARKET GARDENERS

After each trial, we sent to all the participants an evaluation form comprising a mix of open questions and statements that market gardeners had to rate between 1 and 7 according to their satisfaction or their agreement with the statement. The grade 1 always represented a complete dissatisfaction or disagreement whereas the grade 7 always represented a complete satisfaction or agreement. Different themes were addressed in the form. The mean grades given to each theme can be found in Table 4 for both trials. Eight out of eleven market gardeners completed the survey for the 2019 trial whereas seven out of nine market gardeners filled it in for the 2020 trial. Five out of the seven respondents for the 2020 trial also participated and completed the survey in 2019.

Overall, the developed methodology was successful in satisfying market gardeners. For each of the theme we tackled in the survey, market gardeners were moderately to highly satisfied (grades always higher than 4/7, mostly higher than 5/7). Most of them pointed out a good organisation and a good communication as well as a good understanding of the complexity and the requirements of scientific research for both trials. For the 2020 trial, positive comments also included the clarity of the informative documents and the user-friendliness of the laminated sheets.

Table 4 - Results of the evaluation of the 2019 and 2020 participatory trials by market gardeners. Grades are out of seven, 1=very unsatisfied, 7=very satisfied. MG=Market gardeners.

	MEAN GRADE (2019 TRIAL)			**MEAN GRADE (2020 TRIAL)**		
	MG 2019 trial only	MG 2019 & 2020 trial	Global mean	MG 2020 trial only	MG 2019 & 2020 trial	Global mean
Global impression	4,5	4,5	4,5	5,5	4,8	5,00
Trial preparation	5,0	5,8	5,6	5,5	6,6	6,3
Frequency and organisation of passages	5,0	6,3	6,0	6,5	6,4	6,4
Studied intercrop	4,0	3,7	3,8	4,0	5,6	5,1
Plantation distances	4,0	4,7	4,5	5,0	5,2	5,1
Season during which the trial took place	5,0	5,2	5,1	5,0	6,0	5,7
Imposed constraints	4,5	4,3	4,4	6,0	5,0	5,3
Communication frequency	6,0	5,7	5,8	6,5	5,2	5,6
Clarity of explanations	5,5	6,2	6,0	7,0	7,0	7,0
Financial compensation	5,0	6,0	5,7	5,5	6,6	6,3
Consistency between the conduct of the trial and what had been announced	5,5	5,5	5,5	6,0	5,8	5,9
Respect of expectations	5,0	5,8	5,6	6,0	6,2	6,1
Supplied material	/	/	/	6,0	6,4	6,3

The dissatisfaction of the market gardeners was mainly in the design of the trial. For the 2019 trial, the intercrop appeared to be a bad choice as it was difficult to harvest carrots without hurting the onions chives. Moreover, as the onions were harvested little by little, it was hard for market gardeners to keep track of the yield and keep writing it down during the whole trial. Market gardeners also found it difficult to sell all the onions from the trial, as there were many of them. Due to the lack of germination of carrots in some sites, we had to modify the thinning distances, which led to dissatisfaction for some of the market gardeners regarding the planting distances. As far as the time of the year was concerned, the 2019 trial took place in the peak season, when market gardeners already had a lot to deal with. It was consequently difficult for them to maintain their rigour in the management of the trial and to keep coping with what was asked from them. According to some of the participants, it would have been better to make a trial at the beginning of the spring or in autumn. The last main drawback of the 2019 trial was linked to the notetaking for the management practices and harvest data. Almost all market gardeners raised a lack of guidance in the note-taking process and a non-intuitive way of encoding data. Regarding the 2020 trial, the main drawbacks underlined by market gardeners were the following: lack of time during the peak season, difficulty to maintain the necessary rigour during the whole trial, difficulty of harvesting the beans and, for some market gardeners, dissatisfaction regarding the planting distances and the time lag between the plantation of the lettuces and the sowing of the dwarf beans.

Some solutions, proposed by market gardeners, to facilitate and encourage the commitment in the trial were, for example, (i) to reduce the quantity of measurements/information requested from them, (ii) to provide them with a waterproof weighing scale to make it easier to measure yield, (iii) to give them more feedback during the trial, (iv) to give them the opportunity to voice-record the information about crop management instead of writing it down and (v) to allow them to collect information for the whole experimental field, without separating between repetitions and modalities. These propositions give some guidelines of action to improve the methodology.

The personal exchanges we had with market gardeners indicate that the interest derived from their participation in the trials was twofold. On the one hand, being involved allowed them to test in their field at least one intercrop, with a lower risk of financial losses than if they had done it by themselves, thanks to the financial compensation we offered them. Even if the purpose

of the trials was not to evaluate the adoption of a given intercrop by a range of market gardeners, each market gardener could assess the match of the tested intercrop(s) in its own context. The first trial, in particular, allowed them to observe and compare the growth of crops in an intercrop at two different densities, i.e. replacement *vs* additive design, which could help them to choose relevant densities for further tests about intercropping, based on their productive aim and the technical constraints associated with lower or higher densities. Market gardeners who took part in both trials also had the possibility to compare intercrops with different crops. They could do these comparisons during the trial, observing the growth of the crops, but also based on the quantitative data they received at the end of the trials. In this way, they were able to compare their impression with objective data. On the other hand, the methodology we chose – on the edge between participatory on-farm trials and classic field trials – and the exchange we had with market gardeners regarding the objective and the design of the trials and the analysis of the results allowed them to capture the complexity and the needs of a rigorous scientific approach. In our opinion, this awareness could help them to design better further experiments about intercropping. For example, the fact that we imposed market gardeners to have both the intercrop and the corresponding pure crops in their field, offered them a reliable benchmark to assess the impact of intercropping, which is something they might not do on their own.

Besides these two direct benefits, market gardeners could also benefit, although more indirectly, from the response to the research question tackled by the participatory trials. More precisely, the results (cf. Chapter 7) show that (i) they should not compare their intercropping results on an absolute scale with those of other market gardeners but they can compare on a relative scale, i.e. productivity of an intercrop compared to the productivity of the pure crops in the same context, (ii) the intercrops we tested had a similar relative productivity on a large part of the environmental range represented by the sites from the participatory trial and (iii) a strong environmental limitation may be more detrimental to the intercrop than to the corresponding pure crops.

6.3.3. CHALLENGES & BENEFITS OF THE PARTICIPATORY PROCESS

During these two trials, we faced various difficulties that are listed in Table 5.

Table 5 - Main difficulties encountered during the trials. The R and MG columns indicate the people responsible for handling the problems. R=Researchers, MG=Market gardeners.

DIFFICULTY	**R**	**MG**
Poor germination	X	X
Pests attacks		X
Delay in dealing with the problems of market gardeners	X	
Required availability, reactivity and flexibility of researchers	X	
Lack of time of market gardeners		X
Lack of compliance with instructions of market gardeners	X	
Lack of understanding of instructions of market gardeners	X	X
Lack of group communication	X	X
Missing data	X	
Abandonment by some market gardeners	X	
Logistics of the experimental design	X	

Firstly, we had to deal with the problems inherent in field trials, such as poor germination or pests attacks, with the additional difficulty that, as we only went to each site once in a fortnight (2019) or once in a week (2020), we sometimes saw the problem long after it began. We had to rely completely on the market gardeners to warn us in time.

Secondly, when problems arose, we sometimes had to make decisions that would affect the whole trial and all market gardeners without always having the time to consult them all. Some of the decisions we have taken may be questionable but we had to be as responsive as possible as market gardeners were counting on us.

A third type of difficulty we had to cope with was the lack of rigour and compliance with instructions of some market gardeners, which led to a higher heterogeneity, e.g. staggering of carrot sowing between sites or difference in staggering between carrots sowing and onions planting. On the one hand, this allowed us to cover further the variability that can exist between market gardeners. On the other hand, however, it forced us to delete some of the sites from the data for the statistical analysis because they did not respect well enough the design and the constraints we imposed (cf. Chapter 7). Market gardeners are not to blame for this lack of compliance or rigour, as it was obviously not made on purpose, but it reveals either a lack

of time from them to handle the trial well or a lack of understanding of the instructions. Both elements seem to have played a role here, as highlighted by the satisfaction surveys participants had to fill in at the end of each trial (cf. 6.3.2). For both the 2019 and the 2020 trial, some market gardeners expressed a lack of time to manage the trial correctly. As far as the misunderstanding is concerned, none of the market gardeners said that there was a lack of clarity in our explanations. However, some of their statements proved that they did not always understand the purposes of the trial.

The fourth difficulty we encountered was the lack of notetaking regarding cultivation operations and harvesting data. This problem mainly appeared during the first participatory trial, as the tools we provided market gardeners with were not adapted. The use of laminated sheets in the second trial largely counteracted this issue.

A fifth problem we faced was the one of the communication. At the beginning of the trial, we intended to create a group dynamic and tried to encourage communication between the participants regarding the trial. We wanted to solve the different problems linked to the trial by talking all together via a channel for group discussion, e.g. WhatsApp conversation, Slack, Facebook group. This happened to be a failure, as none of the market gardeners took part in the group discussion. Communication during the trial was reduced to individual communication between us and each market gardener by exchange of SMS.

Finally, a last point of attention was the workload that the organisation and monitoring of such trials needed. Engaging in a participatory research required a lot of time upstream, with the building of a network and the development of a trial design adapted to (i) the question we wanted to address as researchers, (ii) the expectations of the market gardeners, (iii) the space available in each site and (iv) the time each market gardener was willing to put in the trial. Moreover, in order to consolidate the relationship with market gardeners, it was necessary for us to be as available as possible to answer their questions. The logistic aspect of a participatory trial is also more complicated and takes more time to organise than for a trial in one experimental station. We had to order seeds and seedlings for all the sites, as well as other equipment, and tour the sites before the beginning of each trial to bring to each market gardener all the necessary material. Nevertheless, even if the work to be done before the start of the trials was

not negligible, the most important workload took place during the trials. In order to ensure a good monitoring of crops growth and given that this monitoring was made by a single researcher, we had to choose measurement techniques that would be as informative as possible while being neither destructive – so that market gardeners could harvest the crops of the experimental field – nor too time-consuming, in order to allow two to three sites to be visited per day.

Despite these difficulties, we think that the developed methodology may be beneficial in many contexts. To begin with, interacting with farmers from the very beginning of the research ensures to focus on questions and issues that are relevant for farmers and involving them in the design of the trials guarantees to tackle these issues/questions in an appropriate way, based on real farming conditions. In the same perspective, involving farmers in the management of on-farm trials is a good way to be able to take into account a diversity of crop management practices, which would be difficult to achieve in agricultural experiment stations. Furthermore, the combination of on-farm trials and participatory approaches to tackle a new research question allows collecting not only information required to answer to the question per se but also the feelings, perceptions and opinions of the participating farmers. In our case, for example, it allowed us to gather information about barriers to the use of intercropping by market gardeners, e.g. difficulties linked to the harvest, technical constraints or difficulties of commercialisation. Finally, the actual involvement of farmers in the management of on-farm trials is an asset when difficulties linked to field trials arise, as researchers can rely on farmers' experience to solve problems and adapt to real-life conditions.

6.3.4. Improvements between the 2019 and the 2020 trials

As the satisfaction of market gardeners was good after the first participatory trial – five out of eight were ready to take part in another trial, the three others were hesitating but none directly said no – we decided to keep the general methodology and organisation. However, the evaluation survey of the 2019 trial highlighted two major problems. Firstly, the chosen intercrop proved to be inadequate for market gardeners. We thus decided to focus on another intercrop, chosen by participants. Due to the change of intercrop, the time of the year during which the trial took place also changed and went from late spring/beginning of summer to beginning of summer/late autumn. Secondly, the notetaking system in 2019 was not user-friendly enough, which

is why we provided market gardeners with laminated sheets in 2020 instead of the Excel spreadsheets used in 2019. This proved to be a success as the information we collected regarding crop management and harvests in 2020 was more complete than in 2019. These two improvements, combined with the change of the studied intercrop, were the major modifications that we made between the two years.

If we look at the grades of the satisfaction surveys (Table 4), we can see that all the market gardeners who took part in the 2019 trial gave higher grades to the 2020 trial than to the 2019 trial. The mean of all grades for these participants went from 5.3/7 in 2019 to 5.9/7 in 2020. Although the difference is small, its suggests that the few changes we made between the two trials increased the average satisfaction of the participants. This improvement of satisfaction was also true for the two market gardeners who only took part in the 2020 trial, as their grades were better, on average, than the mean grades of the 2019 trial. However, the mean grade of these two participants was lower (5.7/7) than the mean grade of the seven others. It may be that taking part in the two trials and seeing the improvement between the first trial and the second one had further increased the satisfaction of these seven market gardeners. The only point on which they seemed less satisfied in 2019 than in 2020 was the frequency of the communication. It may be because, due to the more frequent problems in the 2019 trial than during the 2020 one, we had to contact market gardeners more than during the 2020 trial. This is something we will need to remember in the future.

Despite this slightly negative point, the comparison of the grades of the two trials suggests that even one year of participatory trial can teach us a lot and help us creating a methodology and tools that are more suitable to both farmers and researchers.

6.4. Discussion

6.4.1. General evaluation of the methodology

Organising participatory trials to study the question of the yield variability of intercropping was a two-fold challenge: one regarding the research question itself and the results that would emerge and another regarding the development of a participatory methodology that was not in a logic of appropriation – as it is the case for participatory varietal choice trials (e.g.

Burman et al., 2018; Etten et al., 2019; Tin et al., 2021; Worku et al., 2020) – but rather in a logic of co-experimentation with farmers.

Participatory on-farm trials are far from being a simple process and can be tricky. For a participatory on-farm trial to be successful, it must be well thought beforehand in order to meet some requirements:

- The experimental set-up should be adapted to the research question(s) and to statistical analysis, as for any scientific experimental trial (Riley & Fielding, 2001);
- The experimental set-up should be easy to implement by farmers and adapted to the different locations in which the trial takes place (e.g. it should not require too much space in comparison to the total cultivated area of the farms it is set up on);
- The experimental set-up should bring the homogeneity needed to collect, process and analyse easily the data while at the same time respecting the uniqueness of each farm and farmer;
- Both the research question that is addressed by the trial and the experimental set-up should be understandable by farmers so they can quickly and easily make them their own, respect them and feel engaged in the trial (Mackenzie et al., 2012). A common language must be developed (Chia, 2004; Hoffmann et al., 2007);
- The organisation of the participatory trial should be neither too constraining nor too time-consuming for farmers. However, the engagement of farmers should not be too superficial either (Hoffmann et al., 2007), they must feel involved;
- The experimental set-up and the whole organisation of the participatory trial should allow the research team to collect trustworthy data. It is important for researchers but also for farmers, whose time investment in the research must be compensated by useful results (Hoffmann et al., 2007; Mackenzie et al., 2012).

Moreover, a participatory process also require good interpersonal skills from the part of the researchers – to manage the potential conflicts (Bentley, 1994; Haggar et al., 2001; Mackenzie et al., 2012), to make the information understandable to farmers (Bentley, 1994; Haggar et al., 2001; Mackenzie et al., 2012) and to build a strong trust relationship with farmers (Mackenzie et al., 2012) – and a high level of personal investment, e.g. always be available to answer farmers' questions (Mackenzie et al., 2012).

Overall, we believe that the developed methodology met the majority of the requirements listed above and that the trials were successful.

Firstly, the design we developed for the trial allowed us to collect trustworthy and analysable data despite the heterogeneity between the farms of the participating market gardeners. The data gathered made it possible to answer to the addressed research question (cf. Chapter 7).

Secondly, the design of the trials was well adapted to the conditions of and the implementation by market gardeners. In fact, we had very few comments on the design itself and it was well set up in nearly all sites, therefore showing its understandability and, probably, the usefulness of the summary documents (Appendix K, Appendix L, Appendix M, Appendix N) and the diagrams (Appendix O, Appendix P) we sent to the participants.

Thirdly, we faced a very low abandonment rate although it is stated as a frequent issue in participatory research (Bentley, 1994; Chia, 2004; Hoffmann et al., 2007; Mackenzie et al., 2012). We believe that it is mostly the fact that we defined clearly the role of every actor and the organisation of the trial, as advised by various athours (Chia, 2004; Hoffmann et al., 2007; Mackenzie et al., 2012; Vall et al., 2016), which allowed the smooth running of the trial and the low drop-out rate. It was also probably linked to the fact that we succeeded in reducing the social distance that can exist between researchers and farmers (Mackenzie et al., 2012) – notably thanks to the fact that we were regularly physically present on the sites – and in developing a common language with the participants (Chia, 2004; Hoffmann et al., 2007).

The low abandonment rate and the will of the majority of the market gardeners to take part in a second experimental trial after the conduct of the first one demonstrate that market gardeners were interested and felt engaged in the trial and were satisfied by the methodology. In this regard, we think that the collaborative relationship (Biggs, 1989) we implemented was a good choice. In fact, constraining market gardeners via the signature of a contract, as proposed by Chia (2004) and Vall et al. (2016), could have been felt by the participants as too much pressure and, therefore, could have made them lose all pleasure in the trial. Moreover, the double appropriation of the trials by market gardeners – making the results of the trial their own and understanding the requirements of scientific approach – further confirms the relevance of the developed methodology to please both the involved farmers and the researchers.

However, the proposed methodology was not free from constraints. On the one hand, market gardeners had to manage the experimental field while coping with our instructions, e.g. taking note of the harvested weight.

Therefore, the experimental field took them more time to handle than their other fields. In addition, we also encouraged them to take part in the pre- and post-trial meetings we organised – either physically or remotely – so that they could actively take part in the conception of the design and the evaluation of the trials. These participations were not a big burden compared to the management of the trial and were not compulsory, but still represented an additional cost for the market gardeners. On the other hand, besides the difficulties described in section 6.3.3, we had to cope with a substantial workload, managing both the fulfilment of the measurements and the maintenance of a good relationship with market gardeners, and to deal, on a statistical point of view, with missing data and with sites that did not fully comply with our demands. Overall, however, we think that the benefits that both market gardeners and researchers drew from the trials outweigh the costs.

6.4.2. Scope for improvement

In our opinion, there are two main areas for improvement regarding the interactions with market gardeners during the trial.

The first one is related to communication. On the one hand, some of the statements of market gardeners suggest that there was sometimes a misunderstanding regarding the vocabulary specific to scientific research, e.g. repetition, modality, or the purpose of some of the instructions. For example, two market gardeners proposed the idea of having to measure their work time only for the whole experimental field, without separating between repetitions and modalities. This shows that they did not understand that the aim of measuring the work time was to identify differences between the intercrop and the corresponding pure crops. Therefore, we should have spent more time (i) explaining the fundamentals of scientific experiment, especially as they were interested in the subject, (ii) explaining the rationale for each of the instructions we gave them and (iii) reminding them of the instructions during the trial. On the other hand, the challenges related to germination and pests problems and encoding tools (cf. 6.3.3) might have been handled better by addressing these questions with market gardeners beforehand, during a pre-trial meeting. However, this meant engaging further the market gardeners into the trial and demanding more of their time, which might not have been possible.

The second area for improvement is precisely to reduce the time it takes market gardeners to participate in the trial. This could be made by (i) making a trade-off and ask for less information from market gardeners, (ii) providing them with better encoding forms and involving them in the design of these forms and (iii) supplying them with facilitating tools for the listing of the actions carried out on the experimental field, e.g. flowmeter for the irrigation, chronometer for the working time, waterproof weighing scale for the harvested weight, as suggested by some of them.

Besides these two aspects, a third area of improvement could be to take advantage of the dual status of the trial, which aimed at answering a research question while being, in some ways, a test of a new cropping method for the market gardeners. Therefore, in addition to collect data allowing to answer the research question and to evaluate the satisfaction of market gardeners regarding the interaction with them, we should have put more emphasis on the assessment of the intercrops – as a potentially adoptable cultivation method – by market gardeners, e.g. did they observe differences between the intercrop and the pure crops? Would they re-use this intercrop? If yes/no, why? What would they change? This would have further added to the interest of the participatory aspect of our research by killing two birds with one stone.

6.4.3. Balance in the involvement of market gardeners

We engaged in a process that differed from usual participatory and on-farm research in that it aimed at answering to a research question and at producing knowledge rather than at providing farmers with a solution to a current issue. In other words, we focused on a subject that was closer to primary research than to applied research but studied it in a participatory way. This inevitably led to some tension between the requirements of participatory research and the ones to ensure a reliable statistical analysis of the results and the level of involvement of market gardeners had to be balanced accordingly.

With hindsight, we think that we realised the right level of involvement of market gardeners, maximising the benefits for market gardeners while ensuring proper collection of data and reliable statistical analysis. In fact, on the one hand, reducing the constraints imposed by the researcher and letting market gardeners do whatever they wanted would probably have led to further heterogeneity between sites and to unexploitable results on a statistical point of view. On the other hand, lowering the involvement of

market gardeners would have decreased the direct benefits they drew out of the trials and would have prevented us from considering the diversity of crop management practices among them. Moreover, the market gardeners, who were looking for a certain scientific structure, appreciated this level of involvement. Our trials prove that participatory research and on-farm trials, despite being largely dedicated to the development of practical solutions, are also interesting – both for scientists and farmers – for primary research. Nevertheless, the issue of the lack of time of market gardeners remains and prevents them from engaging more in such approaches, despite their curiosity and interest.

6.5. CONCLUSION

Our attempt of designing and running two participatory trials regarding the variability of yield in intercropping convinced us of the value of such an approach. It was not an easy road: the workload needed to set up and manage such trials was high, they had to be very well thought out beforehand and many problems arose during the process. However, we think that we were able to develop a methodology and an experimental design that allowed us to take advantage of the multi-local scale offered by the participatory approach without sacrificing scientific rigour. Despite the challenge that was set, we succeeded in bringing together the best of both the participatory research and the classic scientific process. With these participatory trials, we proved that it is possible to design a participatory approach that is understandable and easily embraced by market gardeners, rigorous, providing reliable and informative data and able to give an initial answer to a new research question.

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Throughout this chapter, we presented the course of the participatory part of the thesis, with its main advantages and drawbacks. We showed that participatory research is not a quiet river: it presents the researcher with a series of challenges for which he/she is not necessarily prepared and used to. However, our experience highlights the possibility of designing participatory on-farm trials that explore a new research question and provide trustworthy data while being satisfactory for the participating farmers. This chapter may serve as a guide for any researcher willing to take part in a

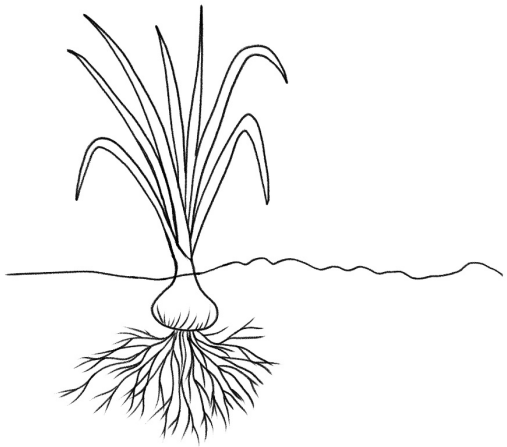
similar process by drawing his/her attention to the benefits he/she can expect, the potential problems and the points to watch out for.

In addition, this chapter underlines the benefits of the participatory on-farm trials we conducted for the participating market gardeners, one of which being the learning, by the market gardeners, of the rigour necessary to develop a scientific trial allowing a reliable analysis of the results. In our opinion, this new knowledge could be useful for them to objectively test and assess the advantages of new cultivation methods, e.g. intercropping, in their farm.

The next two chapters will focus on the analysis of the data collected during the participatory trials.

Chapter 7 |

Consistency of intercropping relative outcome in a range of environmental conditions and crop management practices



We presented, in Chapter 6, the methodology we used in our participatory approach, and particularly in the conception and conduct of our participatory on-farm trials, and we highlighted its main difficulties and strengths.

This chapter is the second one focused on the participatory part of our thesis. It presents part of the results of the participatory trials and addresses directly our third research question by analysing the consistency of intercropping relative outcome across the sites on which the participatory on-farm trials were implemented.

We explain the material and methods used in these trials (section 7.2), we present the results – focused on the biomass yield, the financial yield and the land equivalent ratios – of the 2019 (section 7.3.1) and the 2020 (section 7.3.2) participatory on-farm trials, compare the results of the two trials (section 7.3.3) and discuss our findings (section 7.4).

CHAPTER 7 | CONSISTENCY OF INTERCROPPING RELATIVE OUTCOME IN A RANGE OF ENVIRONMENTAL CONDITIONS AND CROP MANAGEMENT PRACTICES

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7.1. INTRODUCTION

Intercropping consists in growing two crops, or more, on the same plot, at the same time (Andrews & Kassam, 1976; Mead, 1979; Vandermeer, 1992). It can have numerous advantages for the farmer, the consumer and the environment: increased yield (Bulson et al., 1997; Monti et al., 2016; Rao & Willey, 1980; Reddy & Willey, 1981; Yu et al., 2015; Zhang & Li, 2003), reduced impact of crop pests and diseases (Hauggaard-Nielsen & Jensen, 2005; Lin, 2011; Malézieux et al., 2009; Okigbo & Greenland, 1976; Tofinga et al., 1993; Trenbath, 1974), soil conservation (Cong et al., 2015; Leihner et al., 1996; Zougmore et al., 2000), improvement of the quality of harvested products (Bedoussac et al., 2015; Lin et al., 2001; Monti et al., 2016; Muschler, 2001), better use of resources (Awal et al., 2006; Bedoussac et al., 2015; Jensen et al., 2020; Keating & Carberry, 1993; Morris & Garrity, 1993; Vandermeer et al., 1998; Willey, 1990), etc.

Although scientific studies mainly focus on cereals and legumes intercrops for open field cultivation (e.g. Azam-Ali et al., 1990; Bedoussac & Justes, 2010a, 2010b; Carr et al., 1998; Corre-Hellou et al., 2011; Maingi et al., 2001), intercropping also represents a challenge in market gardening. The sector of vegetable production is a good candidate for the adoption of intercropping. In Wallonia (Belgium): (i) the majority of market gardeners are settled on less than two hectares of cultivated land (Dumont & Baret, 2017) and could be attracted by the efficient use of space across the season that can be provided by intercropping (Gebru, 2015; Lithourgidis et al., 2011; Malézieux et al., 2009; Mutsaers et al., 1993); (ii) small market gardeners are usually highly diversified (from 20 up to 45 different vegetables; (Dumont & Baret, 2017), which means that intercropping would not lead to a complete reorientation of their farm; (iii) small market gardeners are usually poorly mechanised (Dumont, 2017) and are therefore unlikely to face the mechanisation difficulties often linked to intercropping (Gebru, 2015; Lithourgidis et al., 2011; Machado, 2009; Vandermeer et al., 1998).

Despite the benefits intercropping could bring to small and medium scale diversified market gardeners, its actual use remains low. The quality of information available to farmers is limited: their sources mainly consist of books in which intercropping advice is usually poorly explained or not explained at all. During meetings with market gardeners, we witnessed the fact that even in a small group (i.e. about ten people) coming from a small

area (i.e. Wallonia), the satisfaction regarding one specific crop mixture seemed to vary more from one person to another than the satisfaction regarding pure crops. These observations highlight the importance of the variability of results of intercrops in market gardening.

The question of the variability in intercropping has already been discussed many times (e.g. Mead et al., 1986; Paut et al., 2019; Pearce & Edmondson, 1982; Rao & Singh, 1990; Rao & Willey, 1980; Raseduzzaman & Jensen, 2017; Vandermeer & Schultz, 1990). However, previous studies generally focused on the yield stability that intercropping could provide. This is of little interest in diversified market gardening (20 to 45 crops (Dumont & Baret, 2017)), as the stability mechanisms provided by a higher biodiversity (Bedoussac et al., 2015; Himanen et al., 2016; Paut et al., 2019; Rao & Singh, 1990; Trenbath, 1999) are probably already at play. On the opposite, the inter-site variability of intercropping outcome has been little studied as such, although some studies about the yield stability in intercropping included plots from different environmental conditions or with different crop management practices (Mead et al., 1986; Pearce & Edmondson, 1982; Rao & Singh, 1990). Yet, this approach could help to understand the lack of consistency between the intercropping advices from market gardening books and to objectify differences of opinion between market gardeners regarding a given mixture.

In order to investigate the variability of the yield – relative to pure crops yield – in intercropping, we ran two field trials, in 2019 and 2020, on 11-14 different sites, in a range of environmental conditions and crop management practices. To get as close as possible to real conditions, the trials were organised in a participatory approach, each experimental field being set up in an existing farm and managed by a volunteer market gardener. We decided to explore the issue of the variability in two contrasted situations, i.e. two mixtures, one each year, based on crops with different physiological and architectural features.

The three main questions tackled in this work are the following: (i) what are the differences of yield of two intercropped crops compared to their pure crops? (ii) are these differences of yield consistent from site to site? (iii) if not, can we identify variables, among crop management practices and environmental characteristics of the sites, which influence the observed differences in yield between sites?

7.2. MATERIAL & METHODS

7.2.1. STUDY ZONES

We addressed the above-mentioned questions through two participatory on-farm trials, which took place in 2019 and 2020. The participatory process (cf. Chapter 6) allowed us to monitor one chosen intercrop at different market gardeners' places across Wallonia and to differentiate between intra- and inter-site variability. Participating market gardeners were chosen on a voluntary basis, as long as they were French-speaking and managing a small to medium-scale (maximum 10ha, Dumont & Baret, 2017) diversified market gardening farm. Participating market gardeners were involved in decision making regarding the intercrop, the plantation dates and distances and the harvest dates and method. Other elements of the design were decided by our research team (cf. Chapter 6).

The 2019 trial took place from mid-April to end of July 2019, in fourteen sites, among which twelve were located in professional market gardening farms owned by ten different market gardeners; one was managed by a research centre in agriculture (CRA-W[16]); and one was located at the market gardening farm of the UCLouvain and managed by our research team. The 2020 trial ran from mid-June to beginning of November 2020, on eleven sites, managed by nine different market gardeners, seven of whom participated in the 2019 trial. One of the eleven sites was located in the market gardening farm of the UCLouvain and managed by our research team. Eight of the eleven sites were located in the same farms as in 2019, but they were not necessarily managed by the same market gardener as in 2019. In both trials, sites were spread throughout Wallonia and represented different environmental and meteorological contexts as well as different crop management practices (cf. Appendix V, Appendix W, Appendix X, Appendix Y). Sites were numbered from "00" to "13" in 2019 and from "01" to "11" in 2020.

[16] Walloon agronomic research centre.

7.2.2. DESIGN OF THE TRIAL

The 2019 trial focused on a mixture of carrots (*Daucus carota* subsp. *Sativus)* and onions chives (*Allium cepa L.*), with four modalities (Figure 36A):

- a pure crop of carrots;
- a pure crop of onion chives;
- a proportional replacement intercrop of carrots and onion chives: for each crop in the intercrop, the number of plants per plot was half that of the corresponding crop in the pure crop plots (Snaydon, 1991). For onions, this was achieved by supressing half of the onion lines while keeping the same distance between plants on the line. For carrots, the number of lines was the same as in the pure crop but the distance between plants along the line was doubled;
- an additive intercrop of carrots and onion chives: in the additive intercrop, the density of each crop was equal to its density in pure crop (Snaydon, 1991). The overall density was therefore the sum of the densities of pure crops.

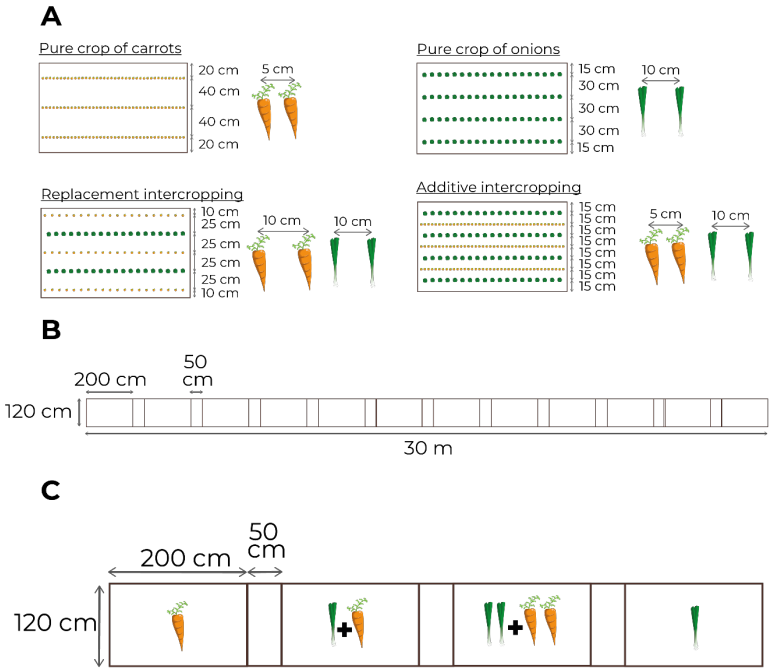


Figure 36 - Design of the 2019 participatory trial. Spatial organisation within each one of the four modalities (A), division of one experimental site into twelve plots (B) and example of the spatial organisation of the modalities within a site (C). For each modality, the intra-row distance is shown above the drawings of the crops (A).

In 2020, in order to experiment with crops with different physiological and architectural features than the carrots and the onion chives, we studied the intercrop between lettuces (*Lactuca sativa* var. *longifolia*) and dwarf beans (*Phasoleus vulgaris L.* var. *nanus*), a leguminous crop. We set up three modalities on each of the eleven sites (Figure 37A):

- a pure crop of lettuces;
- a pure crop of dwarf beans;
- an additive intercrop of lettuces and dwarf beans.

In both trials, we used a randomised complete block design, with three to four (for sites 00, 01 and 13 in 2019) repetitions of each modality in each block (site). Each experimental plot consisted of a parcel of land of 1.20 m width and 2 m long in 2019 (Figure 36B) and of 1.10 m width and 3 m long in 2020 (Figure 37B). Experimental plots were separated from each other by 50 cm in 2019 (Figure 36B) and by 35 cm in 2020 (Figure 37B). The spatial organisation of the modalities within each site was defined in a random but constrained way to ensure their good repartition along the experimental field (Figure 36C, Figure 37C). In the 2019 trial, carrots were sown between the 16th and the 30th of April 2019 and onion chive seedlings were transplanted between the 9th and the 23rd of May 2019. In the 2020 trial, lettuce seedlings were transplanted between the 16th and the 24th of June 2020 and dwarf beans were sown between the 25th and the 30th of June 2020. The actual density of onions in the plots was on average 92% of the expected density, the one of lettuces 86% and the one of beans 64 %. The one of carrots was 57% of the expected density at the beginning of the trial but reached 81% after a second sowing. No significant differences of ratio between actual and expected densities were found between the pure crop plots and the intercropping plots. In 2020, once the lettuces were harvested, spinach was sown in their place but given its very bad germination and growth in nearly all sites, results are not shown here.

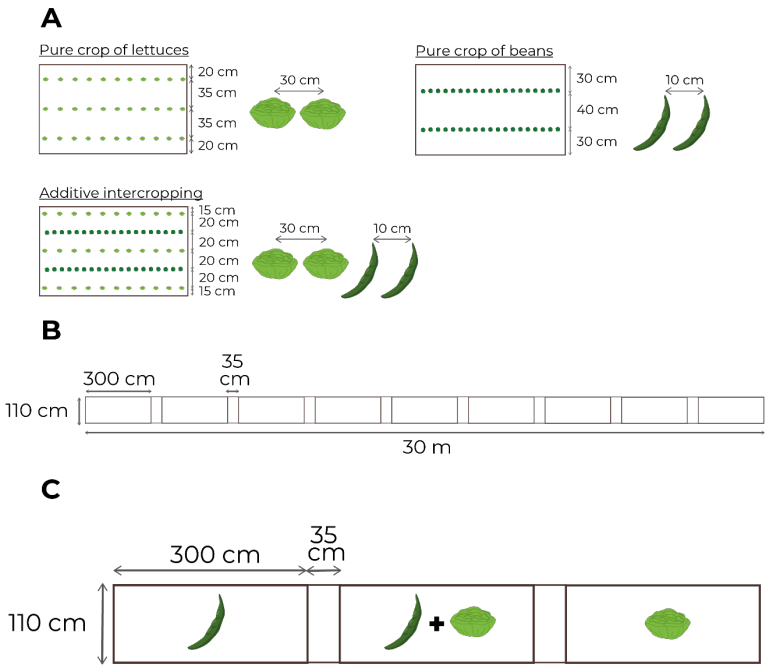


Figure 37 - Design of the 2020 participatory trial. Spatial organisation within each one of the three modalities (A), division of one experimental site into nine plots (B) and example of the spatial organisation of the modalities within a site (C). For each modality, the intra-row distance is shown above the drawings of the crops (A).

7.2.3. Environmental characterisation

The diversity of the sites was assessed prior to the 2019 trial. We did a soil sampling in each site using a 20 cm deep probe and collected ten samples that we pooled and analysed for pH KCl, pH H_2O, percentage of nitrogen, carbon and humus, C/N ratio, NO_3^-, NH_4^+, K, P Na, Mg, Ca and cation exchange capacity (CEC). A soil field capacity and wilting point analysis was performed on three structured samples taken with kopeckis[17] and three unstructured samples taken with a small shovel, collected in each site. Samples were taken in the first ten centimetres of the soil. Soil compaction was measured using a penetrometer at ten different spots in each site. Soil biological activity was assessed via respirometry measurement on soil samples collected after the trial in September 2019. As the majority of the sites on which the trial was set up in 2020 was in farms that already hosted the 2019 trial, only the mineral analysis of the soil was done in 2020. Sites characterisation data are

[17] Metal rings used for the sampling of undisturbed soil.

given in Appendix W (2019) and Appendix Y (2020) for soil analyses and weather data.

Weather data were obtained by averaging data from the two to three nearest stations of the Pameseb[18] network, complemented with on-site rain gauge data collected by gardeners (cf. Appendix S).

7.2.4. CROP MANAGEMENT DATA

We conducted semi-directive interviews with each participating market gardener before the beginning of the 2019 trial to capture the diversity of our sample and to understand the crop management practices and the organisation used in each farm. As the majority of the market gardeners participated in the two trials, this step was only partially repeated in 2020. The crop management characteristics of the sites is available in Appendix V (2019) and Appendix X (2020).

In order to maintain each one's special features and to keep the number of constraints as low as possible, market gardeners were left free to manage the crops as they wished. This freedom was compensated by asking them to record rigorously all the actions they were taking on the trial field regarding weeding, fertilisation, irrigation and pest management with forms provided by us (cf. Chapter 6, Appendix Q, Appendix R). In 2020, a facultative system of working time measurement was also introduced (cf. Chapter 6, Appendix T).

7.2.5. YIELD DATA

Market gardeners were authorised to sell the crops from the trial but, in return, they had to record the yield at the plot level. This first yield quantification is referred to as "actual yield" in the text. However, we thought that relying only on the data returned to us by market gardeners might cause some problems, as the harvest in market gardening is progressive. Moreover, as we did not impose any final date for the harvest, the harvests from the different sites were spread over several months and therefore included a large variability.

[18] Pameseb is a Belgian nonprofit organisation dedicated to the promotion of agrometeorology. It owns a network of 30 weather stations in Wallonia, whose data are used to advice farmers about integrated pest management and irrigation (https://www.pameseb.be/).

In order to compensate for the variability in harvest dates and to ensure the availability of reliable yield data for all sites, we decided to introduce another yield quantification referred to as “adjusted yield” in the text, based on samples of crops we harvested. Once the crops were mature, we collected samples of each one of the crops in each site. In 2019, ten carrots and ten onions bunches were sampled in each plot whereas in 2020, six lettuces and the fruits of ten dwarf bean plants were harvested in each plot. Harvested samples were randomly selected. We picked up the samples from the different sites with as little time difference as possible to ensure a reliable comparison between sites. Samples of carrots and onions chives were harvested between the 19th and the 31st of July 2019, samples of lettuces the 27th of July and the 13rd of August 2020 and samples of beans between the 14th and the 17th of September 2020. We weighed separately all the samples we harvested, calculated a mean weight per plant and then approximated the yield of each plot in each site by multiplying this mean weight by the expected density. In the 2019 trial, the adjusted yield of carrots was calculated considering their total biomass, i.e. shoot and root biomass. In the 2020 trial, the adjusted yield of dwarf beans was calculated based on one single harvest of the plants. In all our results, the yields and the densities are expressed based on the area of a plot and not on the area allocated to each crop within a plot.

Besides the biomass yields, we also looked at the financial yield, as this is the most important variable for many market gardeners. We calculated an actual financial yield and an adjusted financial yield by multiplying respectively the actual biomass yield and the adjusted biomass yield of each crop by an estimated selling price. The selling prices were based on the selling prices in three major grocery stores in Belgium and were the following: 1.38€/kg for carrots, 12.4€/kg for onions chives, 3.76€/kg for beans and 3.63€/kg for lettuces. Prices are for non-organic products. The financial yield of the intercropping modalities was the sum of the financial yields of their component crops. For the 2019 trial, we only considered the root biomass of carrots for calculating the adjusted financial yield. As the separation of the total biomass weight into shoot and root biomass was not available for all sites, we only calculated the adjusted financial yield based on the data of sites 02, 05, 08, 12 and 13. As market gardeners did not distinguish their harvested weights between shoots and roots, the actual financial yield for carrots was based on the total biomass.

From the yield data, we calculated land equivalent ratios (LER). LER is an indicator of the intercrop's performance and expresses how much more or less land is needed in the corresponding pure crops to get the same yield of each component crop than in the intercrop. An LER higher than one means that more land is needed in pure crops than in intercropping to get the same yield. The LER was calculated as follows (Mead & Willey, 1980):

$$LER = \frac{Y_A}{S_A} + \frac{Y_B}{S_B} \quad \text{(eq.3)}$$

where Y_A and Y_B are respectively the yield of crop A and crop B in the intercrop and S_A and S_B are respectively the yield of crop A and crop B in pure crop.

For the 2019 trial, two types of LER were calculated: one based on the total biomass of carrots and onions – the LER on total biomass – and one based on the root biomass of carrots and on the total biomass of onions – the LER on marketable biomass –. The marketable biomass is the part of the biomass that is actually sold but it does not take into account the minimum size required for sale. As the separation between root and shoot biomass was only available for sites 02, 05, 08, 12 and 13, the LER on marketable biomass was only calculated for these sites.

Finally, we also calculated a yield ratio (YR) per crop, i.e. the ratio between the yield of each crop in the intercrop and its yield in pure crop. The YR, which is one of the term of the equation of the LER (eq.3) quantifies the outcome of each one of the crops in the intercrop compared to its pure crop. If there was no interactions between the component crops of an intercrop, the YR should be equal to the ratio between the densities of the crop in intercrop and in pure crop.

7.2.6. Other measurements

We monitored the crop growth by visiting each site once every fortnight (2019) or once every week (2020). During each visit, we took various measurements such as the height of the plants, canopy pictures, etc. These measurements are detailed and their results are presented and discussed in Chapter 8.

7.2.7. DATA PROCESSING AND STATISTICAL ANALYSIS

Due to the participatory nature of the trials, we had to remove some of the sites from the data to guarantee a proper analysis of our results.

We removed six sites from the 2019 trial data: one for abandoning the trial (00), one for setting up the trial too late (06), and four (01, 03, 04, 07) for a very bad germination and growth of carrots. From the 2020 trial, we had to remove completely three sites: one on which weed control was far behind our criteria (01), one on which beans were not sown (06) and one that was abandoned (09).

The final set of data included sites 02, 05, 08, 09, 10, 11, 12 and 13 for the 2019 trial and sites 02, 03, 04, 05, 07, 08, 10 and 11 for the 2020 trial.

All yield variables were analysed through a linear mixed model, with "Modality" as a fixed factor and "Site" as a random factor, as we can make the hypothesis that the participating market gardeners form a random sample of the population of small to medium-scale diversified market gardeners in Wallonia. Our site effect was considered as a block effect. For both the adjusted and the actual yield, we analysed the yield of the two component crops separately – to compare the individual yield of each crop in each modality – and together – summing the yield of both crops in the intercropping modalities to compare the total amount of biomass produced –.

As two different modalities of intercropping were present in the 2019 trial, the "LER on total biomass" and "LER on marketable biomass" were analysed using the same linear mixed model as the yield data. Next to these analyses, the LER and YR values for the 2020 trial were also analysed with a linear random model with "Site" as a random factor and no fixed factor, in order to evaluate the intra- and inter-site variability.

Besides, for each of the variables analysed through a linear mixed model, we calculated the intra-class coefficient (ICC) per modality, using the following formula:

$$ICC = \frac{\sigma_{site}}{\sigma_{site}+\sigma_{res}} \quad \text{(eq.4)}$$

where σ_{site} is the variance of the random effect and σ_{res} is the residual variance.

We estimated the variance of the random effect and the residual variance for each modality using a random model with “Site” as random effect. This model was applied on the subset of data corresponding to each modality. All the calculated ICCs were then analysed together using a linear model with both “Crop”, “Modality” and their interaction as fixed factors.

All statistical analyses were performed in R v.3.4.1 with the *lmer*, *anova* and *rand* functions for the linear mixed models, the *contrast* function to perform custom mean comparisons and the *emmeans* function to perform other mean comparisons.

7.3. RESULTS

We present hereunder the results of the 2019 trial, followed by the results of the 2020 trial. In order to facilitate reading and comprehension, we decided to focus only on one yield quantification for each trial: the adjusted yield for the 2019 trial and the actual yield for the 2020 trial. We choose not to focus on the actual yield for the 2019 trial as it included many missing data and was highly variable regarding carrots, probably because of the repeated sowing done to counteract the low germination. Regarding the 2020 trial, the actual yield was more accurate, as it considered the successive harvests of bean plants, whereas the adjusted yield estimated the bean yield based on one single harvest.

7.3.1. 2019 PARTICIPATORY TRIAL

7.3.1.1. Biomass yield

According to our design, the density of each crop in the replacement intercrop was equal to half its density in pure crop and the density of each crop in the additive intercrop was equal to its density in pure crop. Assuming that each plant would take up as many resources as in pure crop, the ratio between the yields of each crop in intercropping and in pure crop should be equal to the ratio of the densities.

This is what we observed in the replacement intercrop: its yield was not significantly different from half the yield of the corresponding pure crop (Figure 38) either for carrots (p-value=0.45) or for onions (p-value=0.86). It seems therefore that the replacement intercrop performed as expected,

with each crop growing as if it was in a pure crop at a lower density rather than in an intercrop.

In the additive intercrop, the yield of both crops was significantly lower than in the corresponding pure crops (p-values: <0.001 (carrots), <0.001 (onions), Figure 38). However, the impact was greater for carrots: their mean yield decreased by 38.2%, against 21.5% for onions. Even if the yield of each crop in the additive intercrop was lower than in the corresponding pure crop, it remained significantly higher than its yield in the replacement intercrop (p-values:0.021 (carrots), <0.001 (onions)). The yield of each crop in the additive intercrop was therefore between its yield in pure crop and its yield in the replacement intercrop (Figure 38).

We observed a large variability of outcome across sites (Figure 38): the site effect was highly significant for both crops (p-values: <0.001 (carrots), <0.001 (onions)). Nevertheless, there was also a significant and positive correlation between the yield of each crop in each intercropping modality and the yield of the same crop in pure crop (p-values: 0.013 (carrots in the additive intercrop), <0.001 (carrots in the replacement intercrop), <0.001 (onions in the additive intercrop), <0.001 (onions in the replacement intercrop)). The outcome of a crop in a given site in an intercropping modality paralleled its outcome as a pure crop.

The correlation between the yields of onions and carrots was positive and significant for the pure crops (p-value<0.001) and for the replacement intercrop (p-value=0.033) but became non-significant for the additive intercrop (p-value=0.18). If the most productive sites in onions in the pure crop and the replacement intercrop usually were the most productive sites

in carrots in the pure crop and the replacement intercrop, this was not necessarily the case in the additive intercrop.

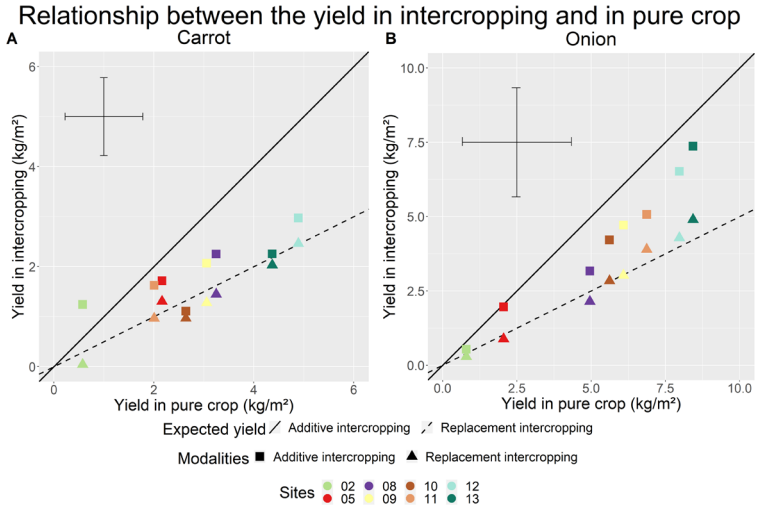


Figure 38 - Relationship between the yield of carrots (A) and onions (B) in intercropping and in pure crop. Each pair of points represents the data of one site. The cross in the top left corner of each graph represents the mean standard deviation of the yield in pure crop (horizontal line) and in intercropping (vertical line) for each crop. The solid and dashed lines represent the expected linear regression between the yield in intercropping and the yield in pure crop for the additive and the replacement intercropping respectively.

7.3.1.2. Land equivalent ratio

With regard to the replacement intercrop, the average LER was equal to 0.95 and was not significantly different from unity (Figure 39). This confirms that the replacement intercrop yielded as expected based on the density and that, on average, one needed as much land in pure crops as in replacement intercrop to get a given yield of each crop. Unsurprisingly, the LER for the additive intercrop was higher than for the replacement intercrop (LER=1.42 on average, p-value<0.001, Figure 39). Moreover, its confidence interval did not include unity, which means that even if the yield of each crop decreased, less land was needed in the additive intercrop than in the corresponding pure crops to get a given yield of each crop.

As the competition between crops in intercropping may have an influence on the relative allocation of biomass to roots and shoots (Ericsson, 1995; Poorter et al., 2012) and as only the roots of carrots are marketed, it is questionable whether the conclusions regarding the LER remained the same if we only considered the marketable yield of carrots. This turned out to be the case, with an average LER of 1.00 for the replacement intercrop and 1.33

for the additive intercrop. The difference between the LER for total yield and the LER for marketable yield suggests that relatively more biomass was allocated to carrot roots than to carrot shoots in the replacement intercrop and relatively more to carrot shoots than to carrot roots in the additive intercrop. However, these differences were not significant (p-values: 1.00 (replacement intercrop), 0.89 (additive intercrop)).

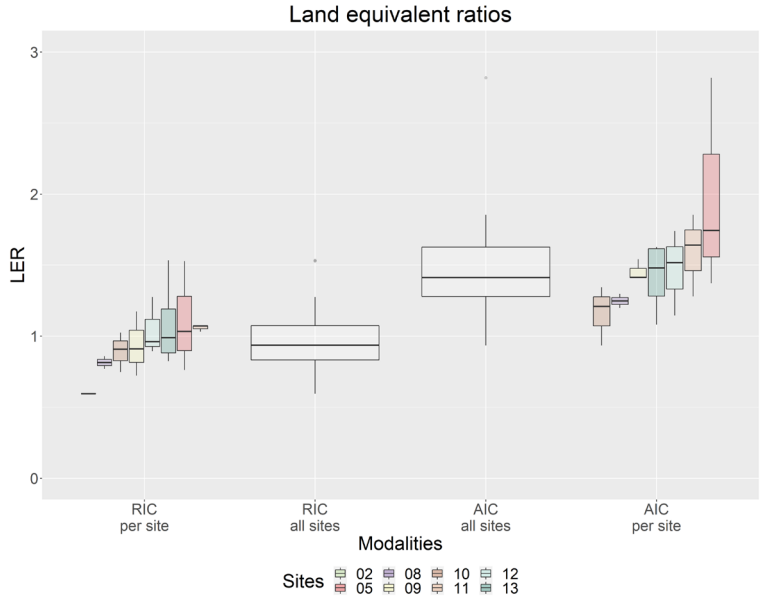


Figure 39 - Boxplot of the land equivalent ratio for the carrot + onion chive intercrops. The land equivalent ratio is presented both per site and on average. AIC=Additive intercrop, LER=Land equivalent ratio, RIC=Replacement intercrop.

7.3.1.3. Financial yield

Even if the biomass yield and LER give us useful information about the intercrop, what market gardeners are primarily interested in is the financial return (Table 6). The mean financial yield of the replacement intercrop (20.89€/m²) was lower than half the sum of the mean financial yields of the pure crops (22.40€/m²). Regarding the additive intercrop, its financial return was significantly higher than that of the pure crop of carrots (p-value<0.001) and equal to that of the pure crop of onions (p-value=0.24). Its mean financial yield (34.22€/m²) was however lower than the sum of the mean financial yield of the pure crops (44.80€/m²).

Table 6 - Median, minimum and maximum financial yield for each modality of the 2019 participatory trial. Only the root biomass of carrots was taken into account in the calculation of the financial yield. The financial yield was therefore only based on data from sites 02, 05, 08, 12 and 13.

MODALITY	MEDIAN FINANCIAL YIELD (€/M²)	MINIMUM FINANCIAL YIELD (€/M²)	MAXIMUM FINANCIAL YIELD (€/M²)
Pure crop of carrots	3.41	0.12	5.77
Replacement intercrop	30.05	1.98	70.35
Additive intercrop	46.15	4.08	102.02
Pure crop of onions	64.26	7.25	130.49

As the biomass of onions represented a higher proportion of the total biomass for both intercropping modalities and as the selling price of onions was ten times that of carrots, onions accounted for a much higher proportion of the financial yield of intercropping modalities than carrots. Given the difference in selling prices between the crops, the replacement intercrop was more profitable than the pure crop of carrots (p-value<0.001) but less than the pure crop of onions (p-value<0.001), which is logical as we replaced a high-income crop by a low-income one.

Similar to the biomass yield, the financial yield was highly variable across sites (p-value<0.001).

7.3.1.4. Consistency across sites

The site effect was highly significant for the biomass yield of both crops (Figure 38) and the financial yield. Interestingly, the site effect was not significant for the LER (p-value=0.23). Although we observed important differences in yields (Figure 38) between sites and although we put ourselves in a situation with a lot of variability – i.e. field experiment, participatory approach, differences in soil, meteorological conditions, crop management practices, plantation and sowing dates between sites – the relative results of the intercropping modalities, i.e. compared to the corresponding pure crops, were consistent from one site to another (Figure 39). This result is further confirmed by the positive correlation between the yields of both crops in pure crop and their yields in intercrop (cf. 7.3.1.1), which suggests that the outcome of carrots and onions in intercropping in a given site was directly related to their outcome in pure crop in the same site and was not more influenced by some environmental or crop management practices than their outcome in pure crop. The analysis of the intra-class correlation coefficient

(ICC) further confirmed that the yield was not more variable among intercropping modalities than among the pure crops. In fact, the ICC was not influenced by the modality (p-value=0.078).

This suggests that the differences of satisfaction between market gardeners regarding a given intercrop could be linked to the differences of yields between sites rather than to the actual performance of the intercrop. Indeed, a market gardener setting up an intercrop without setting up also the corresponding pure crops could conclude that the intercrop does not work, because of a low yield, whereas in fact, the pure crops would not have yielded better. An objective analysis on the part of market gardeners regarding the outcome of a plot should therefore lead to the same conclusion for pure crops than for an intercrop.

Based on our results, it seems, on the one hand, that the replacement intercrop between carrots and onions would not bring significant advantages – apart from the potential benefits of pest repellence – to market gardeners. On the other hand, the interest of an additive intercrop between carrots and onions for market gardeners depends on their strategy and the diversity of their farm. If we focus on the results of biomass and financial yields, the additive intercrop did not produce more than the pure crop of onions and was not more profitable. Consequently, it is better, for a market gardener who only grows onions, not to insert carrots in the field, as this would decrease the yield in onions and would not increase the profitability of the field. Nevertheless, given that the LER for the additive intercrop was strictly higher than one, it would be more profitable for a market gardener growing both carrots and onions in separate fields in its farm to grow them together instead, as two fields of additive intercrop would give him a higher yield than one field of each pure crop. In this situation, the biomass yield gain would be of 23% for carrots (p-value=0.13) and of 57% for onions (p-value=0.005) and the financial yield gain would be of 52.8% (p-value<0.001).

7.3.2. 2020 PARTICIPATORY TRIAL

7.3.2.1. Biomass yield

In the 2020 trial, the density of lettuces and beans in the intercrop was equal to their density in pure crop (i.e. additive design). Assuming that each plant withdraws as many resources in intercropping as in pure crop, the yield of each crop in the intercropping modality should be equal to its yield in pure crop. This was observed for lettuces (p-value=0.51, Figure 40B) but not for

beans, whose yield in intercropping was significantly lower than in pure crops (p-value<0.001, Figure 40A). These results suggest that lettuce plants did indeed take up as many resources in intercropping as in pure crop but that bean plants withdrew less resources than expected. There was probably an asymmetric share of resources between the two component crops.

We observed a large variability of outcome between sites (Figure 40), more for beans (p-value of the site effect<0.001) than for lettuces (p-value of the site effect<0.001). The yield of each crop in intercropping was significantly and positively correlated to its yield in pure crop (p-values: <0.001 (beans), <0.001 (lettuces)) and the yields of both crops were significantly and positively correlated in pure crop (p-value<0.001) as well as in intercropping (p-value<0.001). Therefore, if a site was productive in lettuces, it was usually also productive in beans and if a site was productive in the pure crop of one of the crops, it was usually also productive for the same crop in intercropping.

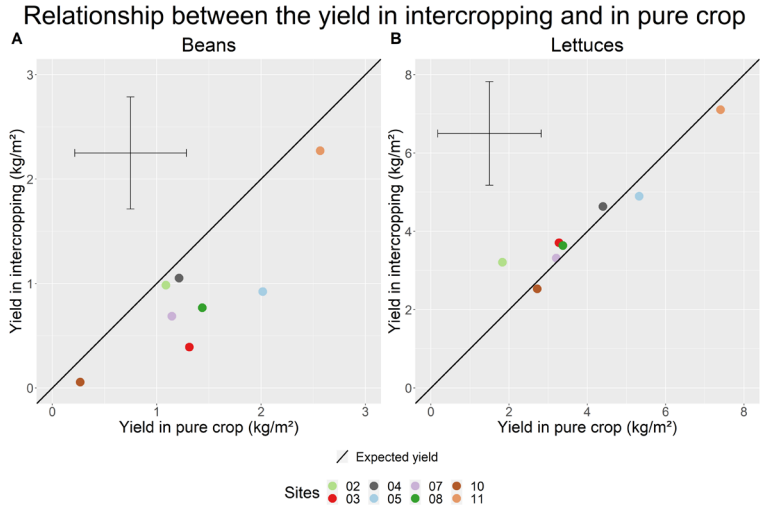


Figure 40 - Relationship between the yield of beans (A) and lettuces (B) in intercropping and in pure crop. Each point represents the data of one site. The cross in the top left corner of each graph represents the mean standard deviation of the yield in pure crop (horizontal line) and in intercropping (vertical line) for each crop. The solid line represents the expected linear regression between the yield in intercropping and the yield in pure crop.

7.3.2.2. Land equivalent ratios

The average LER was equal to 1.61 and was significantly higher than one: to get the same yield of each crop, one needed less land in an additive intercrop between lettuces and beans than in the corresponding pure crops (Figure 41A).

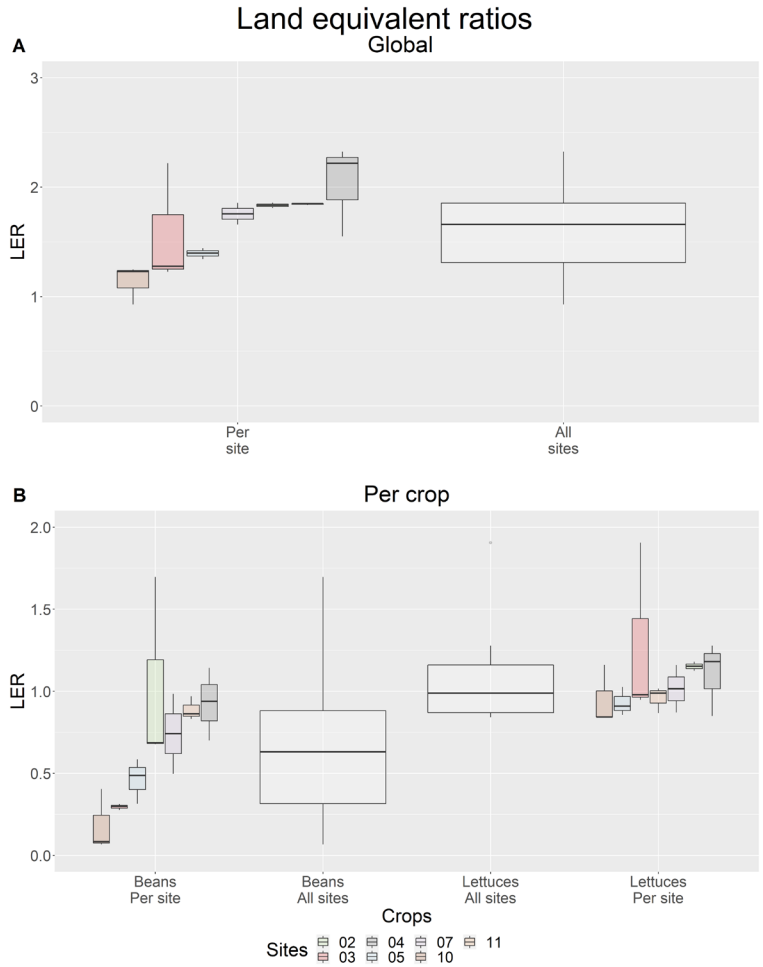


Figure 41 - Land equivalent ratio (A) and yield ratio (B) for the lettuce + dwarf bean intercrop. Both the average land equivalent ratio and the yield ratios across all sites and the land equivalent ratio and yield ratios per site are shown. LER=Land equivalent ratio, YR=Yield ratio.

7.3.2.3. Financial yield

The sales turnover was significantly higher in the intercrop than in both pure crops (p-values: 0.001 (lettuces), <0.001 (beans)) and was not significantly lower than the sum of the sales turnovers of both pure crops, i.e. not significantly lower than expected (p-value=0.60) (Table 7). These results are not surprising: the intercropping modality produced more biomass than each one of the pure crops and the selling prices of its component crops were similar (3.76€/kg for beans, 3.63€/kg for lettuces). Besides, the financial benefit of the intercrop compared to the pure crops of lettuces and dwarf beans was not compensated by an increase in working time: there were no

significant differences between the modalities with regard to the relative time spent by market gardeners on crop management (p-value=0.082). Therefore, the intercrop led to an increase in the absolute financial return as well as an increase in the hourly wage of market gardeners.

The variability between sites remained as high as for the biomass yield (p-value<0.001).

Table 7 - Median, minimum and maximum financial yield for each modality of the 2020 participatory trial.

MODALITY	MEDIAN FINANCIAL YIELD (€/M²)	MINIMUM FINANCIAL YIELD (€/M²)	MAXIMUM FINANCIAL YIELD (€/M²)
Pure crop of beans	4.79	0.25	10.26
Pure crop of lettuces	12.46	2.27	27.35
Lettuce + dwarf bean intercrop	15.14	8.34	36.34

7.3.2.4. Consistency across sites

The site effect was highly significant (p-value<0.001) in all our analyses regarding biomass (Figure 40) and financial yields: there were important yield differences between sites. However, contrary to what was observed in the 2019 trial, the random factor remained significant in the analysis of the LER (p-value=0.045), as well as the "Modality" factor in the ICC analysis (p-value<0.001). In order to understand better the cause of this variability, we analysed the YR of each crop (Figure 41B). Variability of the YR across sites was much higher for beans than for lettuces (Figure 41B). This was confirmed by the statistical analysis, as the random effect was significant for the YR of beans (p-value=0.005) but not for the YR of lettuces (p-value=1). Two groups seem to emerge: sites 03, 05 and 10, which had a similar (p-value=0.89) and a lower (p-value=0.004) bean YR than sites 02, 04, 07, 08 and 11 (Figure 41B).

To identify likely causes of the significant differences in beans, we calculated the correlation between the YR of beans and the different environmental variables we collected during the characterisation of the sites. These include data about the mineral and organic characteristics of the soil (Ca, Mg, K, P, NO_3^-, NH_4^+, CEC, humus, oxidisable carbon, pH, percentage of dry matter), the weather conditions (potential evapotranspiration, percentage of rainy days, cumulative rainfall, incident photosynthetically active radiation, sum of degree-days throughout the trial) and the crop management (cumulative irrigation, cumulative irrigation and rainfall, time shift between the

plantation of lettuces and the sowing of beans, time shift between the sowing of beans and the last harvest of beans by market gardeners, time shift between the last harvest of lettuces and the last harvest of beans by market gardeners). The correlations were all non-significant, expect the one with the concentration of nitrate in the soil, which stood out with a correlation of 0.72 with the YR of beans (p-value<0.001). The fact that the three sites with the lowest beans YR were also the three sites with the lowest nitrate concentration in the soil supports the hypothesis of the role of nitrate concentration in the differences between the beans YRs. The differences in beans YR would thus be linked to a soil effect, which would be consistent with the significant and positive correlation between the yields of lettuces and beans (0.83, p-value<0.001). The sites 02 and 03, which have very different beans YRs, are particularly informative. They belonged to the same farm and were managed by the same market gardener (same irrigation, plantation and sowing dates, weeds management, etc.), but they differed by the soil management, as the market gardener did not apply the same fertilisation in both sites. The effect of the concentration of nitrates in the soil on the YR of beans will be discussed further in Chapter 8.

Despite the variability of the beans YRs, the average LER was higher than unity at all sites. Therefore, it seems that it is beneficial to add beans to a field of lettuces, because it should not reduce the yield of lettuces and may give the market gardener a further gain with beans. The interest of adding lettuces to a field of dwarf beans is more debatable, as the yield of beans decreased when they were intercropped. The decision will depend on which crop the market gardener relies the most. Nevertheless, for a market gardener growing both lettuces and beans, it seems more advantageous to have two fields of a lettuce + dwarf bean intercrop than one field of each pure crop. It would allow him/her to double the lettuce biomass yield (p-value<0.001) and to increase the bean biomass yield by 29% (p-value=0.16) as well as to raise the financial yield by 87.7% (p-value<0.001). Nevertheless, switching from one field of each pure crop to two intercropping fields will increase the occupation time of one of the fields, as beans stay longer in place than lettuces, which could constrain growers who are used to planting another crop after harvesting lettuces grown as pure crop.

7.3.3. COMPARISON OF THE TWO TRIALS

We used the same methodology for the two trials, except for some adjustments to make the trial easier to handle for market gardeners (cf. Chapter 6) and the choice of different crop mixtures. So far, our analysis showed that there were differences of productivity between the two additive intercrops we tested. Nevertheless, the advantage of growing two fields of an additive intercrop instead of one field of each one of the corresponding pure crops was undeniable in both trials.

Besides, in both trials, there were yield differences between the sites but a much lower variability regarding the LERs. The biomass yield in intercropping of the four crops we studied was significantly correlated to their yield in pure crop.

7.4. DISCUSSION

Intercropping is usually associated with a reduction of the risk of yield loss and, therefore, with an improved yield stability compared to pure crops (Bedoussac et al., 2015; Jensen, 1996; Malézieux et al., 2009; Paut et al., 2019; Rao & Singh, 1990; Rao & Willey, 1980; Trenbath, 1999), even though the contrary has also been stated (Pearce & Edmondson, 1982; Vandermeer & Schultz, 1990). The main objective of the two participatory on-farm trials reported here was to compare the relative performance of three intercrops, compared to the corresponding pure crops, managed across a range of crop management practices and environmental conditions.

We chose to tackle the question of variability using participatory on-farm trials. Althoug the participatory on-farm approach allows to multiply the locations on which the trials were set, the number of sites was limited by (i) the difficulty to find market gardeners willing to actively take part in the study and (ii) the possibility for one person to visit each site at least once every fortnight. From the perspective of the study of variability, it might have been interesting to set up the trials on as many sites as possible in order to multiply the number of different environmental conditions. However, the 11-14 sites included in the study already offer a sufficient range of environmental conditions for our study to be reliable and is a number of sites similar to what was used in other variability studies (e.g. Rao & Singh, 1990). Moreover, increasing the number of sites would probably have been done at the cost of reducing the involvement of market gardeners in the trial, as we would probably not have been able to find many more market gardeners

willing to participate actively in the study. We believe that the management of the experimental plots by professional market gardeners adds further interest to our work, as it increases the variability between the sites due to differences in crop management. Therefore, even on 11-14 sites, we set ourselves in a “worst case scenario” to understand variability.

Our results show that there was indeed a large variability regarding the absolute yields of all the modalities across the sites. Nevertheless, they also highlight the consistency of the LERs across these same sites. It seems that the environmental conditions and the crop management practices influenced equally the intercropping modalities than the corresponding pure crops. For all four crops, there were indeed significant correlations between their yields in intercropping and in pure crop and the most productive sites in pure crops were also the most productive ones in intercropping. It seems therefore that the actions improving the yield of a pure crop should also improve the yield of the same crop in intercropping.

These results suggest that the differences of opinions between market gardeners regarding a specific intercrop may not be based on objective assessments of performance of this intercrop but rather on (i) the absence of the corresponding pure crops in their farm to distinguish between the effect of the year and the effect of the intercrop itself, (ii) the large variability of yield between sites, which makes it easy for a market gardener to find situations where intercropping has low yield and/or not to believe the situations in which it achieves high yield, (iii) the balance of yield with other variables used by market gardeners to asses the relevance on an intercrop.

It is usually said that complementarity would be greater if resources are scarce and that intercropping would show its full potential under limited resources (Bertness & Callaway, 1994; Callaway & Walker, 1997; Hinsinger et al., 2011; Malézieux et al., 2009). Nevertheless, this assumption was not verified in our case. The high correlation between the YR of beans in the lettuce + dwarf bean intercrop and the nitrate concentration in the soil indeed reminds us that an environmental limitation might be more detrimental to the intercrop than to the corresponding pure crops. It is however interesting to note that (i) the nitrogen limitation had the same impact in all three sites in which it was present, despite the other differences, e.g. crop management, between these sites and (ii) that despite the effect of the nitrate concentration, the LER of the lettuce + dwarf bean intercrop was less variable from one site to the other than its yield.

Finally, another important conclusion of our work is the undeniable interest of the two additive intercrops we tested for diversified market gardeners: their average LER was significantly higher than unity in all sites, which means they used the land more efficiently than the corresponding pure crops. On the opposite, we did not observe any significant benefit for the replacement intercrop between carrots and onions chives. This contradicts the assumption that crops in the replacement intercrop would experience less competition, due to a lower density, and therefore have better results than expected (Gebru, 2015; Willey, 1990). Our results let us suppose that an additive design might be beneficial, on a yield point of view, for other vegetables combinations. However, we are aware that other elements than yield come into play when choosing to associate two crops, as intercropping generates complexity (Himanen et al., 2016; Paut et al., 2019; Trenbath, 1999), requires other skills and knowledge from market gardeners than pure crops (Himanen et al., 2016; Paut et al., 2019; Trenbath, 1999) and might require more time to manage and might produce crops of lower quality (e.g. smaller carrots roots in the additive intercrop with onions chives, cf. Chapter 8).

The fact that the LER of both additive intercrops was significantly higher than one implies that there was a margin of improvement compared to pure crops: it is possible to produce more biomass on the same area. If we use the resources as reference point, at least three mechanisms may account for this increase in biomass production: (i) the intercrop used a greater amount of environmental resources than the corresponding pure crops thanks to an access to a greater pool of resources, (ii) the intercrop used a greater amount of environmental resources than the corresponding pure crops thanks to a density effect and (iii) the intercrop used the environmental resources more efficiently than the corresponding pure crops. These mechanisms will be discussed in Chapter 8.

*

* *

In this chapter, we presented the first part of the data collected during the participatory on-farm trials and addressed our third research question.

This study is one of the few tackling the question of yield variability in relation to the environment. We showed that despite the high yield variability between sites for all intercrops, their land equivalent ratios were consistent

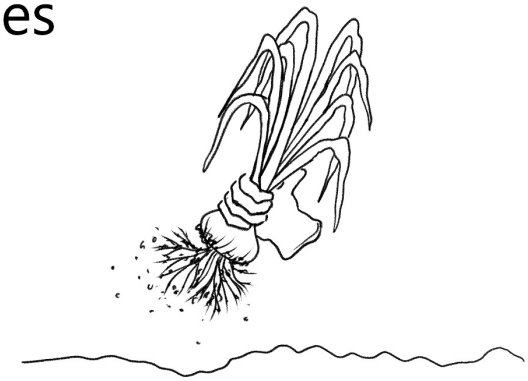
across all sites, i.e. the relative productivity of the intercrops depended more on its component crops and on its temporal and spatial design than on the environmental conditions in which they were cultivated or on the crop management practices of the market gardeners. Nonetheless, the 2020 trial, studying a lettuce + dwarf bean intercrop, allows to qualify this statement. Among the seven sites kept for the analysis of the results of the 2020 trial, three had a LER significantly lower than the four others, a decrease mainly linked to a decrease in the yield ratio of beans. These three sites were the ones with the lowest initial nitrate concentrations in the soil, which suggest that there was a threshold under which the nitrate limitation was too strong for the beans in intercropping to grow as well, compared to the pure crop, as in the other sites.

These results are interesting to understand further intercropping and its interactions with its environment. They are also of importance for the market gardeners. Firstly, they show that market gardeners should not use the biomass yield of intercrops in other farms as a reference to evaluate the productive benefit of this practice, as this biomass yield is highly variable between sites. However, the yield of a crop in intercropping in a site was highly correlated to the yield of the same crop in pure crop in the same site, meaning that market gardeners could expect their yields in intercropping to be proportional to their yields in pure crop. Secondly, the findings presented in this chapter highlight the importance, for a market gardener testing an intercrop, of growing the intercrop but also the two component crops as pure crop – or, at least, to know the mean yield of his/her crops when grown as pure crops – to be able to distinguish between the effect of the year and the effect of intercropping itself. Thirdly, the data collected on working time in 2020 do not show an increase in the amount of work in intercropping. However, this result could change depending on the intercrops considered. Finally, the results of the participatory on-farm trials suggest that (i) replacement intercropping offers no clear productivity advantage, although this could vary depending on the intercrop, (ii) additive intercropping is a beneficial cropping method, regarding productivity, for diversified market gardeners and (iii) the relevance of additive intercropping is more debatable, from the point of view of productive advantage, for market gardeners that are not diversified.

In the next chapter, we will explore further the data from the participatory on-farm trials by analysing the pattens of resource use and resource sharing in the three intercrops we studied.

Chapter 8 |

Patterns of resource sharing in three vegetable intercrops across a range of environmental conditions and crop management practices



In Chapter 6, we presented the methodology we developed in the participatory part of our thesis, with an emphasis on the conception and conduct of the participatory trials. In Chapter 7, we tackled the issue of the variability of intercropping relative outcome in a range of environmental conditions and crop management practices, using the data collected in the participatory trials.

In this chapter, we go a step further by exploring the patterns of resource use and resource sharing between companion crops in the three intercrops we studied during our participatory on-farm trials and try to identify the complementarity and competition interactions between the associated crops that determined their relative yield. This chapter also shows that reliable data regarding the growth of crops can be collected during a participatory on-farm trial and that this type of trial, as long as it is designed in this view, can be an asset to bring physiological consideration in market gardener's field. It highlights the fact that participatory on-farm trials are not only useful for testing new technologies in farmers conditions.

We begin with a brief reminder of the material and methods of the trials (section 8.2) then move on to the results (section 8.3). We present the results separately for the 2019 (section 8.3.1) and the 2020 (section 8.3.2) trials and for both, we analyse the resource uptake, use and sharing at the plot level and at the crop level. We end up by discussing our findings (section 8.4).

CHAPTER 8 | PATTERNS OF RESOURCE SHARING IN THREE VEGETABLE INTERCROPS ACROSS A RANGE OF ENVIRONMENTAL CONDITIONS AND CROP MANAGEMENT PRACTICES

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8.1. INTRODUCTION

It is nowadays well accepted that growing two different crops on the same field may allow to increase the production of biomass per square meter compared to growing them alone (e.g. Bulson et al., 1997; Monti et al., 2016; Reddy & Willey, 1981; Yu et al., 2015; Zhang & Li, 2003). However, despite many years of research, there is still no "ready-made recipe" to design a productive intercrop. The outcome of an intercrop depends on many interactions between the plants and between the plants and their environment (cf. Chapter 2), which define the balance between three major relationships within a crop mixture: complementarity, facilitation and competition (Erskine et al., 2006; Fridley, 2001; Gebru, 2015; Malézieux et al., 2009).

Complementarity refers to the resource partitioning between plants, alleviating the interspecific competition (Duchene et al., 2017; Fridley, 2001). Complementarity can be related to (i) architectural differences, i.e. plants will not uptake their resources at the same place (Fridley, 2001; Trenbath, 1976), (ii) nutritive differences, i.e. plants will not rely on the same form of the resources (e.g. legumes *vs* non-legumes) (Fridley, 2001; Tofinga et al., 1993; Trenbath, 1976) or (iii) temporal differences, i.e. plants will not withdraw resources at the same time (Fridley, 2001; Trenbath, 1976; Yu et al., 2015). When two mixed crops are complementary, they are supposed to exploit a larger space and/or different forms of resources than pure crops (Keating & Carberry, 1993; Midmore, 1993; Natarajan & Willey, 1980a; Willey, 1990; Willey & Osiru, 1972) and, therefore, could use a greater amount of environmental resources than each pure crop (Keating & Carberry, 1993; Natarajan & Willey, 1980a, 1980b; Rao & Singh, 1990; Willey, 1990; Willey & Osiru, 1972). This suggests that the overall optimal density could be greater in an intercrop than in the corresponding pure crops (Hauggaard-Nielsen et al., 2006; Natarajan & Willey, 1980b; Willey & Osiru, 1972).

Facilitation refers to the processes through which one crop exerts a positive effect on the other (Callaway, 1995; Vandermeer, 1995), e.g. the increase in nutrient availability for one of the crops thanks to the solubilisation of soil nutrients by the root exudates of the other crop (Latati et al., 2014; Li et al., 2004; Zhang & Li, 2003).

Finally, competition refers to the negative effect that one plant can have on the other (Vandermeer 1989). For crops to be in competition for a resource, the uptake of this resource by one of the crops of the mixture must prevent the other one from acquiring it (Schenk, 2006; Snaydon, 1996). Competition usually occurs for light, water and nutrients in intercropping (Donald, 1963; Snaydon, 1996; Trenbath, 1974; Wilson, 1988).

The balance between these three interactions determines the outcome of an intercrop and explains the difference that can be observed between the actual yield of each crop in the mixture and its expected yield, extrapolated from the pure crop. However, this balance is sensitive and may shift from one predominant relationship to another with changes in the environment, e.g. facilitation is expected to be more important in harsh conditions whereas competition dominates in rich ecosystems (Azam-Ali et al., 1990; Callaway, 1995; Callaway & Walker, 1997; Hinsinger et al., 2011; Malézieux et al., 2009; Schenk, 2006), and in crop management, e.g. planting distances (Ren et al., 2017).

In addition, a density effect may also influence the yield of intercrops. Above a certain density, increasing the number of plants per square meter only offers a marginal yield gain or no gain at all: at high density, plants are likely to compete for resources and get individually fewer resources than at lower density. The increased biomass production in intercropping is often attributed to their access to a greater pool of resources through complementarity. However, it may also be that crops in pure stands are at suboptimal densities and that they do not use entirely the available resources (Trenbath, 1976). In this case, switching from a pure crop to an additive intercrop could increase the total amount of resources captured and therefore the biomass production without any complementarity effect.

In Chapter 7, we presented the results relative to yield variability of two participatory field trials conducted to study a carrot + onion chive and a lettuce + dwarf bean intercrops in a range of environmental conditions and crop management practices. The present chapter aims at investigating the uptake, use and share of resources between component crops and therefore partly tackles research question A, as we will try to identify the complementarity and competition interactions between component crops that determined the productivity of the intercrops. On the basis of the architectural and physiological characteristics of the crops (Table 8), we hypothesise that (i) both intercrops, in additive design, will yield more than

each corresponding pure crop thanks to their complementarities and the greater pool of resources they should have access to, (ii) carrots and onions should compete for light due to their poor shoot spatial complementarity, (iii) lettuces and dwarf beans should compete for soil resources due to their poor root spatial complementarity but this competition might be alleviated by the ability of the dwarf bean to fix the atmospheric nitrogen, (iv) no density effect should be observed in the additive intercropping modalities as the densities used in pure crops were chosen by professional market gardeners and are likely to be optimal.

8.2. MATERIAL & METHODS

The design of the participatory on-farm trials and of the participatory methodology they are based on are explained respectively in Chapter 7 and Chapter 6. The following section explains the physiological measurements performed during these trials and the derived variables (Table 9).

8.2.1. EXPERIMENTAL DESIGN

We organised two participatory trials, during two consecutive years. The first one took place in 2019 and focused on the study of an intercrop between carrots (*Daucus carota* subsp. *Sativus*) and onions chives (*Allium cepa L.*). Four modalities were set up in fourteen different sites: (i) a pure crop of carrots, (ii) a pure crop of onion chives, (iii) a proportional replacement intercrop of carrots and onion chives, in which the density of each crop was equal to half its density in pure crop (Snaydon, 1991) and (iv) an additive intercrop of carrots and onion chives, in which the density of each crop was equal to its density in pure crop (Snaydon, 1991). The second trial, set up in 2020, studied an intercrop between dwarf beans (*Phasoleus vulgaris L.* var. *nanus*) and lettuces (*Lactuca sativa* var. *longifolia*). Three modalities were established in eleven different sites: (i) a pure crop of lettuces, (ii) a pure crop of dwarf beans and (iii) an additive intercrop of lettuces and dwarf beans, in which the density of each crop was equal to its density in pure crop. The main architectural and growth cycle characteristics of the four crops are listed in Table 8. More information about the design of the experimental trials is available in Chapter 7. The measurements taken during the participatory trial are explained hereunder and summarised in Table 9.

Table 8 - Main architectural and growth cycle characteristics of carrot, onion chive, dwarf bean and lettuce. Information about botanical family, growth cycle duration, shoot height and shoot architecture are derived from websites of Agrosemens, Gerbeaud, Jardiner-malin, Binette & Jardin, Rustica, Ooreka and Wikipédia, from the technical sheets of Argouac'h (2005), LPC bio (Fleurance & LCA-CA41 2013, Perret & Bio Centre 2013, Service Culture & Conserves du Blaisois 2013) and réseau GAB/FRAB network (n.d., n.d., n.d., n.d.), and from the books of Hervé-Gruyer & Hervé-Gruyer (2019). Information about the rooting depth and rooting spread are derived from Kutschera et al. (2009), Nishida (2011) and Weaver & Burner (1927). Lat. Root spreading=Lateral root spreading.

CROP	BOTANICAL FAMILY	TYPE	GROWTH CYCLE DURATION (DAYS)	SHOOT HEIGHT (CM)	SHOOT ARCHI-TECTURE	TYPE OF ROOT SYSTEM	ROOTING DEPTH (CM)	LAT. ROOT SPREADING (CM)
Carrot	Apiaceae	Root	90-120	$40.01^{\pm 19.99}$	Upright	Taproot	$115.19^{\pm 69.23}$	$95.38^{\pm 54.87}$
Onion chive	Alliaceae	Bulb	70	$36.00^{\pm 17.00}$	Upright	Fasciculated	$50.39^{\pm 26.75}$	$71.86^{\pm 23.66}$
Dwarf bean	Fabaceae	Fruit	70	$43.97^{\pm 9.42}$	Bush	Taproot	$76.82^{\pm 25.66}$	$124.11^{\pm 22.48}$
Lettuce	Asteraceae	Leaf	30-60	$32.00^{\pm 14.63}$	Rosette	Taproot	$96.00^{\pm 56.00}$	$77.45^{\pm 46.29}$

Table 9 - Measurements performed during the 2019 and 2020 participatory trials

MEASUREMENT	TOOL(S)	2019	2020	FREQUENCY	LINKED VARIABLE(S)
Canopy pictures	RGB camera	X		Every fortnight	Soil coverage
	Multispectral camera		X	Every week	Soil coverage
Profile pictures	RGB camera	X		Every fortnight	Crop height
Crop height	Ruler	X		Every fortnight	Crop height
	Ruler		X	Every week	Crop height
Number of leaves of crops	Manual counting		X	Every week	Number of leaves
Lettuce diameter	Ruler		X	Every week	Diameter
Harvested weight	Weighing scale	X	X	Once, at harvest	Adjusted yield, mean weight
	Weighing scale	X	X	Once, at harvest	Actual yield
Pictures of vegetables at harvest	RGB camera	X	X	Once, at harvest	Vegetable size

8.2.2. GROWTH MONITORING

During the 2019 trial, the growth of the crops was monitored with two techniques. Firstly, two side pictures of the profile of each repetition of each modality were captured every two weeks in each site, one at each side of the plot. A meter was placed vertically in the camera field of vision, with the "0" corresponding to the ground. The resulting pictures were analysed manually (using Image J) and the height of each plant whose top was visible on the picture was measured. This was done for the two species. Secondly, we measured manually every fortnight the height of the highest leaf of three onion plants selected randomly in each repetition of each modality in each site. The same three plants were measured during the whole trial, unless they died due to pests. No such measurement was done for carrots.

As the method of the profile pictures lacked accuracy, we decided, for the 2020 trial, to conduct manual measurements of the height, diameter – for lettuces only – and number of leaves of the crops. These measurements were done every week on three lettuces and three dwarf bean plants in each repetition of each modality in each site. The measured plants were randomly selected at the beginning of the trial and remained the same for the whole season.

8.2.3. SOIL COVERAGE & LIGHT INTERCEPTION

For the 2019 trial, the acquisition of the soil coverage and light interception data was done in the same way as described in Chapter 3, except that (i) the ceptometer was not used and the estimation of iPAR was therefore based only on soil coverage, (ii) two pictures were taken for each repetition of each modality in each site at each passage and (iii) the pictures were taken every fortnight instead of every week.

For the 2020 trial, the acquisition of the soil coverage and light interception data was done in the same way as described in Chapter 4. However, instead of capturing one set of eight pictures, we captured two sets of eight pictures for each repetition, modality and site at each passage, resulting in 2263 sets of eight pictures collected during the 2020 participatory trial (cf. Appendix I).

In the participatory trials, the estimation of the cumulative iPAR was done for every day, repetition and modality in each site using the average of the data from the two to three nearest weather stations from the Pameseb[19] network. The variables derived from this data and used in the participatory trials are listed hereunder:

- Evolution of the percentage of soil coverage for the plot (2019, 2020) and for each crop (2020);
- Cumulative amount of photosynthetically active radiation intercepted (iPAR) by the plot (2019, 2020) and by each crop (2020);
- Radiation use efficiency based on fresh weight (RUE_{fw}) for the plot (2019, 2020) and for each crop (2020).

Neither the cumulative intercepted PAR expressed as a percentage of the incident radiation nor the energy share were calculated for the participatory trials.

8.2.4. Vegetable size

Once the crops were mature, we collected some plants in each repetition of each modality in each site. In 2019, we picked up ten carrots and ten bunches of onions in each plot whereas in 2020 we sampled six lettuces and the fruits from ten bean plants in each plot. Carrots and onions were collected at the same date whereas lettuces and beans samples were harvested on average 30 days apart. These plants were weighed in order to get the mean weight per plant – or per fruit for the beans – in each plot. We also took pictures of the collected plants and analysed these pictures with ImageJ to extract the area – or the bulb diameter for onions – of each one of the vegetables. This gave us an approximation of the size of the vegetables. Pictures of bean fruits were not taken.

[19] Pameseb is a Belgian nonprofit organisation dedicated to the promotion of agrometeorology. It owns a network of 30 weather stations in Wallonia, whose data are used to advice farmers about integrated pest management and irrigation (https://www.pameseb.be/).

8.2.5. YIELD DATA

The biomass yield was calculated as explained in Chapter 7 (cf. 7.2.5). Two types of yield were estimated: the "actual yield" and the "adjusted yield".

The actual yield will be used for the 2020 trial, as it allows to take into account the successive harvests of bean plants. On average, the bean harvest started 24 days after the beginning of the lettuce harvest and ended 51 days after the end of it. The lettuce harvest was spread over an average of 22 days while the one of beans was spread over an average of 49 days. For the 2019 trial, since the actual yield was largely variable and influenced by successive sowing of carrots, which happened at different times in the different sites to correct for the low germination of carrots, we decided to focus only on the adjusted yield. In order to facilitate the reading, the term "Yield" will be used in the subsequent sections, although it represents the adjusted yield for the 2019 trial and the actual yield for the 2020 trial.

By default, the yields and the densities are expressed based on the area of the whole plot rather than on the area of the plot allocated to each crop. Also, the total biomass yield is considered rather than the marketable yield for all crops except for beans, for which only the fruits have been harvested and weighed. The total biomass yield of lettuces and onion chives is equal to their marketable yield, as it is the whole plant that is sold for these crops.

8.2.6. DATA PROCESSING AND STATISTICAL ANALYSIS

As the trials were in open-field and organised within a participatory approach, we faced various problems that forced us to remove some sites from the data to ensure a proper analysis. More information about this is available is Chapter 7. Our final sets of data included sites 02, 05, 08, 09, 10, 11, 12 and 13 for the 2019 trial and sites 02, 03, 04, 05, 07, 08, 10 and 11 for the 2020 trial.

As the temporal trends of height and soil coverage were too variable to be properly analysed using a linear regression, we decided to analyse the time-series data of height (2019 only) and soil coverage (2019, 2020), by simplifying them using a ranking method. We assigned, for each measurement date, site and repetition, a rank to each modality according to its mean value. The modality with the highest value was attributed the rank "1" whereas the one with the lowest value was attributed the rank "4". We then compiled this information in a contingency table, for which we assessed

the independence between rows – the modalities – and columns – the ranks – using a Chi-Square test.

The punctual data, i.e. yield data, total amount of intercepted PAR across the season, vegetable size and mean weight per plant, were analysed using a linear mixed model, with "Modality" as a fixed factor and "Site" as a random factor. The data of both crops in each intercrop were analysed separately.

In 2020, the time-series data of diameter, number of leaves and height were analysed through a linear mixed model with "Modality" and "Days after sowing/plantation" as fixed factors and "Site" as random factor. The punctual data, i.e. yield data, vegetable size, mean weight per plant/fruit, were analysed through a linear mixed model with "Modality" as fixed factor and "Site" as random factor. The data of both crops were analysed separately.

All statistical analyses were performed in R v.3.4.1 with the *lmer* and *anova* functions for the linear mixed models, the *contrast* function to perform custom mean comparisons, the *emmeans* function to perform other mean comparisons, and the *chisq.test* function for the analysis of the contingency tables.

8.3. RESULTS

The results of both trials are presented below, starting with the 2019 trial. Results are presented at two levels: firstly at the plot level, which aims at comparing the total quantity of biomass produced and the resources used by each modality and secondly at the crop level, whose objective is to compare the growth of each crop in the different modalities and to understand how the biomass produced was distributed between the component crops in the intercropping modalities.

8.3.1. 2019 TRIAL

8.3.1.1. Plot level

On the plot level, the most productive modality was the additive intercrop, on a par with the pure crop of onions (p-value=0.055). It was followed by the replacement intercrop and, in last position, the pure crop of carrots, whose yield was significantly lower than that of all other modalities (p-values: <0.001) (Figure 42). The yield of the additive intercrop was significantly lower than expected based on the density, i.e. lower than the sum of the yields of

both pure crops (p-value=0.043), whereas the replacement intercropping yielded as expected (p-value=0.93). The responses of each intercrop to the density – biomass production as expected in the replacement intercrop, lower than expected in the additive intercrop – suggests that the saturation, i.e. the level at which increasing further the density only provides a marginal gain in yield, was reached at a density between those of the two intercrops. This result also indicates that the saturation was not yet attained at the densities of the pure crops.

The differences in biomass production between the intercropping modalities and the two pure crops should be linked to either a difference in the amount of resource removed or a difference in the efficiency of use of these resources. Our data allow us to explore these assumptions for light.

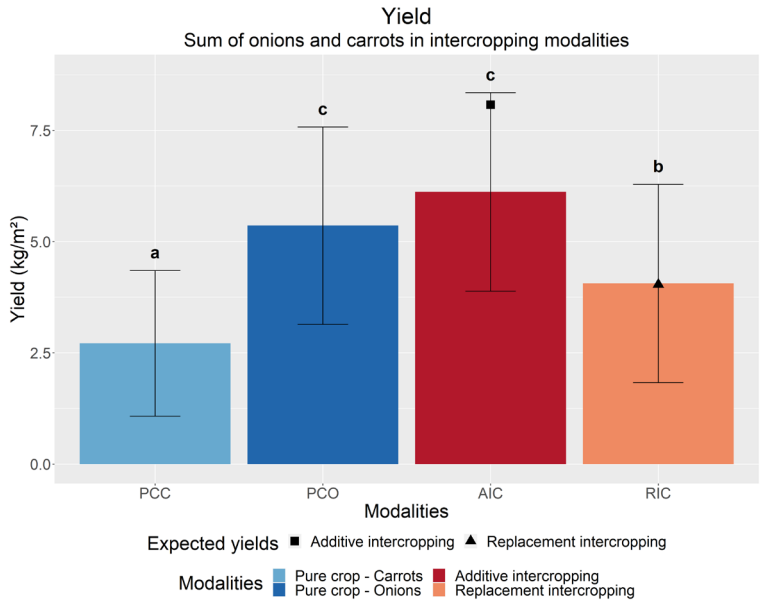


Figure 42 - Average yield for each modality of the 2019 participatory trial. Yields of carrots and onions are summed in the intercropping modalities. AIC=Additive intercropping, PCC=Pure crop of carrots, PCO=Pure crop of onions, RIC=Replacement intercropping.

Firstly, both intercrops produced significantly more biomass than the pure crop of carrots (p-values<0.001). As the biomass produced by a plant is proportional to the PAR it intercepts (Bai et al., 2016; Gallagher & Biscoe, 1978; Monteith et al., 1977), the intercrops should have intercepted more light than the pure crop of carrots. This was true for the additive intercrop (p-value<0.001, Figure 43) but not for the replacement intercrop (p-value=0.97, Figure 43). Moreover, the yield difference between the additive

intercrop and the pure crop of carrots (+126%) was higher than the difference in iPAR (+40.5%). Therefore, it seems that the intercropping modalities converted the intercepted radiation into biomass better than the pure crop of carrots. The RUE_{fw} of the intercrops was indeed equal in both intercrops (p-value=0.51) and significantly higher than that of the pure crop of carrots (p-values: <0.001 (additive), 0.001 (replacement), Figure 44A, C and D).

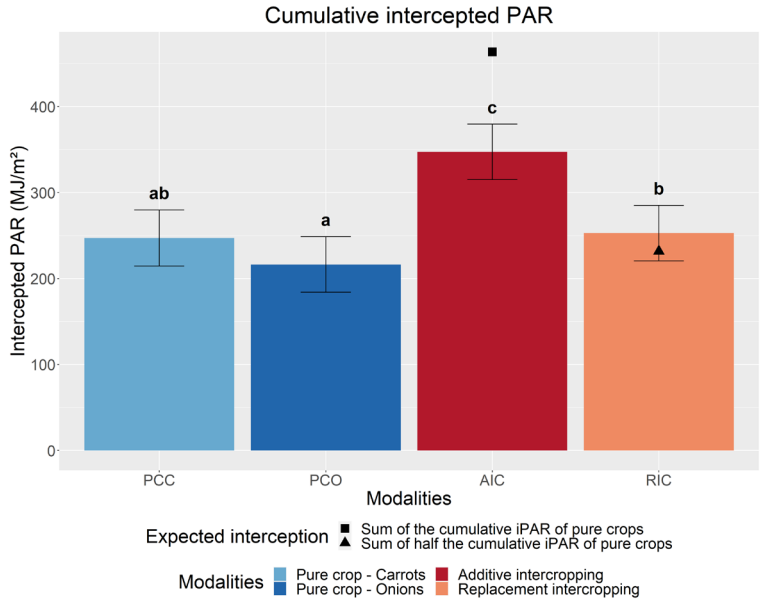


Figure 43 - Average cumulative amount of photosynthetically active radiation intercepted by each modality of the 2019 participatory trial, estimated based on the evolution of soil coverage. AIC=Additive intercropping, iPAR=Intercepted photosynthetically active radiation, PAR=Photosynthetically active radiation, PCC=Pure crop of carrots, PCO=Pure crop of onions, RIC=Replacement intercropping.

Secondly, the replacement intercrop, although it intercepted significantly more radiation (p-value<0.001), produced less biomass than the pure crop of onions (p-value<0.001). This can be explained by the significantly lower RUE_{fw} of the replacement intercrop compared to the pure crop of onions (p-value<0.001, Figure 44B and C). The same reasoning applies to the additive intercrop: it produced as much biomass as the pure crop of onions (p-value=0.055) while intercepting significantly more PAR (p-value<0.001) because of a significantly lower RUE_{fw} (p-value<0.001, Figure 44B and D).

These differences in RUE_{fw} between the intercrops and the pure crops seem quite expected when comparing the RUE_{fw} of the two pure crops. While intercepting roughly the same amount of PAR throughout the trial (p-

value=0.07), the pure crop of onions produced nearly twice as much biomass as the pure crop of carrots (p-value<0.001), meaning that onions were, in general, twice as efficient as carrots in converting intercepted radiation into biomass (p-value<0.001, Figure 44A and B).

As the light intercepted by an intercrop is distributed between its two component crops, it seems reasonable to assume that the intercrop would convert the intercepted radiation less well than the pure crop with the highest RUE_{fw} but better than the pure crop with the lowest RUE_{fw}. In our trial, the mean of the $RUEs_{fw}$ of the pure crops was not significantly different from the average $RUEs_{fw}$ of the intercrops (p-values: 0.13 (replacement intercropping), 0.95 (additive intercropping)), which would suggest that the differences of RUE_{fw} between the intercrops and the pure crops were in fact the result of intrinsic differences between the two crops rather than linked to a real effect of intercropping.

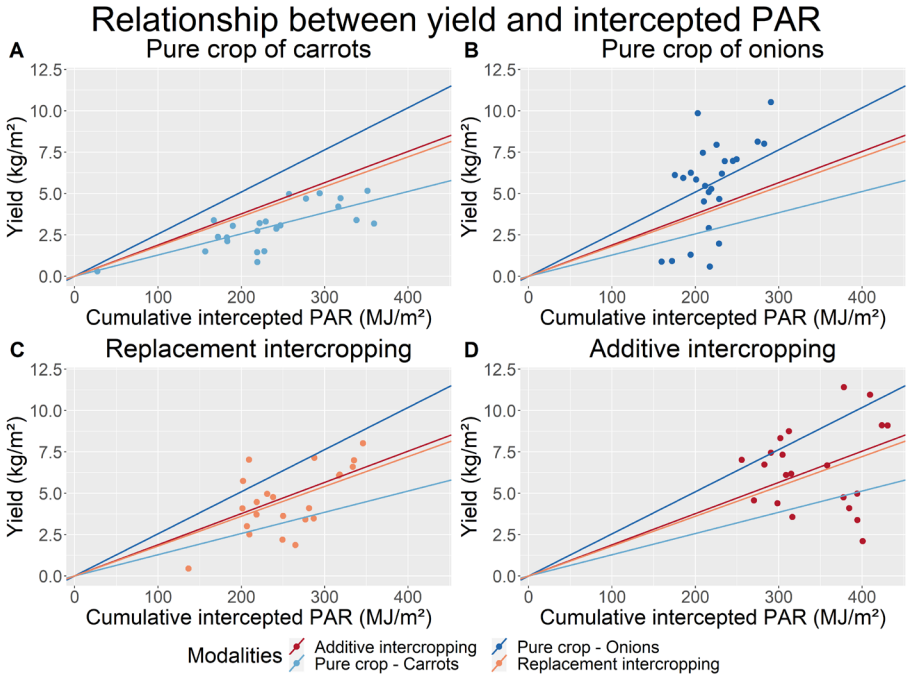


Figure 44 - Relationship between the yield and the cumulative amount of photosynthetically active radiation intercepted throughout the 2019 participatory trial for the pure crop of carrots (A), the pure crop of onions (B), the replacement intercrop (C) and the additive intercrop (D). Each point represent one repetition in one site. Linear regressions were obtained using a linear model with the interaction between cumulative intercepted PAR and modality as fixed factors. Regressions were forced by (0,0). The large vertical distribution of the points in (B) is probably due to an overestimation of the soil coverage – and hence of the cumulative intercepted PAR – in some plots of onion pure crop. PAR=Photosynthetically active radiation.

The difference in RUE_{fw} between carrots and onion chives may either come from the leaf angle of onions that allow the intensity of intercepted PAR to be closer to the optimum or from an overestimation of the soil coverage of carrots, and hence an overestimation of iPAR, due to their leaf indentation, which was not considered in the soil coverage estimation. In the latter case, the same error should apply for the intercropping modalities. It should therefore not influence greatly our conclusions regarding the differences in RUE_{fw} between intercrops and pure crops.

8.3.1.2. Crop level

The analysis at the plot level revealed that the intercropping modalities intercepted either as much or more radiation than the corresponding pure crops and that their efficiency in converting this radiation into biomass was intermediate to that of the pure crops. This second part will focus on how the produced biomass was distributed between crops.

The yields of carrots and onions in the replacement intercrop were roughly equal to half their yields in pure crop (p-values: 0.45 (carrots), 0.86 (onions), Figure 45), which was expected based on their density in the replacement intercrop. This indicates that neither carrots nor onions were affected by the presence of the other crop and that each crop in the replacement intercropping could be considered as a pure crop at half-density.

On the opposite, in the additive intercrop, both crops yielded less than in pure crops (p-values: <0.001 (carrots), <0.001 (onions)) although each crop was at the same density in pure crop and in additive intercropping. This yield loss was greater for carrots (-38.2%) than for onions (-21.5%) and resulted, for both crops, from a reduction in the mean weight per plant (-39.1%, p-value<0.001 (carrots), -21.5%, p-value<0.001 (onions), data not shown). The carrot weight decrease arose from a reduction in root length (-20.6%, p-value<0.001, data not shown) and a reduction in root diameter (-10.3%, p-value=0.015, data not shown). Conversely, no difference in onion bulb diameter was observed between the additive intercrop and the pure crop (p-value=0.54, data not shown) and we assume that the decrease in onion mean weight was linked to a decrease in leaf biomass. However, no difference of onion shoot height was observed between modalities (p-value=0.98, data not shown). On the opposite, carrot shoots were significantly taller in the additive intercrop than in the other two modalities (p-value=0.003, data not shown).

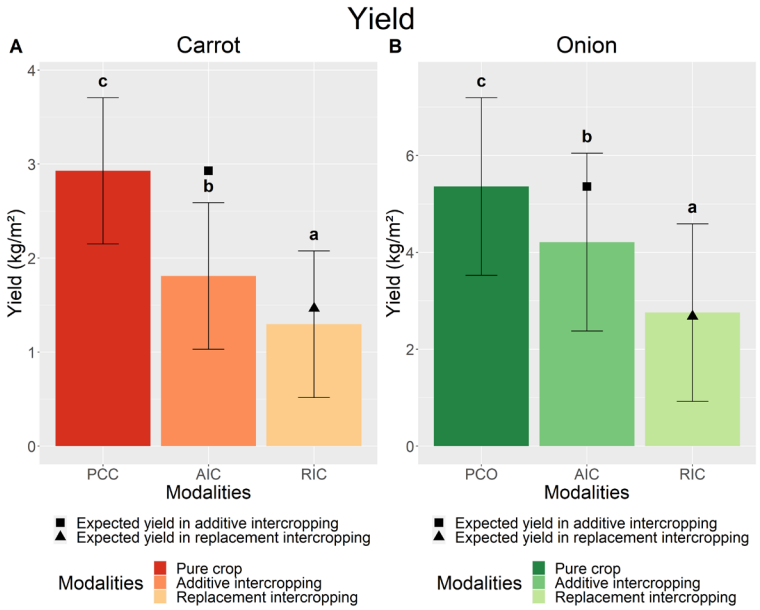


Figure 45 - Average yield per modality for carrots (A) and onions (B). PCC=Pure crop of carrots, PCO=Pure crop of onions, RIC=Replacement intercropping, AIC=Additive intercropping.

The yield decrease of both crops in the additive intercrop suggests that although the additive intercrop probably took more resources than the corresponding pure crops, as was shown for light (cf. 8.3.1.1), each plant of the additive intercrop removed fewer resources than in the corresponding pure crop, i.e. plants competed for some resources, with carrots removing even less resources, compared to its pure crop, than onions.

The data presented so far allow us to formulate assumptions regarding the resources for which crops competed in the additive intercrop. On the one hand, onions produced less leaf biomass than in pure crop. Besides, they were taller than carrots and dominated the canopy. Based on this data, we can assume that onions intercepted as much radiation as in pure crop: carrots did not shade them and a light-limitation should probably have resulted in an increase in shoot height to avoid shading. This suggests that their growth was limited by a soil resource, for which carrots were probably more competitive thanks to their more extensive root system (Table 8). Data regarding root biomass of onions would have been useful to further confirm the hypothesis of soil resource limitation for onions. On the other hand, carrots had taller shoots but smaller roots in the additive intercrop compared to the pure crop. This reduction in the root/shoot ratio assumes that carrot growth was limited by radiation (Callaway et al., 2003; Ericsson, 1995;

Kasperbauer & Karlen, 1986; Snaydon, 1996), which is consistent with carrots being shaded by onions and with the increase in the height of carrot shoots – considered as a usual shade-avoidance reaction (Ballaré, 1999; Holmes & Smith, 1975; Pierik et al., 2012; Smith, 2000) – in the additive intercrop.

8.3.2. 2020 TRIAL

8.3.2.1. Plot level

In the 2020 trial, the most productive modality was the intercrop (Figure 46), which produced significantly more biomass than the pure crop of lettuces (p-value=0.001) and the pure crop of beans (p-value<0.001). It was not significantly less productive than what was expected based on the density (p-value=0.62). It was therefore a case of transgressive overyield (Trenbath, 1974), i.e. the intercrop produced more biomass than the pure crop of lettuces. As for the 2019 trial, the higher biomass production of the intercropping modality should be explained by either a higher amount of resources removed or by a higher efficiency in the use of resources. Again, our data allow us to explore these hypotheses for radiation resource.

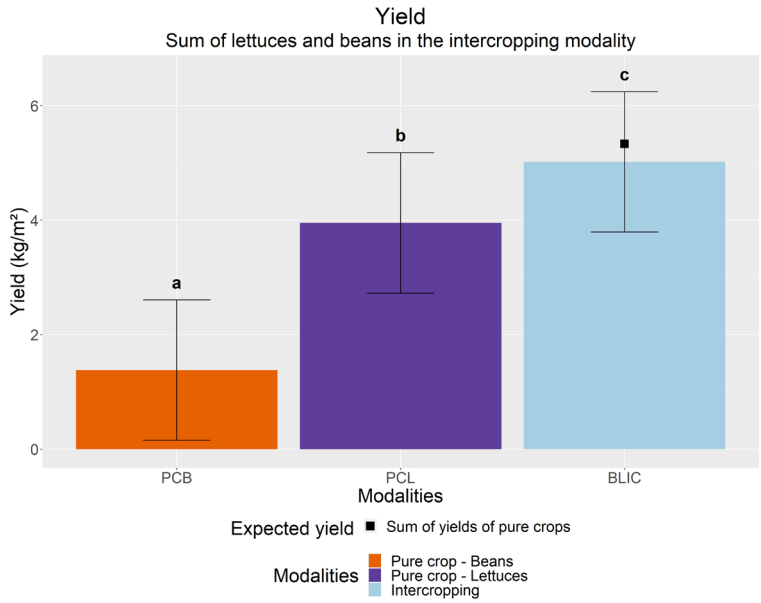


Figure 46 - Average yield for each modality of the 2020 participatory trial. Yields of beans and lettuces are summed in the intercropping modalities. BLIC=lettuce + dwarf bean intercrop, PCB=Pure crop of beans, PCL=Pure crop of lettuces.

The lettuce + dwarf bean intercrop intercepted significantly more radiation than the pure crop of lettuces (p-value<0.001, Figure 47), which is consistent with the fact that it produced more biomass (Figure 46). However, the intercrop was less efficient at converting this radiation into biomass (p-value<0.001): it produced 27% more biomass while intercepting 126% more light. The increased light interception in intercrop occurred therefore with a lower RUE_{fw} (Figure 48).

On the opposite, while the intercrop intercepted as much radiation as the pure crop of beans (p-value=0.68, Figure 47), it produced significantly more biomass (+264%, Figure 46). The intercrop therefore had a much more efficient use of radiation than the pure crop of beans (p-value=0.00, Figure 48).

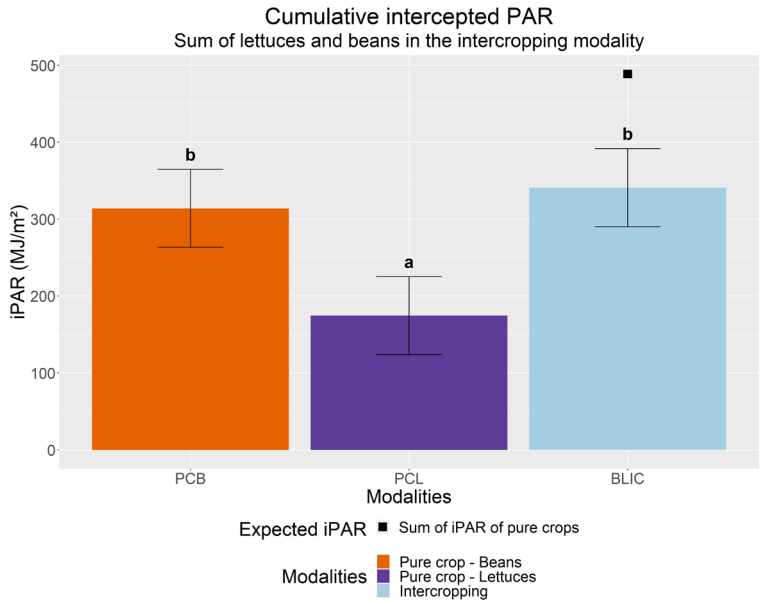


Figure 47 - Average cumulative amount of photosynthetically active radiation intercepted by each modality of the 2020 participatory trial, estimated based on the evolution of soil coverage. BLIC=lettuce + dwarf bean intercrop, PCB=Pure crop of beans, PCL=Pure crop of lettuces.

Similar to what we observed in 2019, the RUE_{fw} of the intercrop was intermediate between those of the pure crops (Figure 48) and not significantly different from the mean of the $RUEs_{fw}$ of the pure crops (p-value>0.05).

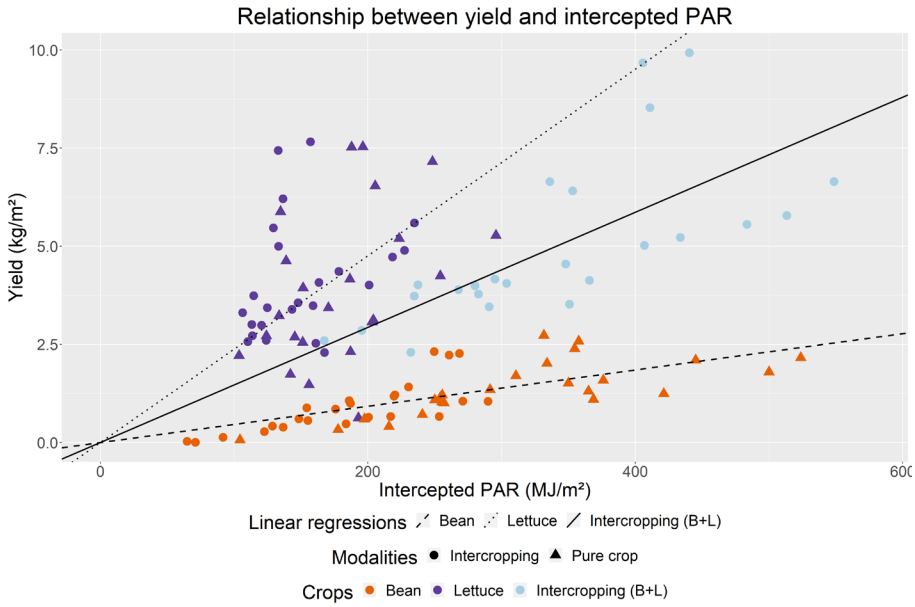


Figure 48 - Relationship between the yield and the cumulative amount of photosynthetically active radiation intercepted throughout the 2020 participatory trial. Each point represent one repetition in one site. Linear regressions were forced by (0,0) and obtained using a linear model with the interaction between the crop (either bean, lettuce or the intercrop) and the intercepted PAR as fixed factor. B=Bean, L=Lettuce, PAR=Photosynthetically active radiation.

8.3.2.2. Crop level

The plot level analysis revealed that the intercrop produced significantly more biomass and intercepted at least as much radiation as any of the corresponding pure crops. The crop level analysis will focus on the distribution of the produced biomass between the component crops of the intercrop, i.e. dwarf beans and lettuces.

Based on the results at the plot level (Figure 46, cf. 8.3.2.1), one might expect that the biomass of each crop in the intercropping modality was not significantly different from its biomass in pure crop. This turned out to be the case for lettuces (Figure 49B): their yield in intercropping was not significantly different from their yield in pure crop (p-value=0.51). On the opposite, the yield of beans was 35.5% lower in the intercrop than in the pure crop (p-value<0.001, Figure 49A). Interestingly, the yield difference between

beans in pure crop and in intercrop decreased between the first and the last harvest, which suggests that beans took advantage of being alone after the harvest of lettuces and were able to recover for part of their yield loss during this time, i.e. compensatory growth (e.g. Awal et al., 2006; Huang et al., 2017; Zhang et al., 2017). The difference was however not significant (p-value=0.081).

The difference between the results per crop and the global results is likely explained by the fact that the yield of the lettuce was about five times higher than the yield of beans and that the yield of lettuces was higher, although not significantly, in intercropping than in pure crop. Accordingly, the significant difference for bean yield between intercropping and pure crop was masked by the large share of lettuces in the intercrop.

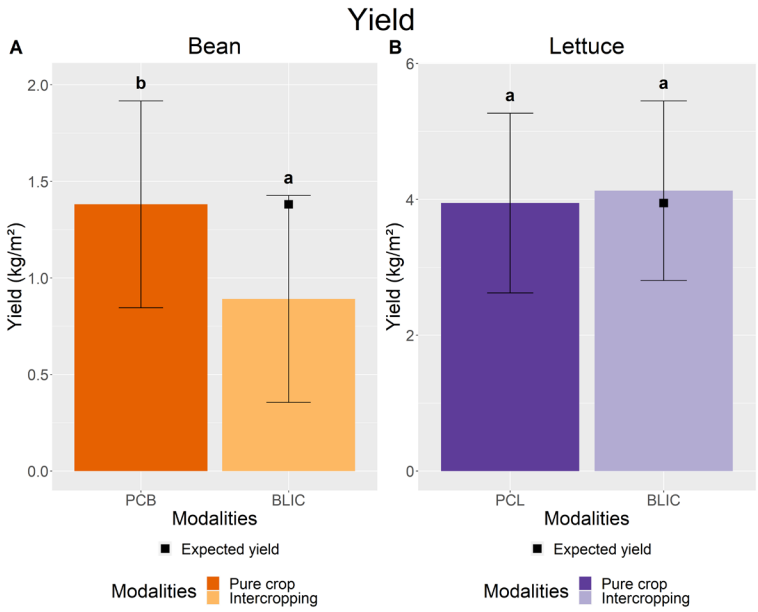


Figure 49 - Average yield for beans (A) and lettuces (B) in each modality. BLIC=Lettuce + dwarf bean intercrop, PCB=Pure crop of beans, PCL=Pure crop of lettuces.

The decrease in bean yield in intercropping resulted from a reduction in the mean weight of the bean fruits (p-value<0.001, data not shown) and a reduction in the number of fruits harvested on each plant (p-value<0.001, data not shown). The shoots of beans in the intercropping modality were also significantly smaller (p-value<0.001, Figure 50A) and had significantly fewer leaves (p-value<0.001, Figure 50B) than in the pure crop. The response of beans to the intercrop was therefore a general manifestation of growth reduction.

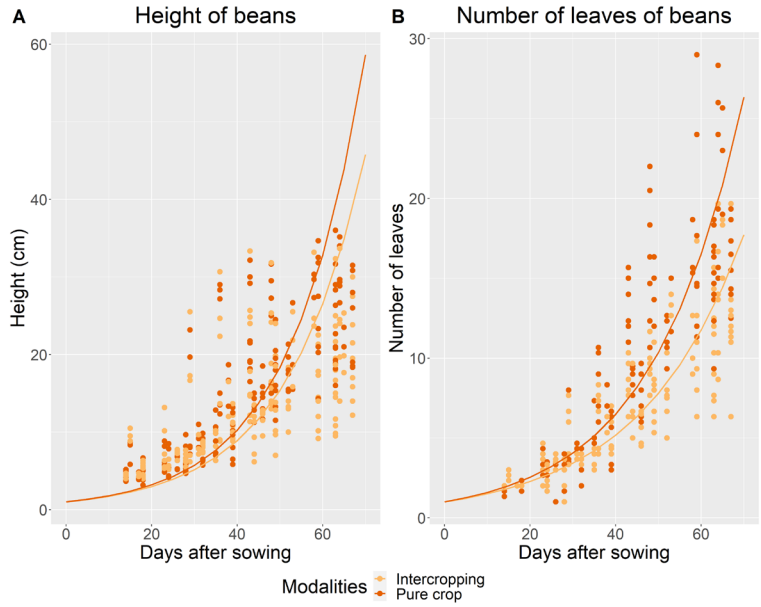


Figure 50 - Evolution of the height (A) and the number of leaves (B) of beans in each modality in the 2020 participatory trial. Regressions were obtained using a linear model with the interaction between modality and days after sowing as fixed factor. Adjusted R^2: 0.951 (height), 0.973 (number of leaves).

The results of yield, growth and mean weight per plant show that there was an uneven share of resources between the component crops in the intercropping modality, in favour of the lettuces.

If we decompose the light intercepted by the whole plot (Figure 47, cf. 8.3.2.1) into that intercepted by each component crop (Figure 51), the pattern remains the same as for yield: lettuces intercepted as much radiation in intercropping as in pure crop (p-value=0.80) whereas beans intercepted 40% less radiation in intercropping than in pure crop (p-value<0.001). Both crops had the same RUE_{fw} in intercrop and in pure crop (pvalues: 1.00 (beans), 0.084 (lettuces), Figure 48). The loss of iPAR of beans was consistent with their yield loss (35.5%) and suggests that the presence of lettuces prevented beans from intercepting as much radiation as in pure crop, causing their yield reduction in the intercrop.

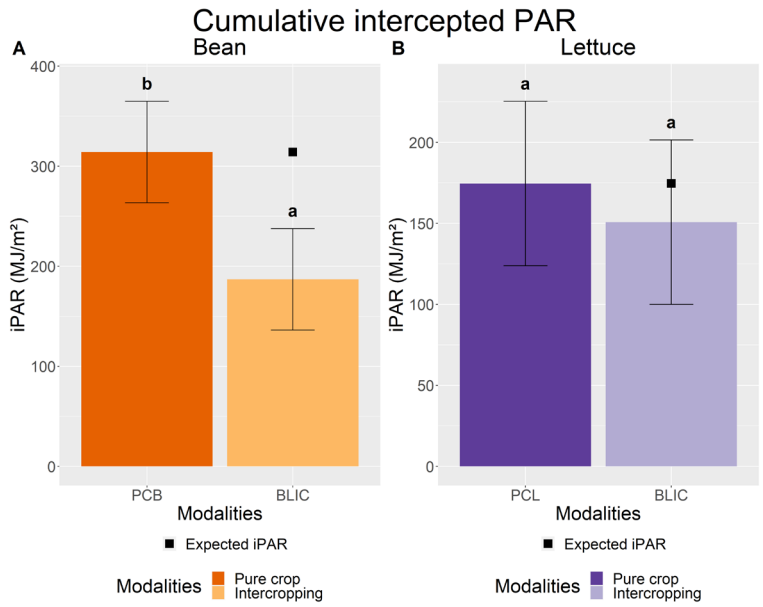


Figure 51 - Cumulative photosynthetic active radiation intercepted on average, during the whole season, by lettuces and beans in each modality of the 2020 participatory trial. iPAR=Intercepted photosynthetically active radiation.

As the lettuces were planted before the sowing of beans, it is not surprising that they occupied the aerial strata first. However, one could have thought that, given the rosette architecture of the lettuces, the beans would have been able to grow above them and would not have been hindered by the presence of lettuces for their interception of light. Moreover, the usual shade-avoidance response, i.e. an increase in shoot height, was not observed for beans in this case (Figure 50A). Therefore, it might be that the decrease in radiation interception by beans was not directly caused by the shading of lettuces but was the result of a decreased growth caused by another limitation.

One plausible limitation explaining this particular response of beans might be the existence of competition for nitrate between lettuces and beans that was revealed in Chapter 7 (Figure 52). Nitrate is a key nutrient for both lettuces, which are known to accumulate high quantity of nitrate in their leaves (Anjana & Iqbal, 2007; Maynard et al., 1976; Santamaria et al., 1999) and dwarf beans, whose atmospheric nitrogen fixation is poorly effective (Graham, 1981; Graham & Rosas, 1977; Hardarson et al., 1993; Larue & Patterson, 1981; Wilker et al., 2019) and only effective after flowering (Peña-Cabriales et al., 1993; Service Culture & Conserves du Blaisois, 2013). It seems therefore likely that these two crops would compete for soil nitrate, even

more in the context of a low-nitrate soil. Besides, various studies focusing on the accumulation of nitrate in lettuce leaves show a steep increase of the nitrate content in lettuces at the beginning of their growth followed by either its decrease (dilution effect) or its stagnation (Broadley et al., 2003; Burns et al., 2011; Dapoigny et al., 1996), which suggests that lettuces absorb nitrate early in their cycle.

Following this hypothesis, the competition for nitrate would have reduced bean growth at all sites, causing the decrease in iPAR and biomass production overall. The decrease was pushed to a further extent in sites with a lower initial nitrate concentration (i.e. 03, 05 and 10), in which the RUE_{fw} of beans in intercrop was lower than in the other sites (i.e. 02, 04, 07 and 11).

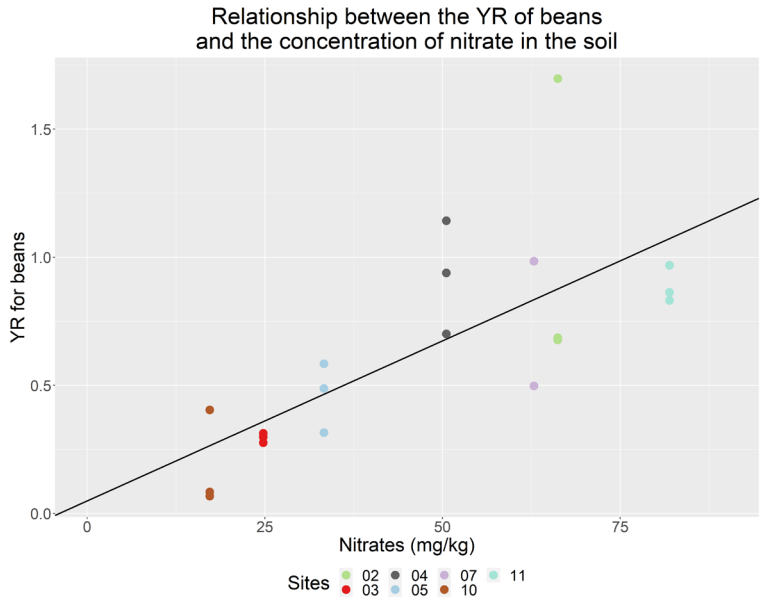


Figure 52 - Relationship between the concentration of nitrate in the soil of the different sites of the 2020 participatory trial and the YR of beans. Nitrate concentration is expressed by kilogram of dry soil. Each point represents one repetition in one site. Linear regression was obtained using a linear model with nitrate concentration as fixed factor.Adjusted R^2=0.497. YR=Yield ratio.

8.4. Discussion

In 2019, the replacement intercrop yielded as expected and both onions and carrots produced as much biomass as if they were in a pure crop at half-density. However, in the additive intercrop, both crops produced less biomass than their corresponding pure crops despite being planted at the same density. Based on the available data, we can make the assumption that

this reduction in the yield manifested itself by a decrease in the leaf biomass for onions and in the root size for carrots. This observation, in addition to the dominance of the canopy by the onions and the higher carrot shoots in the additive intercrop than in pure crop, suggests that onion growth was limited by a soil resource whereas light availability limited carrot growth. In 2020, only the bean yield was affected by the intercrop: beans were smaller, produced fewer leaves and fruits and their fruits were lighter in the additive intercrop than in pure crop. We observed a decrease in the amount of PAR intercepted by beans in the intercrop compared to the pure crop and a high correlation between the concentration in nitrate in the soil and the yield ratio of beans, suggesting a competition for both light and nitrate between lettuces and beans.

The variables measured in these participatory trials may seem insufficient to depict the complex relationships between crops in intercropping. Their primary goal was in fact to investigate the yield variability in intercropping compared to the corresponding pure crops in different environmental contexts (cf. Chapter 7) rather that to explore resource sharing. Moreover, we were constrained in our choice of measurements by the participatory aspect of the trials (cf. Chapter 6 and Chapter 7). The measurements we took allowed nonetheless to get a better understanding of the interactions between crops in the three intercrops we studied. Furthermore, the analysis performed in this chapter shows that it is possible to explore physiological issues based on the data collected during participatory on-farm trials. Our results go even further by proving that this set-up was more than relevant: the differences between the sites enabled us to identify the importance of nitrate in the lettuce + dwarf bean intercrop, would otherwise have gone unnoticed.

8.4.1. Resource sharing between associated crops

On the basis of light-related measurements, we were able to identify a pattern of resource uptake between the component crops of the two additive intercrops we studied. There was some asymmetry in resource sharing in both intercrops, as, on average, onion chives and lettuces lost less yield than carrots and dwarf beans respectively. Despite this aspect, their results were quite different. On the one hand, carrots and onion chives were both impacted by being in an intercrop and the asymmetry between their yield losses was relatively low. This suggests that there was, in this intercrop, some form of symmetric competition. On the other hand, in the lettuce +

dwarf bean intercrop, only dwarf beans were impacted by being intercropped. Lettuces were dominant and prevented dwarf beans from acquiring both enough light and enough nitrate, resulting in low bean yield, particularly in sites with lower initial nitrate concentration in the soil.

Interestingly, the fact that intercropping lettuces and dwarf beans impeded the growth of beans while allowing a normal growth of lettuces was observed at all sites in the 2020 trial. This suggests that it was more the characteristics of the trials (e.g. planting distances, sowing date) and/or the architectural and physiological features of the two mixed crops than the context, i.e. environment and crop management, in which they were intercropped that determined the balance of resource uptake by the two associated crops. A slightly lower consistency was observed for the carrot + onion chive intercrop: five out of the eight sites had higher yield loss for carrots than for onions whereas it was the opposite for the three remaining sites. As carrots and onions were co-dominant, it seems likely that a slight change could tip the balance one way or the other.

Finally, it is worth noting that the patterns of resource sharing in the two additive intercrops were consistent with our findings from Chapter 5. On the one hand, the carrot + onion chive intercrop consisted of two crops with similar growth dynamics – at least in our trial, as carrots and onions were harvested at the same time – and similar maximum soil coverage. As was the case for this type of intercrops in Chapter 5, the two crops developed at the same pace and prevented one another from reaching their expected yield, although none of them dominated completely the mixture. On the other hand, the lettuce + dwarf bean intercrop appears similar to the intercrops between dwarf bean and broccoli, kale, collard cabbage or fennel from Chapter 5: a crop with a faster development was implemented first, developed as if it was in pure crop and dominated the mixture, resulting in yield loss of its companion crop. However, in the participatory on-farm trial, the dwarf bean was the dominated crop rather than the dominant one.

Despite having major differences in their resource sharing pattern, the two additive intercrops had similar land equivalent ratios (LER) and were both advisable for market gardeners on a biomass production point of view, as shown in Chapter 7. The analysis we have done in the present chapter reminds the importance of dissecting the results of an intercrop into the results of its component crops, as two intercrops with the same LER may not respond to the same objective.

8.4.2. Resource uptake, resource use efficiency and complementarity

It is interesting to notice that the lettuce + dwarf bean intercrop did not seem to benefit from the theoretical nutritive complementarity that can exist between a legume and a non-legume (Bedoussac et al., 2015; Corre-Hellou et al., 2006; Jensen, 1996b; Malézieux et al., 2009; Martin & Snaydon, 1982; Trenbath, 1976). Based on various results about legume-cereal intercrops (e.g. Andersen et al., 2007; Azam-Ali et al., 1990; Bedoussac & Justes, 2010a; Corre-Hellou et al., 2006; Henrik Hauggaard-Nielsen et al., 2008; Jensen, 1996b; Trenbath, 1976), both the higher competitive capacity of lettuces – resulting from their earlier establishment compared to beans (Andersen et al., 2007; Harris, 1967) and their deep and fast-growing (Weaver and Burner 1927) root system (Andersen et al., 2007; Hauggaard-Nielsen et al., 2001; Trenbath, 1974) – and the low concentration of nitrate in the soil in sites 03, 05 and 10 should have promoted the fixation of atmospheric nitrogen of beans, by such reducing their yield loss. However, beans are known to be poor fixators (Graham, 1981; Graham & Rosas, 1977; Hardarson et al., 1993; Larue & Patterson, 1981; Wilker et al., 2019) and their atmospheric nitrogen fixation is only efficient from the flowering phase (Peña-Cabriales et al., 1993; Service Culture & Conserves du Blaisois, 2013). Beans should therefore have relied on soil nitrogen for the beginning of their growth cycle (Peña-Cabriales et al., 1993) – as was observed for peas by Mahon & Child (1979) – and competed with lettuces. Moreover, the competition for light between lettuces and beans, to the disadvantage of the beans, may have reduced their nitrogen fixation due to partial shade (Lawn & Brun, 1974).

In the introduction (cf. 8.1), we developed the idea that the complementarity between associated crops should allow intercrops to produce more biomass than the corresponding pure crops by increasing the use efficiency of resources (Malézieux et al., 2009; Reddy & Willey, 1981; Willey, 1990) and/or by giving access to the crops to a bigger pool of resources (Keating & Carberry, 1993; Midmore, 1993; Natarajan & Willey, 1980a; Willey, 1990; Willey & Osiru, 1972). Our measurements allow us to explore these hypotheses for light. Regarding the use efficiency of resources, it is, according to us, difficult to be conclusive. In both additive intercrops, the RUE_{fw} was intermediate to that of the corresponding pure crops. Consequently, the intercrops used the light better than one of the pure crop and less well than the other. The dissection of the intercrop RUE_{fw} into the RUE_{fw}s of the two crops in 2020 showed, nonetheless, that both crops

converted the radiation into biomass as efficiently in intercrop than in pure crop. An effect of intercropping on resource efficiency seems therefore unlikely, at least for the 2020 trial. Regarding the amount of resources taken, the lettuce + dwarf bean intercrop only intercepted significantly more radiation than one of the two pure crops. Favouring the temporal complementarity between crops is usually presented as a way of maximising light interception (Awal et al., 2006; Keating & Carberry, 1993; Liebman & Dyck, 1993; Natarajan & Willey, 1985; Willey, 1990; Zhang et al., 2008). In our case, however, the domination of lettuces over beans has reduced the light interception of the latter too much for this effect to be manifested. The interception of light by the additive intercrop was nevertheless higher than in the pure crops of lettuces. On the opposite, we observed that associating carrots and onion chives in an additive design allowed to intercept significantly more radiation than the two corresponding pure crops, therefore verifying the second hypothesis for the 2019 trial.

Regarding competition for resources, our starting hypotheses regarding the competitive interactions between the associated crops were that (i) carrots and onions should compete for light due to poor shoot spatial complementarity and (ii) lettuces and dwarf beans should compete for soil resources due to poor root spatial complementarity. Our results suggest that the first hypothesis was true. In the carrot + onion additive intercrop, the decrease in root size of carrots and the increase in their shoot height indeed indicate a competition for light between the crops. However, the decrease in onion mean weight per plant while they dominated the canopy suggests that there was also a competition for soil resources. We would have anticipated the differences in root architecture between crops to lead to a good complementarity rather than to competition. Nevertheless, the more extended root system of carrots compared to onions probably gave them a better competitive ability for soil resources, as was observed by Egbe et al. (2010) in a maize + cowpea intercrop. This result also reminds that more than root depth, it is the distribution and activity of roots according to the depth that should be taken into account, as a crop may have a very deep root sytem while still having the majority of its laterals in the top ten centimeters of the soil (Barron-Gafford et al., 2017; Gao et al., 2010; Schroth, 1998; Smith et al., 1999; Van Noordwijk et al., 2015). The second hypothesis also proved to be true. In the lettuce + dwarf bean intercrop, we showed that there was mainly a competition for belowground resources – most probably for nitrate – between the crops. This competition led to a decrease in light interception

by dwarf bean, which was linked to a growth decrease of beans caused by the competition for soil resources rather than to a competition for light. This result was expected based on the architecture of the crops, lettuces and dwarf beans having different shoot architecture but similar root architecture.

To further analyse the ability to predict the resource sharing between associated crops based on their architectural and physiological characteristics, it would be interesting to repeat the trials (i) over several years and/or (ii) in sites with more constrated climatic conditions – rainfall, temperature, incident radiation – than those on which we carried out the trials. Many studies (e.g. Huang et al., 2018; Olowe & Adeyemo, 2009; Wekesa et al., 2015) as well as the trials we perfomed in agricultural experiment station (cf. Chapter 5) showed the importance of growth dynamics in the interactions between associated crops. As the climatic conditions may influence the growth dynamics of crops, it would be interesting to see if the patterns of resources sharing that we observed and which held up on different soils and with different crop management practices is maintained across more diverse climatic conditions.

We cannot exclude that part of the increased resource removal in intercropping may be caused by a simple density effect. We believe that the increased light interception in the carrot + onion chive intercrop was linked, at least partially, to that. The yield results of the replacement intercrop allow us to state that there was, for both crops, a linear relationship of the yield and the density between the density used in the replacement intercrop and the density of the pure crop. Accordingly, there would still be some margin of available resources and an increase in density compared to the pure crops would increase the yield further, albeit at a reduced marginal gain. This is what we observed in the additive intercrop. It does not escape to our notice that, following this reasoning, it would be possible to find the ideal density of each intercrop, i.e. the density that would allow to use the available resources in the most efficient way. This finding also suggests that the densities used in pure crop were suboptimal, as already stated as an explanation for the increase in biomass production in intercropping by Trenbath (1976). Nevertheless, as market gardeners chose these densities, based on their experience and with a large consensus, it seems there should be some practical reasons for their use, e.g. ease of use of weeding tools.

The fact that the two additive intercrops intercepted more incident radiation than three out of the four pure crops leads us to assume that intercrops would in fact be better at using the available resources – not in the sense that they produced more biomass by using the same amount of resources but in the sense that they used a greater part of the available resources – and would therefore more fully exploit the productive potential of an environment. It would be interesting to verify that this increased take of available resources was also true for soil resources. If this was the case, it raises the question of resource depletion: by growing intercrops, will the soil be depleted faster? Some authors support this view (Li et al., 2014; Reddy & Willey, 1981; Willey, 1990). Nevertheless, the positive impact of intercropping on the abiotic environment (cf. Chapter 2), e.g. increase in soil carbon content (Duchene et al., 2017) and soil water storage (Callaway, 1995), could counterbalance this increased demand for resources. Further studies are needed to decide on this issue.

8.5. CONCLUSION

We monitored the growth of three different intercrops – two between carrots and onions chives, with different densities, one between dwarf beans and lettuces – and the corresponding pure crops on 11-14 sites, characterised by environmental and crop management practices differences, through a participatory approach. Our results show that both additive intercrops produced at least as much yield as the most productive pure crop, mainly thanks to the interception of higher amount of radiation. However, there was a different pattern of resource sharing between the component crops: in both intercrops, the share of resources between the associated crops was asymmetrical but this asymmetry was much higher in the lettuce + dwarf bean intercrop – in which only beans lost yield – than in the carrot + onion chive intercrop – in which both crops lost yield –. Besides, this pattern of resource sharing was maintained at nearly all sites in both trial, therefore emphasising the importance of planting arrangement and crop characteristics rather than environmental conditions and crop management practices in the determination of resource sharing in intercrop.

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* *

This chapter was dedicated to the analysis of resource sharing between associated crops in the three intercrops studied during the participatory on-farm trials.

The results of this analysis help advance scientific knowledge about intercropping. They highlight the differences in resource sharing between the carrot + onion and the lettuce + dwarf bean intercrops and show that these differences were partly expected based on the differences in root and shoot architectures between crops. In addition, the observed patterns were overall consistent (i) across the different sites in which the trials were set and (ii) with the variables identified as important in the determination of the outcome of an intercrop in Chapter 5. This suggests that is it possible to identify some general principles in intercropping, which could lead to a better prediction of their results and to the design of better guidelines to help select crop associations that meet the desired objectives. In this chapter, we also show that the increase in biomass production per square meter in additive intercropping was linked to an increase in resource uptake rather than to an increase in resource use efficiency, therefore raising the question of resource exportation and soil depletion by intercropping, for which we do not have an answer yet. Finally, this analysis of resource sharing emphasises the relevance of participatory on-farm trials. Without the diversity of environment in which the trials were set, we would not have spotted the linked between the yield ratio of beans and the concentration of nitrate in the soil. This is a proof that participatory trials, if well designed, are not restricted to the test of a new technology in farmers' conditions but also allow to collect trustworthy data, which can be used to explore physiological issues.

From the point of view of the use of intercropping, the results from this chapter suggest that the key of intercropping productivity is the spatial and temporal planning, as well as the choice of the crops, rather than the context in which the intercrops are grown and that the variables identified in Chapter 5 seem indeed important to take into account. However, more research – about other crops and/or in more diverse environments – is required to refine more these broad conclusions. We can nonetheless hope that the presentation of a simplified version of the results from this chapter may help market gardeners to understand better how associated crops can interact.

Chapter 9 |
General discussion



At the start of this thesis, we chose to focus on intercropping in market gardening, despite being aware that this subject has hardly been addressed by scientific studies and that very little reliable and comprehensive data would be available. We knew from the beginning that studying intercropping in market gardening would not be an easy venture.

This choice of combining the topic of intercropping with the one of market gardening was not made by chance but rather the result of a real desire from our part. The driving force behind this thesis was towfold: to disentangle the actual knowledge regarding intercropping in an attempt to predict their results and guide their choice and to provide professional market gardeners with trustworthy, precise and objective data regarding intercropping in market gardening. The discrepancy between, on the one hand, the complexity of intercropping and the lack of scientific data and, on the other hand, the large number of mainstream books on vegetable growing that present intercropping as a panacea was one of the triggering factor behind our choice of subject for this PhD.

In order to fill this gap and to meet our wish and main objective, our study was guided by three research questions:

(A) Which interactions influence outcome and benefits in intercropping?
(B) Which criteria use to choose productive intercrops?
(C) Is the productivity of an intercrop more dependent on environmental conditions and crop management practices than the productivity of pure crops?

These research questions tackled two aspects of intercropping: the theoretical framework of intercropping and the implementation of intercrops on real farms.

In the present chapter, we review the qualities and weaknesses of our approach, summarise our main findings and discuss some perspectives. To facilitate reading, Figure 53 hereunder represents the nine chapters of the thesis and their respective focus.

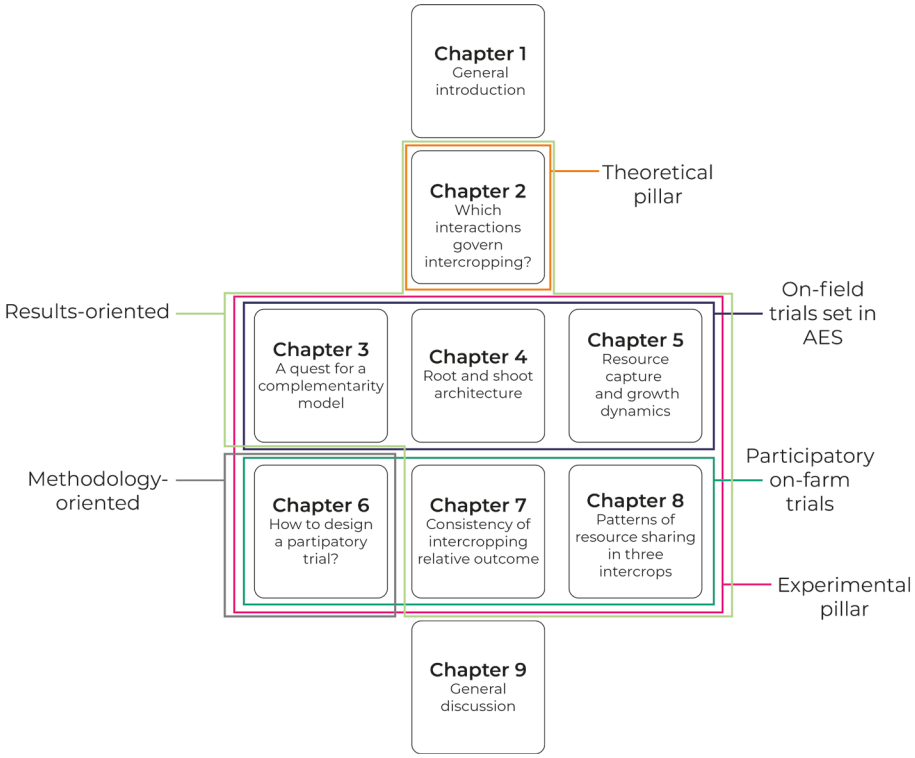


Figure 53 - Chapters of the thesis and their respectice focus. AES=Agricultural experiment station.

CHAPTER 9 | GENERAL DISCUSSION

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9.1. METHODOLOGICAL DISCUSSION

9.1.1. AN EXPLORATORY APPROACH

One may say that there are two types of scientists: those who follow paths that are already open and seek to understand them better and those who open new ones. In this PhD, we embarked deliberately in the second track and developed an exploratory study.

From our preliminary contacts with market gardeners, it was clear that they were looking for a global understanding of intercropping and better guidelines for choosing which crops to combine. Given the large number of possible pairwise combinations in market gardening, an exploratory study, embracing a variety of intercrops rather than a thorough examination of a single intercrop was the logical first step within the time frame of a PhD thesis.

This explanatory approach came with trade-offs. The major one was probably the use of yield as the main indicator of an intercrop advisability. As discussed in the general introduction (cf. Chapter 1), it makes sense, for various reasons, to use the yield as the reference indicator. However, it has been proven that intercropping can bring much more than an increase in yield (cf. Chapter 1). Therefore, using the yield as the only indicator is reductive and could lead to certain intercrops being advised against when they may have other relevant benefits. Nonetheless, to study a diversity of intercrops at the same time, we had to rely on simple variables; it would not have been realistic to add an additional constraint. We tried to compensate for this simplification by considering data on other variables, e.g. financial yield and time spent in the field, in the results of the participatory trials (cf. Chapter 7).

Our approach inevitably affected the design of our experiments: the number of modalities (cf. Chapter 3, Chapter 4 and Chapter 5) or of sites (cf. Chapter 7 and Chapter 8) in the trials was large. As a consequence of their complexity and as the trials were managed by one single person most of the time, the measurements were chosen by seeking the best balance between information content and operating costs. We believe that we collected as much information as we could considering the available human resources. Moreover, these measurements were sufficient to understand the general resource sharing within intercrops. Similarly, we decided to focus only on one

to two spatial designs for each intercrop and on one staggering of sowing/plantation dates.

The variability between sites and between intercrops is a key topic that we chose to tackle using as many sites or intercrops as possible rather than to repeat the same trials two years in a row. This choice was in line with the track we decided to follow and responded, for the participatory on-farm trials, to some requests from market gardeners to correct flaws in our design and to change the intecrop studied. It may however diminish the generalisability of our findings

We think that the exploratory approach enabled us to improve our global understanding of intercropping by identifying general trends before diving into more in-depth studies of selected intercrops or mechanisms. Accordingly, this thesis paved the way for the scientific study of intercropping in market gardening, identified some key points of interest and should help guide future research.

9.1.2. A STORY OF COMBINATIONS

Our research was based on two pillars: a theoretical one, aiming at answering our first research question (A) in the most systemic and comprehensive way, and an experimental one, designed to answer the second (B) and third (C) research questions using respectively on-field and participatory on-farm trials.

In each pillar, we also used a combination of two approaches. Our theoretical pillar rested on a thorough literature review to which was added a visual approach, in order to show, graphically, the interactions, processes and elements involved in intercropping that we identified (cf. Chapter 2). Our experimental pillar, for its part, consisted of classic on-field trials in AES (cf. Chapter 3, Chapter 4 and Chapter 5) and of participatory on-farm trials (cf. Chapter 6, Chapter 7 and Chapter 8). The combination of all these approaches allowed us to tackle different issues of intercropping and, brought together, they supplemented each other and provided us with a good global view of the intercropping system.

In the following sections, we review the benefits and limitations of the different methods we used.

9.1.3. THOROUGH LITERATURE REVIEW AND NETWORKING

We started our literature review at the beginning of the thesis, with an open-mind and with the idea of gathering as much information as possible about the functioning of intercropping. Contrary to what is often expected in review papers, we proceeded in a heuristic way, looking for further information on every process depicted as important in intercropping. Working "out of the standards" allowed us to stay eyes wide-open. We did not restrict ourselves to intercropping-focused papers but also dug in other types of papers, e.g. ecology papers, soil microbiomass-related papers, etc., which allowed us to comprehend – and represent – better the processes influenced by or influencing intercropping. We believe that this way of working allowed us to give a thorough representation of the intercropping system and that the large number of papers considered should compensate for any bias there could be in our review.

The networks of interactions (cf. Chapter 2, Appendix B) derived from this review had to be intilligable by farmers, with translation and minor changes. Therefore, we set out to find a good balance between our will of completeness, the readability of the networks and their understandability by non-scientists, which inevitably led to some simplifications. We believe that the resulting networks are a good tool to comprehend the intercropping system as a whole

9.1.4. ON-FIELD TRIALS IN AGRICULTURAL EXPERIMENT STATION

The question related to the variability across sites and this related to the intercrops required, respectively, a large number of sites and a large number of intercrops. Given the time frame and the available resources, these questions were addressed in separate trials.

The trials addressing the complementarity models were conducted in the market gardening farm of UCLouvain, i.e. an agricultural experiment station (AES). Besides the complexity of the design, this choice was also influenced by the large variability we expected to see between intercrops. Setting up the trials in an AES allowed us to manage all intercrops and pure crops in the same way and to control some other variables, e.g. weed pressure via frequent weeding, water stress via irrigation, in order to reduce the variability. There was however a trade-off between controlling the variability and ensuring the survival of the crops on one side and putting the crops in limiting conditions to reveal the complementarity effect in intercropping. We

played it safe and, consequently, the light was likely to be the only limiting resource in these trials.

The decision of studying more than 30 different intercrops in a relatively controlled environment enabled us to underline some key characteristics explaining the differences in outcome between them. It may be that fewer or no trends would have been detected in a less controlled environment. Nevertheless, the choice of ensuring the survival of the crops over the one of putting them in limiting conditions probably hindered the competition for belowground resources between crops, therefore suppressing root complementarity effects.

9.1.5. A PARTICIPATORY APPROACH

Given that one of the driving force of this thesis was to provide professional market gardeners with reliable information regarding intercropping, engaging in a participatory process was an obvious choice and we opted to involve market gardeners in our process from the beginning of our research. The exploratory approach of our work allowed us to consider the needs of market gardeners regarding intercropping: it is only after meeting market gardeners that our research questions were clearly formulated, which ensured we would address significant and useful issues in the further steps of the thesis.

In addition to the definition of the research questions, a participatory approach was also used for half of our trials (cf. Chapter 6, Chapter 7 and Chapter 8). As explained in Chapter 6, this part was not always a bed of roses. We were in fact confronted with a series of difficulties during these trials. There was of course the one of finding appropriate measurements to capture as much information as possible in a non-destructive way and with transportable measuring devices, the one of managing the implementation of a dozen of experimental fields disseminated across Wallonia or the one of handling incomplete data. Retrospectively, the two main obstacles were probably the following: communicate in the right way with involved market gardeners and find the good balance between our needs and their availability.

Regarding communication, it was in fact a challenge to find the right words to explain to market gardeners the differences between their objectives and ours and the requirements of a successful scientific experiment. This

difficulty arose from both differences of perspective and misunderstanding of some scientific terms, e.g. “Modality”, “Repetition”.

Regarding the balance of needs, the complexity came from the tension between our urge to standardise the distinct sites in order to ensure a valid comparison of the results from the different sites and the room for manoeuvre to be left to market gardeners so that they do not find participation in our trials too restrictive and time-consuming.

With hindsight, we think we succeeded to manage both the communication and the duality between the constraints and expectations of market gardeners and ours, as we collected reliable data (cf. Chapter 7 and Chapter 8) while keeping the market gardeners engaged and satisfied (cf. Chapter 6). Our results even show a double appropriation of the trials by market gardeners: on the one hand, they made the results of the trials their own and on the other hand, they captured the complexity and the needs of a rigorous scientific approach.

Engaging in this process required a significant commitment from our part both mentally – there was a significant pressure to ensure both the involvement and satisfaction of market gardeners and the collection of reliable data – and physically – monitoring a dozen of experimental fields disseminated across Wallonia all alone was not a piece of cake –. We believe that it was worth it, as the participatory approach allowed us (i) to formulate research questions that were in agreement with the needs of market gardeners, (ii) to open our eyes to some of the constraints of intercropping and to take a more critical look to our results and (iii) to anchor part of our trials in the reality of the field, taking into account the variability between market gardeners, all this without compromising the scientific quality of the data collected. In our opinion, our results are a proof that it is possible to construct in a short period of time – we noticed a improvement of our methodology the second year compared to the first (cf. Chapter 6) – a participatory approach methodology that is relevant, sensible and adapted to farmers' constraints without sacrificing too much the rigour of scientific studies. This reinforces our belief that participatory research should be encouraged and is, to some extent, compatible with disciplinary research.

9.2. MAIN FINDINGS

9.2.1. COMPLEXITY AT ITS BEST

We started this thesis being apprehensive about the complexity of intercropping. As it combines the responses of two crops to their biotic and abiotic environments as well as their mutual interactions, intercropping is hard to comprehend and we were not disappointed in this respect.

The complexity of intercropping was highlighted many times thoughout this thesis. The literature review, for example, helped us to identify the main interactions and mechanisms that play a part in the outcome of an intercrop and allowed us to answer our first research question (A). Most importantly, it underlined the diversity of processes and elements that intervene in the intercropping system (cf. Chapter 2).

The visual representation of these processes via several networks of interactions and a global system map is a way to handle this complexity. They allow the researcher to see at a glance (i) the complexity of the system, (ii) the relative importance of the different compartments intervening in each main intercropping-related theme, e.g. competition for light, and (iii) the interactions regarding each intercropping-related theme. Moreover, these tools may serve as a map, in the original sense of the word, as they could allow each researcher to situate its own study in the global intercropping system. With this in mind, these maps may also help a researcher to pinpoint the main interactions that need to be taken into account in his/her study. If our research show the extent of intercropping complexity, we think that the resulting toolbox – although it may not be complete – might help others to handle it better by offering a comprehensive view of the intercropping system. These networks might even be the starting point of interactive and collaborative maps, in which every researcher could add its findings.

The on-field trials in AES (cf. Chapter 3**,** Chapter 4 and Chapter 5), aimed at verifying the explanatory – and predictive – value of some architectural and growth cycle characteristics of the crops in relation to the differences in outcome between a diversity of intercrops. Despite the fact that we controlled some external variables, e.g. water availability through irrigation, the influence of the studied characteristics was unclear. This result further emphasises the complexity of intercropping and reflects the struggle to choose an intercrop and predict its results based on theoretical processes whose importance in intercropping seems to be agreed upon in scientific

studies and on which are based the recommendations found in market gardening books.

9.2.2. VARIABILITY, YOU SAY?

The question of yield variability in intercropping was addressed in two different ways throughout this thesis: the inter-site variability of the relative yield of specific intercrops and the variability of outcome between different intercrops. While many studies addressed yield variability in intercropping with a view to verifying the greater resilience and yield stability of intercrops compared to pure crops. (Mead et al., 1986; Paut et al., 2019; Pearce & Edmondson, 1982; Rao & Singh, 1990; Rao & Willey, 1980; Raseduzzaman & Jensen, 2017; Vandermeer & Schultz, 1990), we tackled variability in order to find its causes, e.g. identifying what can induce differences in LER between intercrops or between the same intercrop grown in different sites.

The inter-site variability was the subject of the participatory on-farm trials (cf. Chapter 6, Chapter 7 and Chapter 8). Based on our literature review (cf. Chapter 2), we expected to see (i) differences in yield between sites, both in pure crops and in intercrops and (ii) difference in the relative outcome of the intercrops, i.e. the ratio between the yield of the crops in intercropping and in pure crop.

Our first assumption proved to be true: there were differences in biomass yield between the sites for all modalities, which suggests that the yield of both intercrops and pure crops was indeed dependent on the conditions in which they were cultivated. However, despite the high variability in these trials – experimental fields were set up in farms with different soil and weather conditions and managed by different farmers –, when there was no environmental limitation, land equivalent ratios were consistent from site to site, i.e. the sites in which the intercrop yield was low were the sites in which the pure crops yield was low as well. This suggests that the yield of intercrops was equally influenced by the environmental conditions and the crop management practices as the yield of the corresponding pure crops. For market gardeners, this implies (i) that they cannot compare their performances on an absolute scale but can on a relative scale and (ii) that the productivity of their intercrops is determined by the productivity of the corresponding pure crops in their field. Our results however also show that below a certain threshold of resource availability, intercrops may be more affected than pure crops. Nonetheless, intercrops were influenced in the same way in all the sites in which the limitation was present.

Our results make it possible to objectify the opinions of market gardeners regarding intercropping and emphasise the importance, for a market gardener willing to implement intercropping, of comparing the performance of an intercrop to the performance of the corresponding pure crops to be able to assess its relevance objectively. This finding also echoes the discussion regarding the indicators used to assess the suitability of an intercrop (cf. Chapter 1): if the opinion of market gardeners regarding intercrops varies more than their opinion regarding pure crops, it is probably because other factors that the biomass production are at stake, e.g. the easiness of management, the quality of the products, etc.

In addition to the inter-site variability of the relative yield of intercrops, our results also allow to discuss the variability of outcome between different intercrops, thanks to the high diversity of intercrops we studied in this thesis. We observed indeed that intercrops did not all performed the same and that some seem to be more advisable than others are (cf. Chapter 5, Chapter 7).

Moreover, some global trends were identifiable. On the one hand, intercrops used the resources – light, water, nutrients – on average at least as well as the corresponding pure crops. Indeed, among the 36 intercrops – based on 22 different pure crops – we studied, only one had a LER significantly lower than unity and more than one third had a LER significantly higher than unity. Our results are therefore in line with the many studies showing the potential yield benefit of intercropping (Bulson et al., 1997; Monti et al., 2016; Rao & Willey, 1980; Reddy & Willey, 1981; Yu et al., 2015; Zhang & Li, 2003). However, the fact that about two-thirds of our LERs were not significantly different from unity allows to qualify this statement by showing that the yield increase is not 100% guaranteed. On the other hand, in general, intercropping decreased crop yield, although not always significantly, compared to what was expected based on their yield in pure crop: 36% of the component crops produced significantly less biomass than expected and only 4.5% of them produced significantly more biomass than expected. Moreover, there was usually an asymmetry between the yields of two companion crops: one crop dominated the mix and was less affected than the other was. Finally, in the on-field trials in AES (cf. Chapter 3, Chapter 4 and Chapter 5), where light was probably the most limiting resource, all the intercrops we studied responded to some-light related processes.

Overall, we observed less variability than expected based on the complexity of interactions in intercropping and the diversity in our trials – differences in environmental conditions, crop management practices, crops used –.

9.2.3. COMPLEMENTARITY AND COMPETITION, FRIENDS OR FOES?

The analyses of our results led us to put into perspective two key concepts linked to intercropping: competition and complementarity. The concept of complementarity refers to the physiological and architectural differences that exist between crops and allow them to use resources in different ways in space and time (Andersen et al., 2007; Hooper, 1998; Loreau & Hector, 2001; Trenbath, 1974) whereas that of competition refers to a process during which two plants, or two populations of plants, interact which each other in such a way that at least one has a negative impact on the growth, the survival and/or the reproduction of the other (Depuydt, 2014). These two concepts are very often opposed, the first being the rationale for why some intercrops may use the land more completely than the corresponding pure crops (Keating & Carberry, 1993; Natarajan & Willey, 1980a, 1980b; Rao & Singh, 1990; Willey, 1990; Willey & Osiru, 1972) and the second the rationale for why some crop combinations prevent their component crops from reaching their expected yield, i.e. the yield they are supposed to attain based on the outcome of the corresponding pure crops (Weidlich et al., 2018; Wendling et al., 2017; Zhang & Li, 2003). In a physiological perspective, where the objective of intercrops is to maximise the yield of both crops, complementarity should therefore be something each intercrop should tend to whereas competition should be avoided at all costs.

The distinction between complementarity and competition may be less clear-cut than expected. Both arise from interactions between the combined crops (Table 10, cf. Chapter 2). When considering the processes, the boundary between these two concepts is thin. In fact, what can be considered in some context as a competition interaction may, in another context, be considered as complementarity. Shading is probably the easiest example. On the one hand, shadow must be avoided in intercropping, as it reduces the photosynthesis of the shaded crop (Duchene et al., 2017; Tsubo et al., 2001; Zhang et al., 2008). On the other hand, shadow may also be beneficial, as it prevents the leaves of the shaded crop from reaching saturation and can improve the radiation use efficiency (Keating & Carberry, 1993; Monteith et al., 1991; Willey, 1990; Zhang et al., 2008). Moreover, if competition is usually seen as something to avoid, this may not always be

the case. For instance, competition for nitrogen can stimulate the fixation of atmospheric nitrogen by legumes, therefore reinforcing the benefit of intercrops between a non-legume and a legume (Andersen et al., 2007; Azam-Ali et al., 1990; Bedoussac & Justes, 2010b; Corre-Hellou et al., 2006; Henrik Hauggaard-Nielsen et al., 2008; Jensen, 1996b; Trenbath, 1976). Therefore, it seems to us that complementarity and competition, even if they do not necessarily involve the same processes and interactions, are kind of two sides of the same coin and all intercrops will most probably be exposed to both complementarity and competition. Staying in a framework opposing them for the analysis and selection of intercropping may convey a more dualistic image than it is in reality as it may give the impression that some interactions may be prevented at all costs, e.g. shading of one crop by the other, whereas they may be beneficial in some contexts.

This theoretical framework also delivers the message that all competition and all yield loss should be avoided. Yet, reaching a LER of 2, i.e. an intercrop in which each crop produces as much biomass as its pure crop, is probably utopian. Each environment has a productivity potential regarding intercropping, i.e. a reachable maximum regarding LER, and the aim of intercropping should probably not be to avoid any competition but to maximise the use of resources in order to attain this potential. In this matter, it might be useful to try to understand intercrops by focusing on the uptake, use and share of resources by companion crops rather than focusing on pre-defined complementarity and competition interactions. This may favour a more systemic approach of intercropping and enables to develop a two-tier analysis of intercrops: (i) an analysis at the plot level, i.e. “How much resource is removed by the intercrop and how much biomass is produced?” and (ii) an analysis at the crop level, i.e. “How are the resources taken and the biomass produced partitioned between the component crops?”, as was done in Chapter 8. This two-tier analysis allows a direct parallel to be drawn with the kind of analysis of an intercrop farmers would do, i.e. at the plot level, “How much resource is needed to manage the intercrop, e.g. workforce, money?” and at the crop level, “What is the marketability of the two crops?”.

Table 10 - Example of processes leading to competition, complementarity and facilitation for the three main resources for which plant compete (Barron-Gafford et al., 2017; Duchene et al., 2017; Hinsinger et al., 2011; Keating & Carberry, 1993; Latati et al., 2016; Mommer et al., 2016; Monteith et al., 1991; Qiao et al., 2016; Schenk et al., 1999; Schenk, 2006; Tarafdar & Jungk, 1987; Tsubo et al., 2001; Willey, 1990, 1990; Zhang & Li, 2003; Zhang et al., 2008).

RESOURCE	COMPETITION	COMPLEMENTARITY	FACILITATION
Light	Reduction of photosynthesis Differences in growth dynamics	Reduction of leaf saturation Differences in light requirements over time Differences in growth dynamics	
Nutrients	Pre-emption of resources Root aggregation Allelopathy Differences in growth dynamics	Root segregation Use of alternative form of nutrients (e.g. atmospheric nitrogen) Differences in nutrient requirements over time Differences in growth dynamics	Nutrient solubilisation Nutrient transfer Enrichment through root decomposition Root aggregation
Water	Pre-emption of water Hydraulic descent Root aggregation Allelopathy Differences in growth dynamics	Root segregation Differences in water requirements over time Difference in growth dynamics	Hydraulic lift Root aggregation

9.2.4. TOWARDS PREDICTING THE OUTCOME OF INTERCROPS?

The two on-field trials set in AES (cf. Chapter 3, Chapter 4 and Chapter 5) were designed to test the reliability of some crop and intercrop characteristics as criteria for intercropping design, with the idea of formulating some guidelines for intercrop selection. The choice of crops to intercrop is indeed one of the challenges faced by market gardeners, as the information on this topic consists mainly of recommendations from mainstream market gardening books (cf. Chapter 1) with no or little

information regarding the context in which these recommendations were formulated or their aim.

Our starting hypotheses were not completely successful at accounting for the observed differences in yield. However, a more in-depth analysis of our results enabled us to identify some common characteristics between intercrops with similar evolution and outcome, which were useful in explaining the differences in biomass productivity between the intercrops studied in the two trials (cf. Chapter 5).

While we cannot assert the predictive value of these characteristics and their reliability as selection criteria, our results highlight the relevance of the scanning approach, i.e. prioritise the number of studied intercrop and maximise it according to our tools, to pinpoint some global trends regarding the functioning of intercropping. The thoughtful construction of further experimental trials involving a large number of intercrops might result in the end in the development of trustworthy and reliable intercropping guidelines, usable by farmers. Moreover, the results of our participatory trials regarding the variability of intercrop outcome in a range of environmental conditions suggest that it is more the spatial and temporal design of the plot and the characteristics of the crops that influence the share of resources between associated crops. This let us believe that it should be possible to develop guidelines that would be relevant for a certain range of conditions.

Finally, we believe that the disentangling of the processes involved in intercropping and the networks of interactions – once translated and slightly simplified – may help market gardeners to understand better the principles behind intercropping and serve as an additional tool to help them in their selection of crop combinations.

9.2.5. OUR CONTRIBUTIONS...

By answering – or trying to answer – to our three research questions, we think we were able to contribute to both the scientific uncertainties about intercropping and the operationalisation of intercropping.

9.2.5.1. ...to the scientific uncertainties about intercropping

We chose to break away from the usual approach of studying crop combinations by engaging ourselves on the track of an exploratory approach, as we think that part of the difficulty to understand and predict intercropping

comes from the preponderance of papers focusing on one specific combination and the general orientation of research towards cereal-legume intercropping. We believe that this choice has paid off and allowed us to make interesting contributions to the scientific knowledge regarding intercropping.

Our study highlights the complexity of the intercropping system and provides tools to researchers to facilitate the comprehension of this complexity. It reinforces the idea that on-field trials should help to understand better the functioning of intercrops and to verify the relevance of some theoretical concepts and it proposes a new way of studying intercrops, by comparing a diversity of crop combinations at the same time. It also provides some thought about the concepts of competition and complementarity (cf. 9.2.3). Finally, our trials tackled the issue of the yield variability in intercropping in a new manner, focusing on the impact of environmental context and crop management practices on the relative outcome of intercrops, and showed the consistency of intercropping relative outcome in a range of conditions as long as no clear environmental limitation was present.

9.2.5.2. …to the operationalisation of intercropping

Some of our findings may help to overcome partially the lack of objective information regarding intercropping between vegetables and may contribute to ease its setting up in professional market gardening farms.

Firstly, based on the average LER of the 36 intercrops we studied, it seems advisable for diversified market gardeners and from a biomass production point of view, to grow two plots of an intercrop between two crops rather than one plot of each of the corresponding pure crops. However, we already emphasised that yield is balanced by other criteria, e.g. workforce needed, decrease in the marketability of the crops, etc. during the process of intercrop selection by market gardeners. Taking into account these other evaluation criteria in studies regarding intercropping should favour the relevant implementation of this practice.

Secondly, the two trials designed to test the reliability of some criteria regarding intercrop selection showed that the criteria usually used in market gardening books, although they make sense, seem not to be the ones that influence the competition relationships and the outcome of an intercrop the most (cf. Chapter 3). These trials underlined the importance of the maximum soil coverage and of the growth dynamics of associated crops in the

performance of intercrops when light is the most limiting resource, which should probably be the case in most market gardening farms. Our results suggest that it is not vain to try to find general principles regarding intercropping and they open the door for further research regarding intercropping guidelines.

Finally, besides the multiplicity of evaluation criteria other than yield, our study also underlined the diversity of objectives farmers may have when setting up intercropping regarding biomass production: for instance, one farmer may associate two high-value crops and would want to have an even production of both crops in the intercrop whereas another may associate a high-value crop with a low-value one and would therefore want to maximise the yield of the high-value crop, the yield of the other crop being a bonus. This highlights the importance of stating the objective for which the intercrops are designed when developing intercropping guidelines.

9.3. PERSPECTIVES

The study of intercropping between vegetables in temperate regions has been largely disregarded by researchers. In our opinion however, studying intercropping in the context of market gardening is an important road to follow, as, as shown in this thesis, it may lead to findings that are relevant beyond the confines of market gardening. According to us, our research open three avenues for the study of intercropping.

The first one regards the study of interactions between associated crops. We highlighted, throughout this thesis, the complexity of intercropping and the difficulty of interpreting on-field results about it. Particularly, our results were hard to analyse when staying in confines of predefined hypotheses regarding competition and complementarity (cf. Chapter 3 and Chapter 4). However, by using the reverse approach, i.e. analysing our results with an open mind rather than trying to find the effect of our starting hypotheses, we were able to highlight some intercrop characteristics related to their outcome. This leads us to think that four recommendations may help to disentangle the information about intercropping and to emphasise general trends.

Firstly, given the diversity of possibilities regarding crop combinations, an approach where the number of studied intercrops is maximised seems needed to identify general principles and relevant combinations. More precisely, the design of our second on-field trial set up in AES proved to be

particularly relevant: studying all the pairwise combinations between a certain number of crops enabled us to distinguish between the effects linked to one particular crop and those linked to the association of two crops. We think there is in this design some interesting path to follow to understand better the interactions that arise when crops differing in their architecture and growth dynamics are intercropped.

Secondly, as explained above, we think it is important, in such studies, to have an exploratory mind. It was when we looked at our results with new eyes rather than with hypotheses to verify that we were able to highlight the characteristics of the crops that influenced the outcome of the studied intercrops. In our opinion, by varying the conditions in which the trials are conducted, e.g. varying the limiting resource, we should be able to identify other characteristics influencing the share of resources between associated crops.

According to us, combining an exploratory approach both in the number of intercrops and in the number of interactions studied – as was done in this thesis – should engage researchers in a learning process whose first step would be to identify the interactions that matter the most in intercropping, in general or in specific cases. A further step would then be to tackle more precisely these interactions/pairs.

Thirdly, as we emphasised the importance of growth dynamics, it seems essential to combine the exploratory and combinatory approach with measurement of time-series data, e.g. evolution of soil coverage, interception of radiation along the season, evolution of biomass production, etc. Regarding this matter, it would probably be interesting to combine on-field trials with the use of architectural modelling. This seems particularly promising for the study of light distribution among complex canopies such as the ones of intercrops. In addition, it is important to select appropriately the ecophysiological measurement used in experimental trial so that they can confirm or disprove that the targeted interactions actually occur.

Finally, although a LER higher than unity is usually associated with complementarity effects, if the total density is not the same in the intercrop and in the pure crops, we cannot distinguish between the cases in which the increase in biomass production in intercropping is linked to a density effect – in which case the increase in biomass production should also happen in the pure crop at higher density – or to an actual complementarity effect. This raises the question of the reference in intercropping and, more specifically,

of which density of the pure crops use for comparison. Indeed, if comparing the intercrop to the pure crops grown at the density usually used by farmers makes perfect sense, increasing the density of the pure crops so that they reach their highest biomass production or their highest radiation use efficiency, for example, may also be relevant in an ecophysiological approach. Therefore, there is probably no single pure crop density reference and it is important to reflect its choice based on the context of the study and its objective.

The second avenue relates to intercropping as an optimisation of resource use. Up to now, intercrops have usually been studied in a physiological approach, with the aim of maximising the productivity of the two component crops. However, given the close relationships that exist between intercrops and their biotic and abiotic environments and the many benefits of intercropping beyond biomass production, it may be appropriate to move beyond the physiological framework to a systemic approach. In this respect, intercropping should be analysed through the perspective of resource use, with the idea of maximising the use and use efficiency of the available resources of a system through intercrops rather than maximising the yield of the crops. By authorising a broader definition of the word “resource” than in a physiological approach – where “resource” usually refers to the light, nutrients and water that plants use – this approach would allow to consider at once a series of different indicators. Labour-related variables, such as workforce or time, for instance, could be taken into account as resources whose use efficiency must be maximised. In the same view, it would be interesting to study intercropping from different environmental compartments, e.g. monitor the evolution of the soil micro-biomass under intercropping *vs* pure crop. This calls for a more multidisciplinary study of intercrops. Moreover, a systemic approach based on the use of resources should also require a contextualisation of the studies: the objective of intercropping should not be to maximise the productivity in absolute terms but to make the most efficient use of the resources available in each environment in which it is implemented. These recommendations are in line with the principles of agroecology – as a science studying in a holistic and multidisciplinary way the agroecosystems in order to increase their durability while optimising their efficiency and taking into account the specificity of the contexts (Wezel & Soldat, 2009) –. We believe that the studies on intercropping could benefit from drawing their inspiration from agro-

ecological approaches such as the ones described by Duru et al. (2015) for the study of biodiversity-based agricultural systems.

Finally, the third avenue is related to the operationalisation of intercropping. The final objective of intercropping studies should indeed be to ease their implementation by farmers. However, the transmission of information from scientists to farmers is a difficult task, even more regarding a subject as complex as intercropping. In this matter, promoting participatory research is, according to us, one of the keys. Indeed, participatory research allows for the definition of research questions in agreement with farmers' needs and the consideration of farmers' own characteristics, which is in line with the greater contextualisation above-mentioned. Moreover, we proved during this thesis that is was possible to tackle new research questions in a logic of co-experimentation with farmers without sacrificing scientific rigour and that such an approach was relevant as it highlighted the importance of some technical constraints. Nevertheless, as explained before, participatory approach is not an easy road. If the learning process that is its own is clearly one of its main benefits, it implies a continual adaptation of the research to farmers' needs. Besides participatory research, one must also think about how to communicate effectively the fruit of its research to the farmers. Regarding intercropping, this means being able to produce simple guidelines about a complex topic. Again, a participatory approach may be helpful regarding this matter. Indeed, asking farmers what information they need the most and how to present them in the most useful way should be the first step. The second step requires the researcher to adapt his/her vocabulary and simplify the information so that it is still correct but understandable by farmers. This is a particularly difficult task, for which researchers are rarely trained and which is still little recognised by the scientific community but which is one of the most important, in our opinion. In particular, we think it is important to provide farmers not only with decision-support tools but also with learning-support tools (Duru et al., 2015), to give them the keys to understand the practice they want to set up and adapt the provided guidelines to their conditions.

We think that combining these three avenues might help advance the understanding of intercropping by going outside the current confines of intercropping studies. Regarding the subject of intercropping in market gardening *per se*, the topic is so vast and had been so little addressed so far that the possibilities for study are almost endless: impact of the spatial and temporal design of the plots on the outcome of the intercrops, influence of

intercropping on the damage caused by pests and diseases, effect of intercropping on the workload of market gardeners, etc. Our thesis laid the foundation stone and it proves the relevance of giving credit to this topic. However, we are aware that, right now, the ball remains in the court of market gardeners, who need to pursue their own experiments until scientific research decides to support them.

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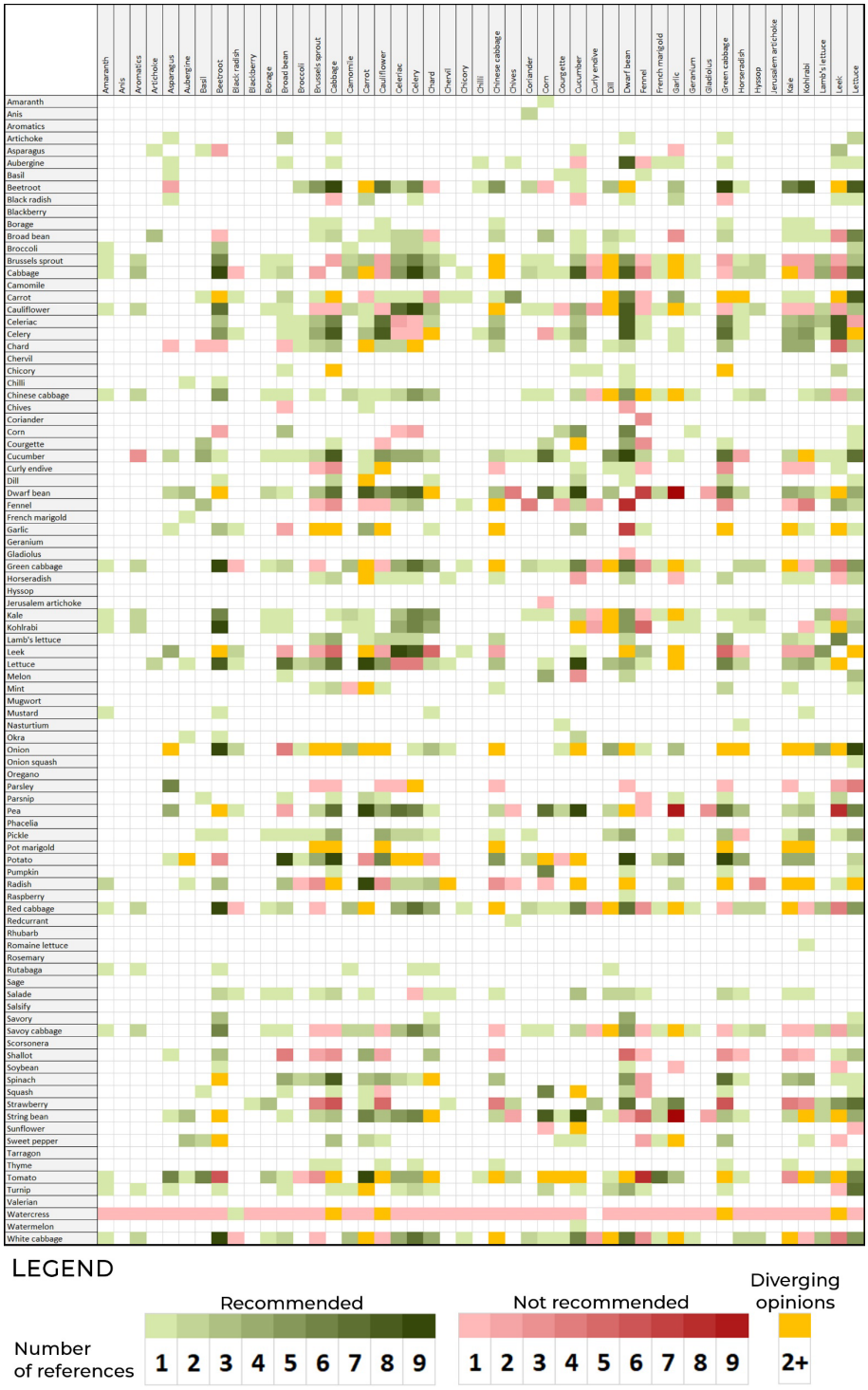
Appendix A. TABLE OF INTERCROPPING RECOMMENDATIONS

The table presented on the next two pages gathers the recommendations regarding intercropping between vegetables from fourteen different references:

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A green cell means that the intercrop between the vegetable of the corresponding row and the vegetable of the corresponding column is advised by at least one of the references and is beneficial at least for the vegetable of the corresponding row. A red cell means that the intercrop between the vegetable of the corresponding row and the vegetable of the corresponding column is not recommended by at least one of the references and is detrimental, at least for the vegetable of the corresponding row. The darker the tone of green/red, the higher the number of references advising for/against the corresponding intercrop. An orange cell means that at least two references were contradictory regarding the corresponding intercrop, i.e. one reference recommending it and the other advising against it. A white cell means that no recommendations was found for the corresponding intercrop.

A RShiny application (https://associations-cultures-maraichage.shinyapps.io/reseaux-associations-fr/) was built based on this table in order to visualise better the recommendations and to allow selecting for some type(s) of recommendations in particular.



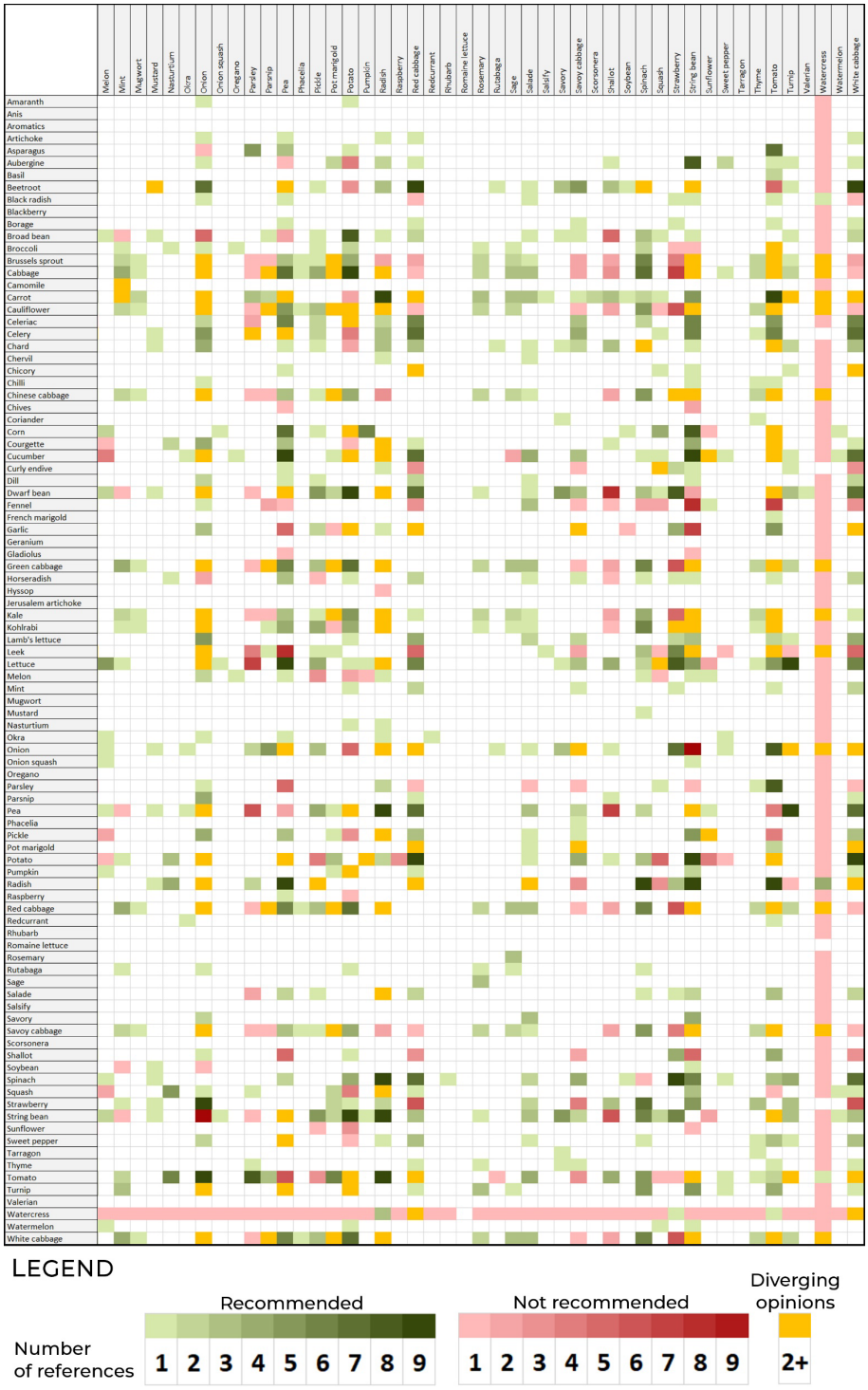
LEGEND

Number of references

Recommended: 1 2 3 4 5 6 7 8 9

Not recommended: 1 2 3 4 5 6 7 8 9

Diverging opinions: 2+


Melon
Mint
Mugwort
Mustard
Nasturtium
Okra
Onion
Onion squash
Oregano
Parsley
Parsnip
Pea
Phacelia
Pickle
Pot marigold
Potato
Pumpkin
Radish
Raspberry
Red cabbage
Redcurrant
Rhubarb
Romaine lettuce
Rosemary
Rutabaga
Sage
Salade
Salsify
Savory
Savoy cabbage
Scorsonera
Shallot
Soybean
Spinach
Squash
Strawberry
String bean
Sunflower
Sweet pepper
Tarragon
Thyme
Tomato
Turnip
Valerian
Watercress
Watermelon
White cabbage
Amaranth
Anis
Aromatics
Artichoke
Asparagus
Aubergine
Basil
Beetroot
Black radish
Blackberry
Borage
Broad bean
Broccoli
Brussels sprout
Cabbage
Camomile
Carrot
Cauliflower
Celeriac
Celery
Chard
Chervil
Chicory
Chilli
Chinese cabbage
Chives
Coriander
Corn
Courgette
Cucumber
Curly endive
Dill
Dwarf bean
Fennel
French marigold
Garlic
Geranium
Gladiolus
Green cabbage
Horseradish
Hyssop
Jerusalem artichoke
Kale
Kohlrabi
Lamb's lettuce
Leek
Lettuce
LEGEND
Recommended
Not recommended
Diverging opinions
Number of references
1 2 3 4 5 6 7 8 9
1 2 3 4 5 6 7 8 9
2+

Appendix B. NETWORKS OF INTERACTIONS IN INTERCROPPING

This appendix gathers the fifteen networks of interactions, which are graphical representations of the interactions described in Chapter 2. Each network focuses on a particular theme. According to the theme, the complexity of the network varies from 20 nodes up to 51. In each network, we classified the nodes between the two component plants of the intercrop, the biotic environment, the abiotic environment, the farmer- and crop management-related variables and the interactions and emergent properties of the intercrop. Five types of links were used to describe the relationships between nodes: quantitative synergistic, qualitative synergistic, antagonistic, undetermined and characteristic/component. The legend used for both compartments of nodes and types of links is the same in all networks and is presented hereunder. An index of all the nodes is available in Appendix B.16 and a list of the acronyms is presented hereunder.

List of the networks

Appendix B.1 Perception of neighbour
Appendix B.2 Shoot spatial complementarity
Appendix B.3 Root spatial complementarity
Appendix B.4 Nutritive complementarity
Appendix B.5 Temporal complementarity
Appendix B.6 General competition
Appendix B.7 Competition for aboveground resources
Appendix B.8 Competition for belowground resources
Appendix B.9 Mobilisation & transfer of nutrients
Appendix B.10 Transfer of water
Appendix B.11 Impact of the abiotic environment
Appendix B.12 Impact of the biotic environment
Appendix B.13 Crop management & impacts for farmers
Appendix B.14 Impact on the abiotic environment
Appendix B.15 Impact on the biotic environment

Legend of the networks

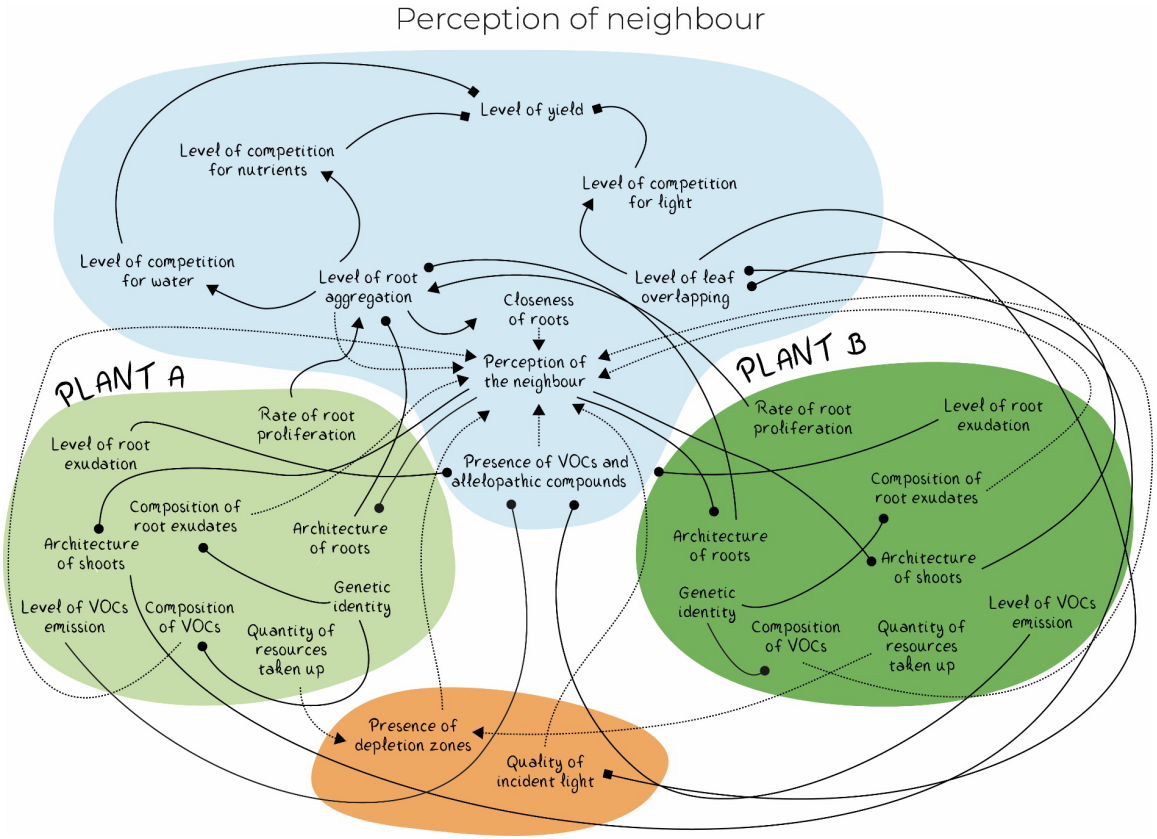
LEGEND OF THE NETWORKS



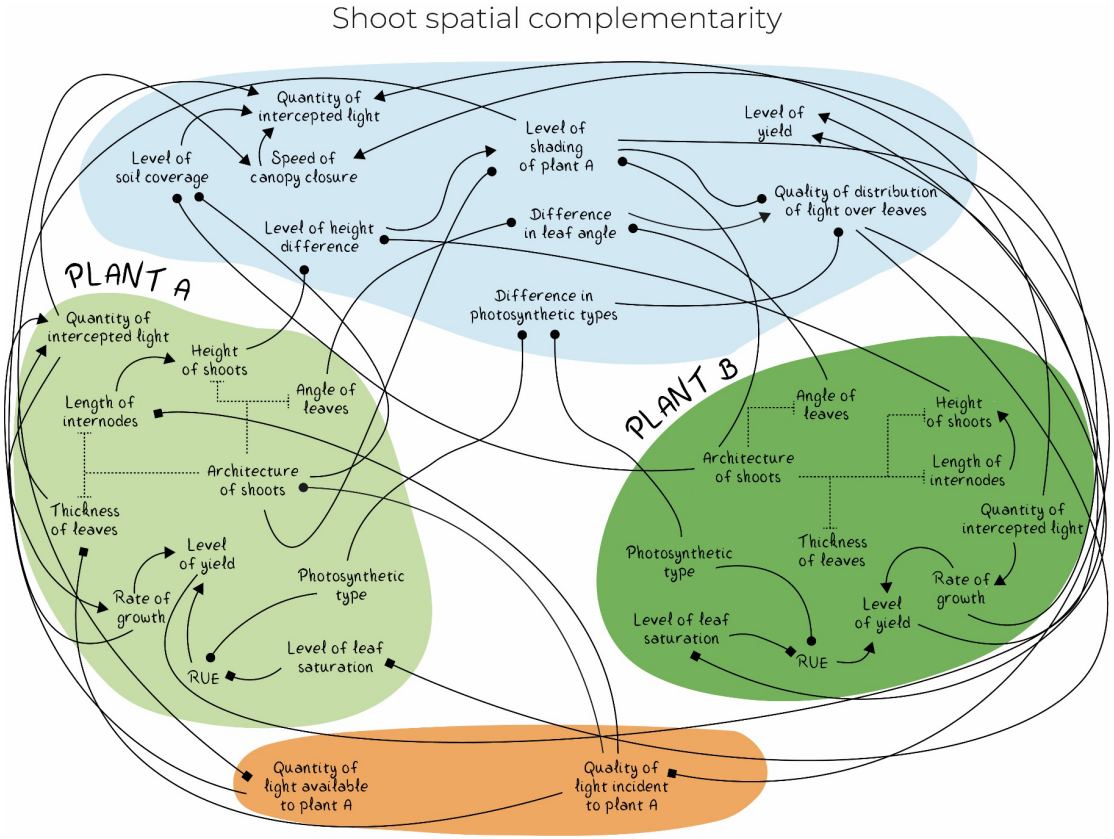
List of acronyms

RUE – Radiation use efficiency
WUE – Water use efficiency
VOCs – Volatile organic compounds

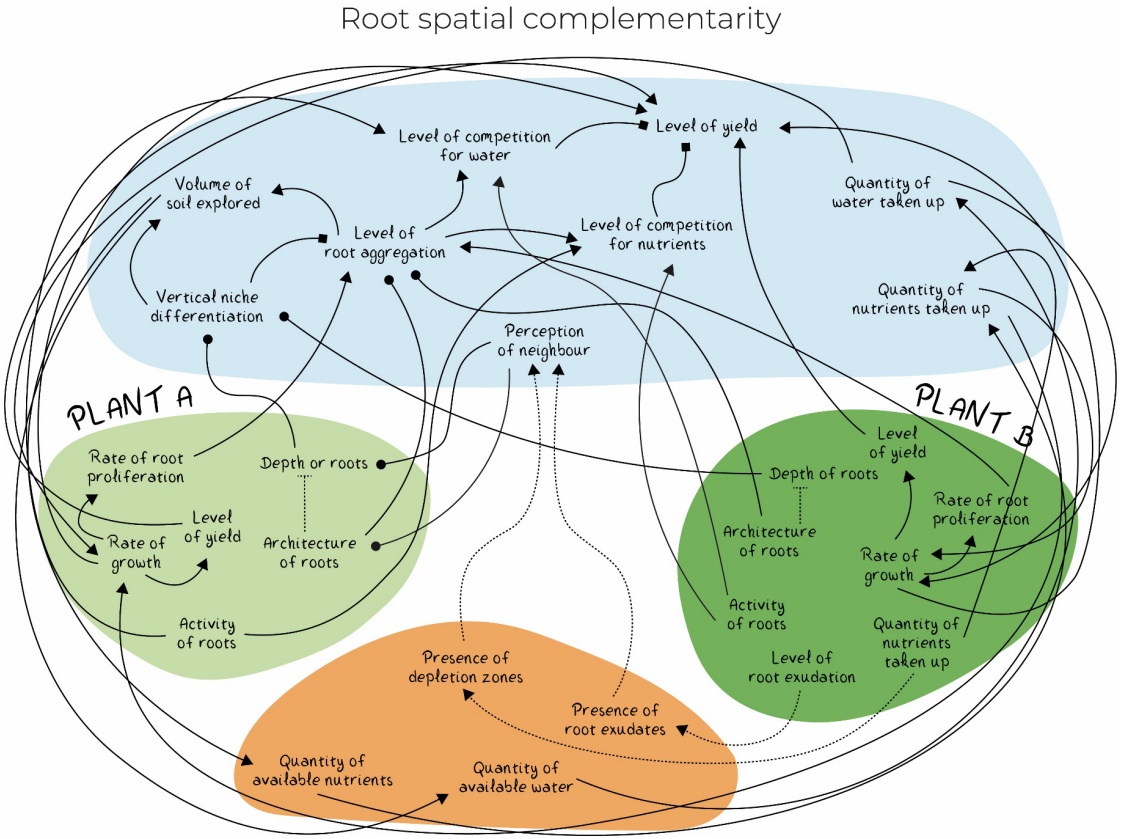
B.1 Perception of neighbour



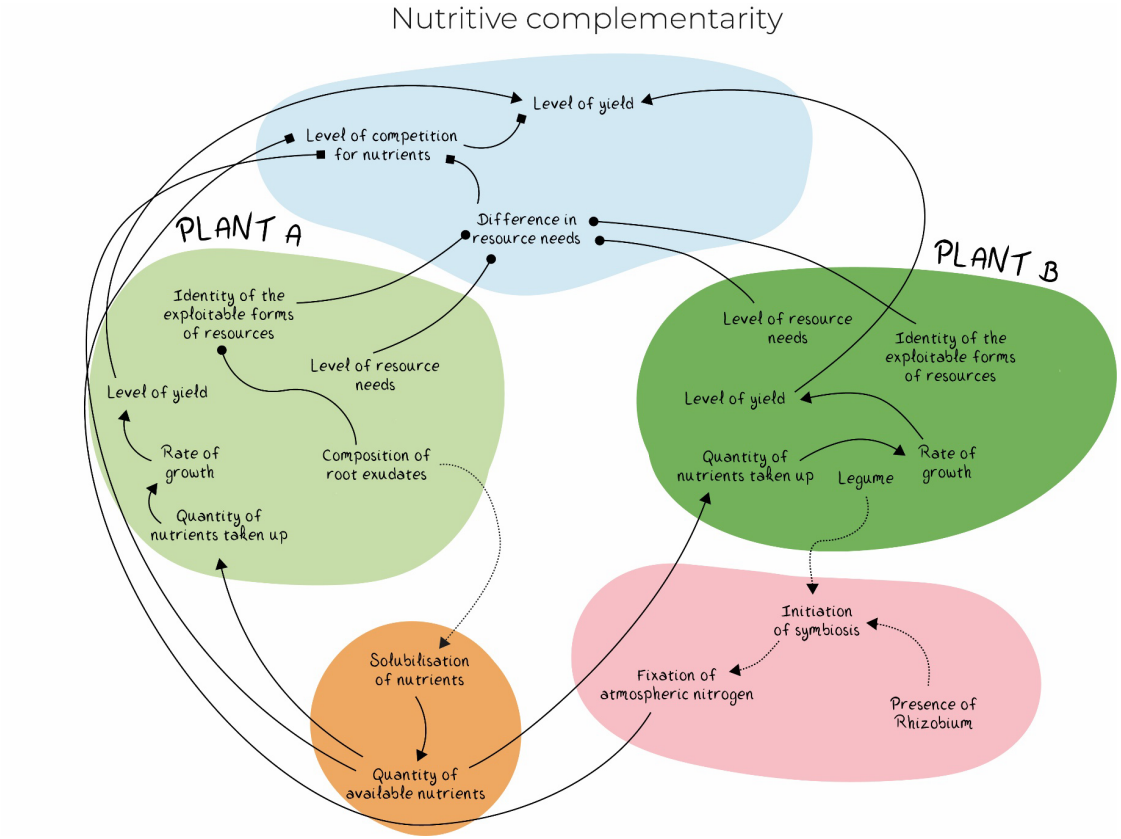
B.2 Shoot spatial complementarity



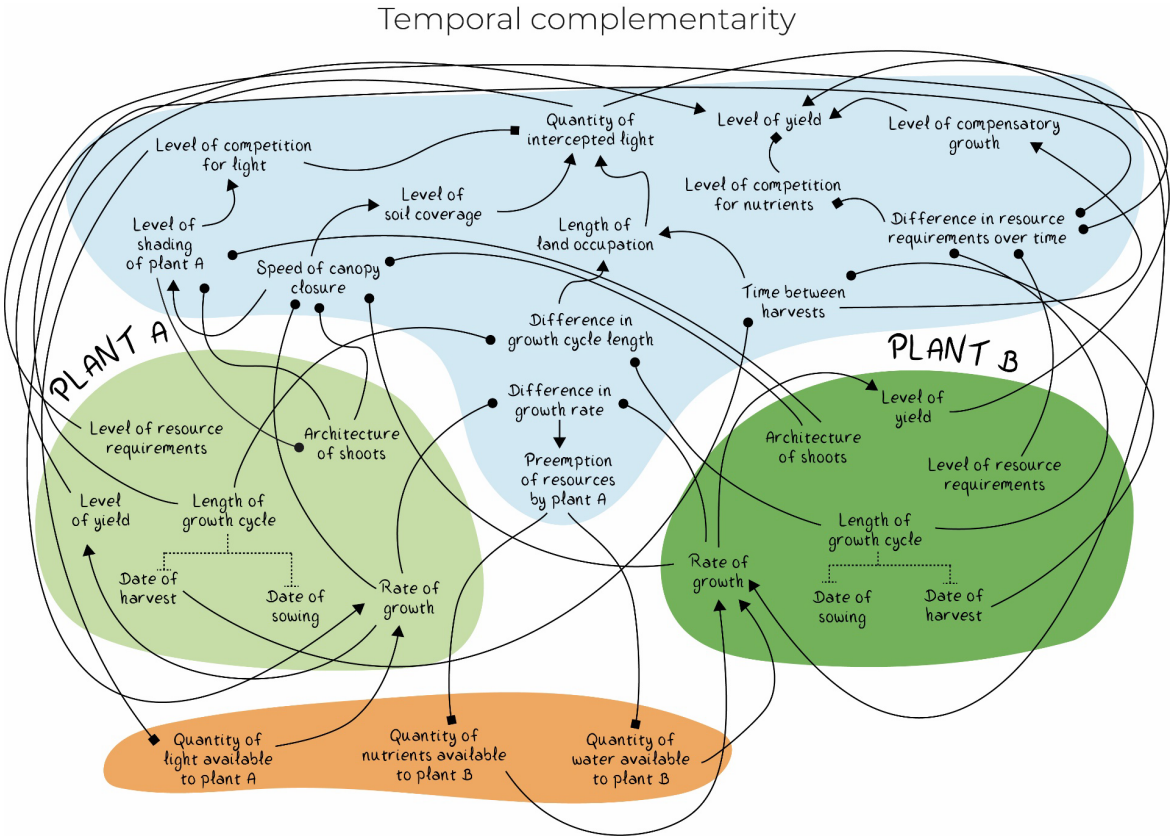
B.3 Root spatial complementarity



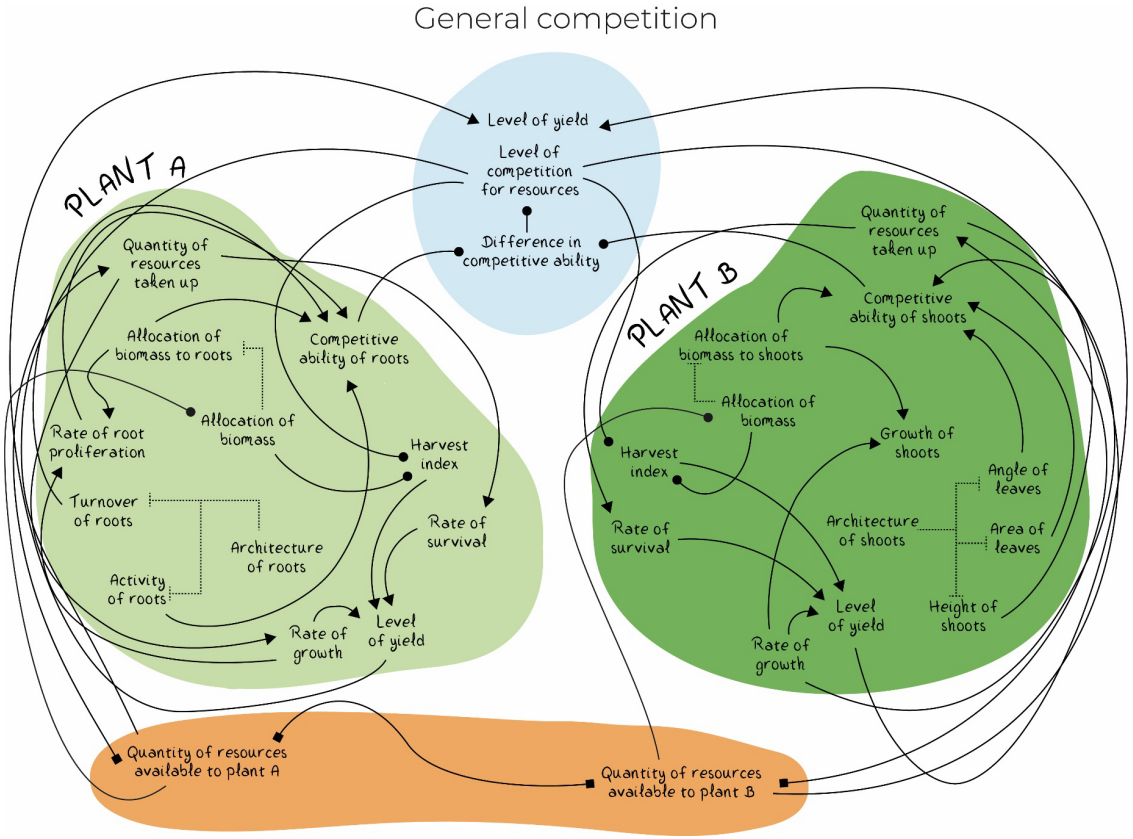
B.4 Nutritive complementarity



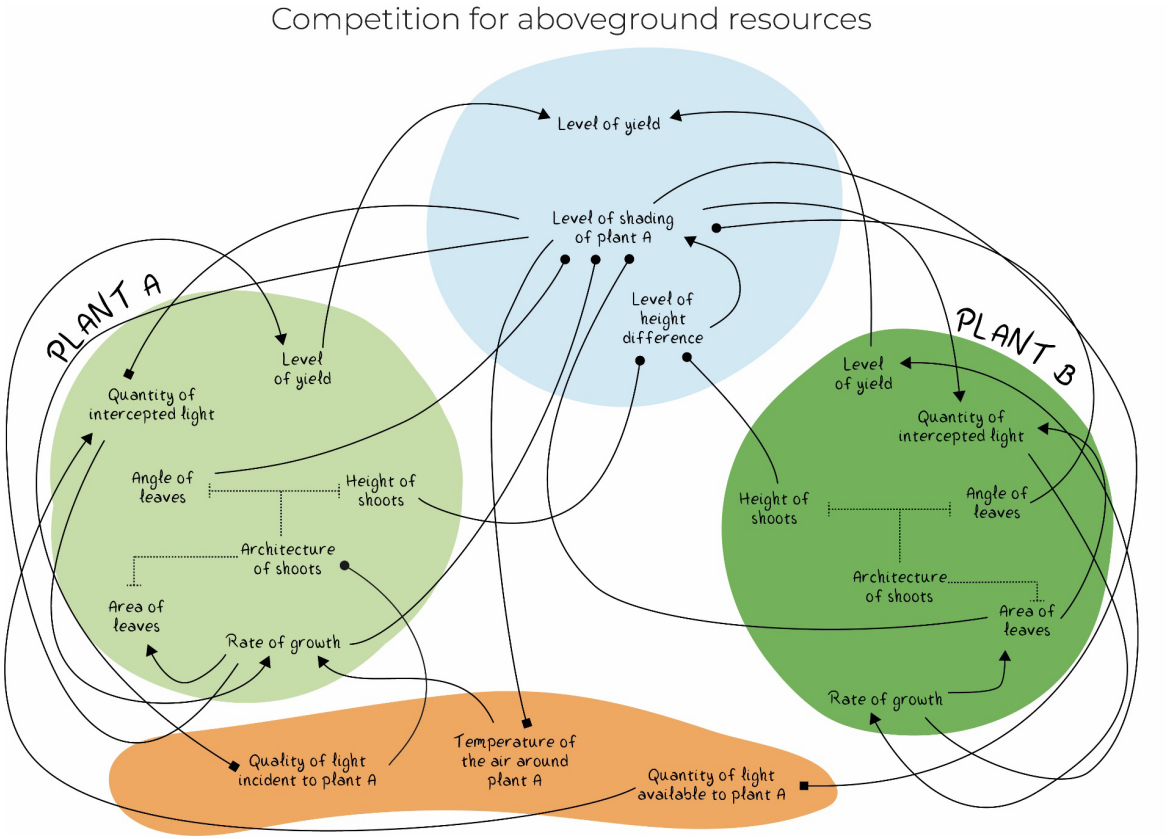
B.5 Temporal complementarity



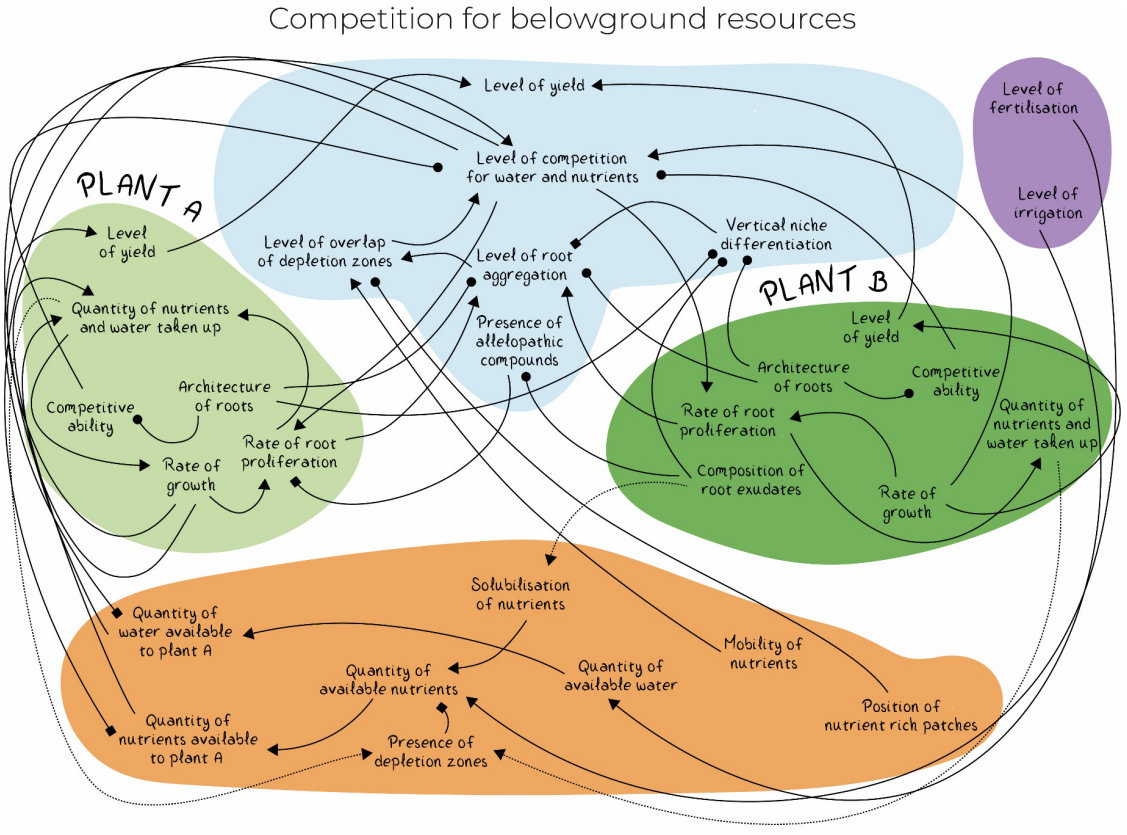
B.6 General competition



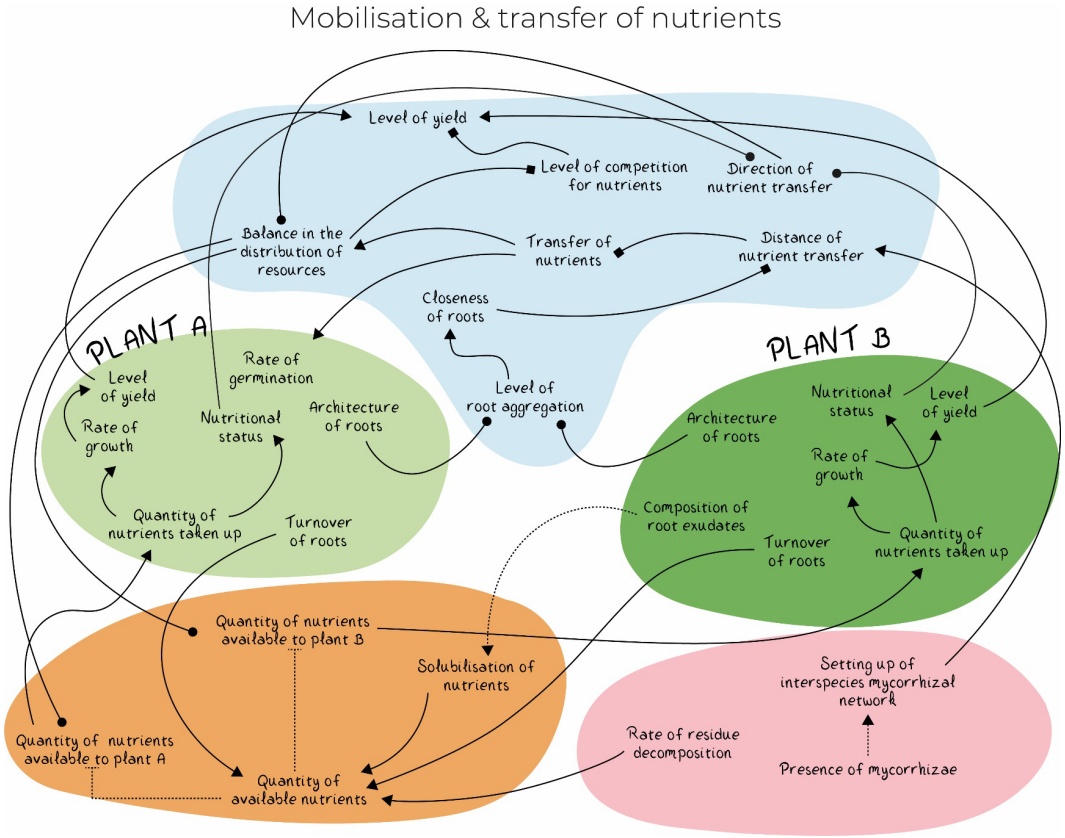
B.7 Competition for aboveground resources



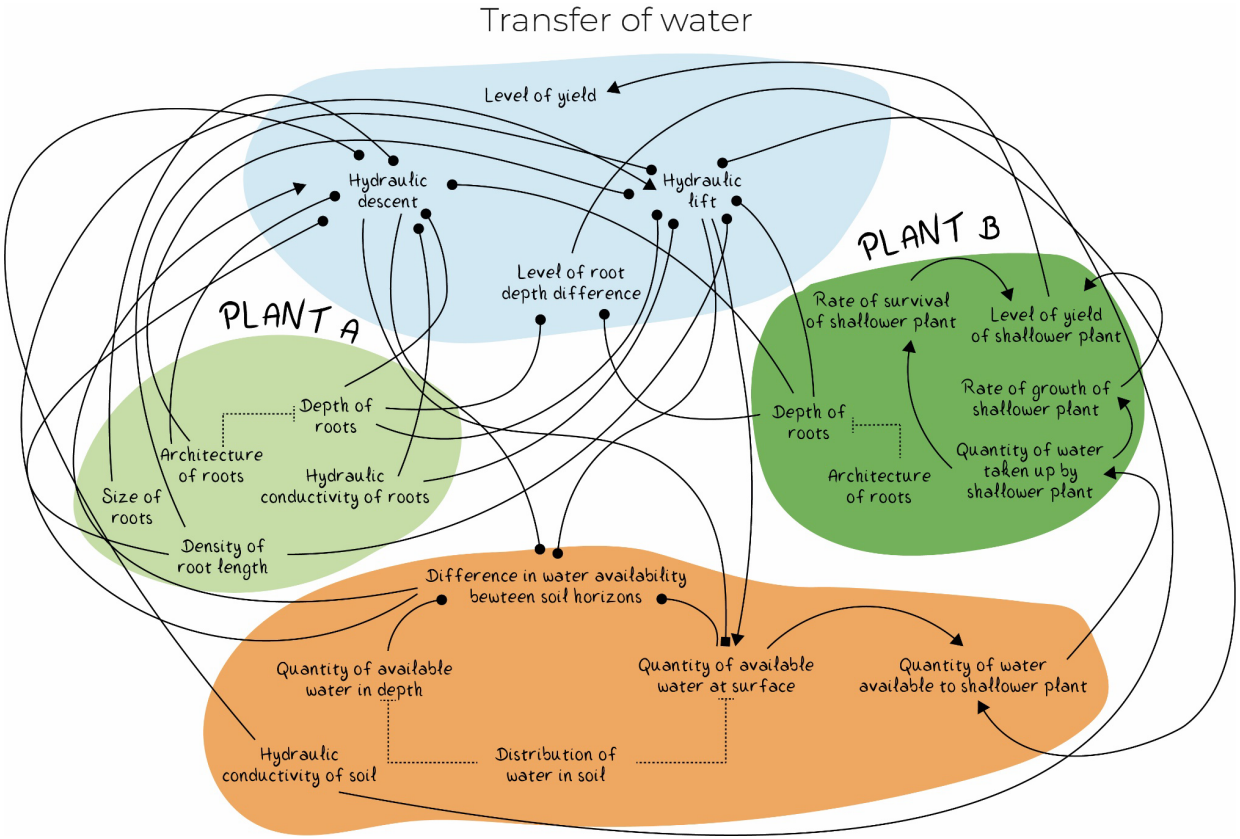
B.8 Competition for belowground resources



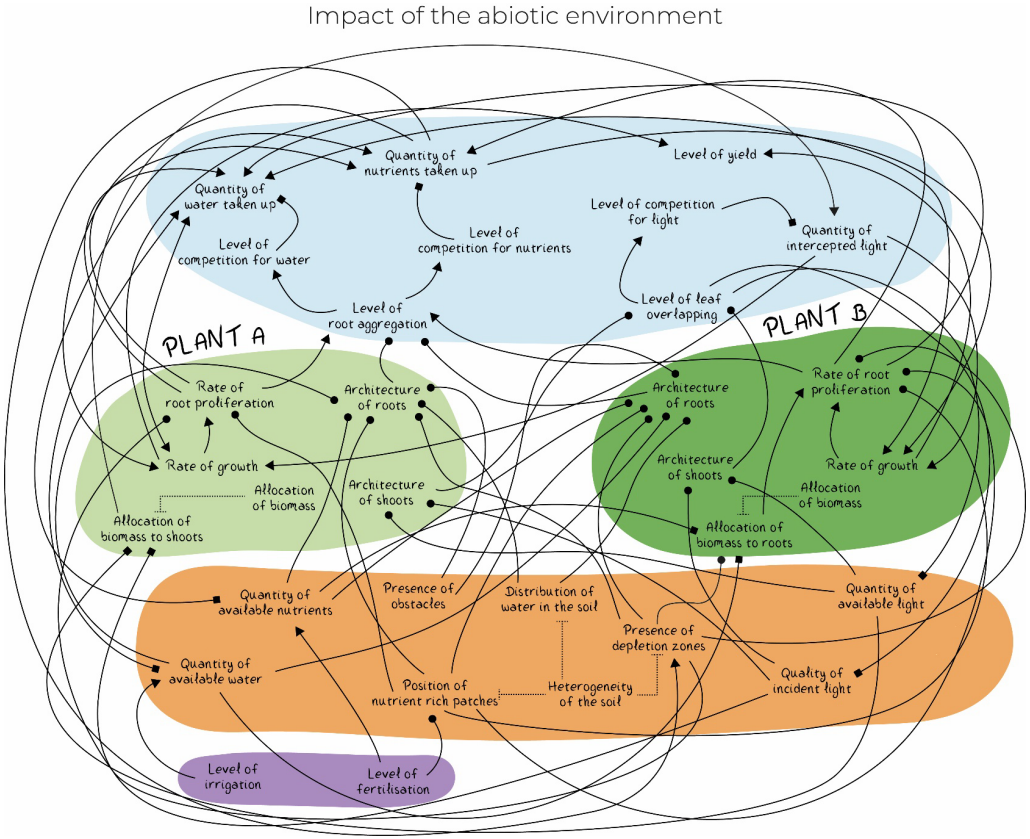
B.9 Mobilisation & transfer of nutrients



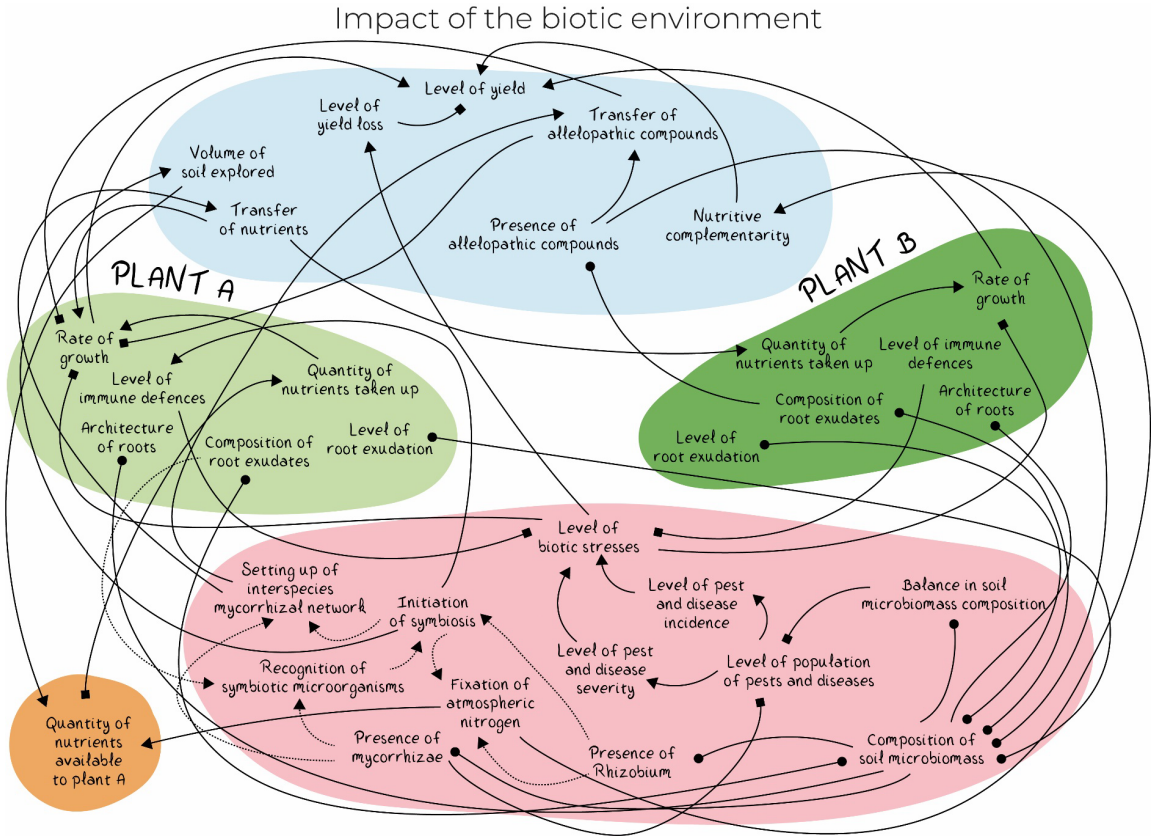
B.10 Transfer of water



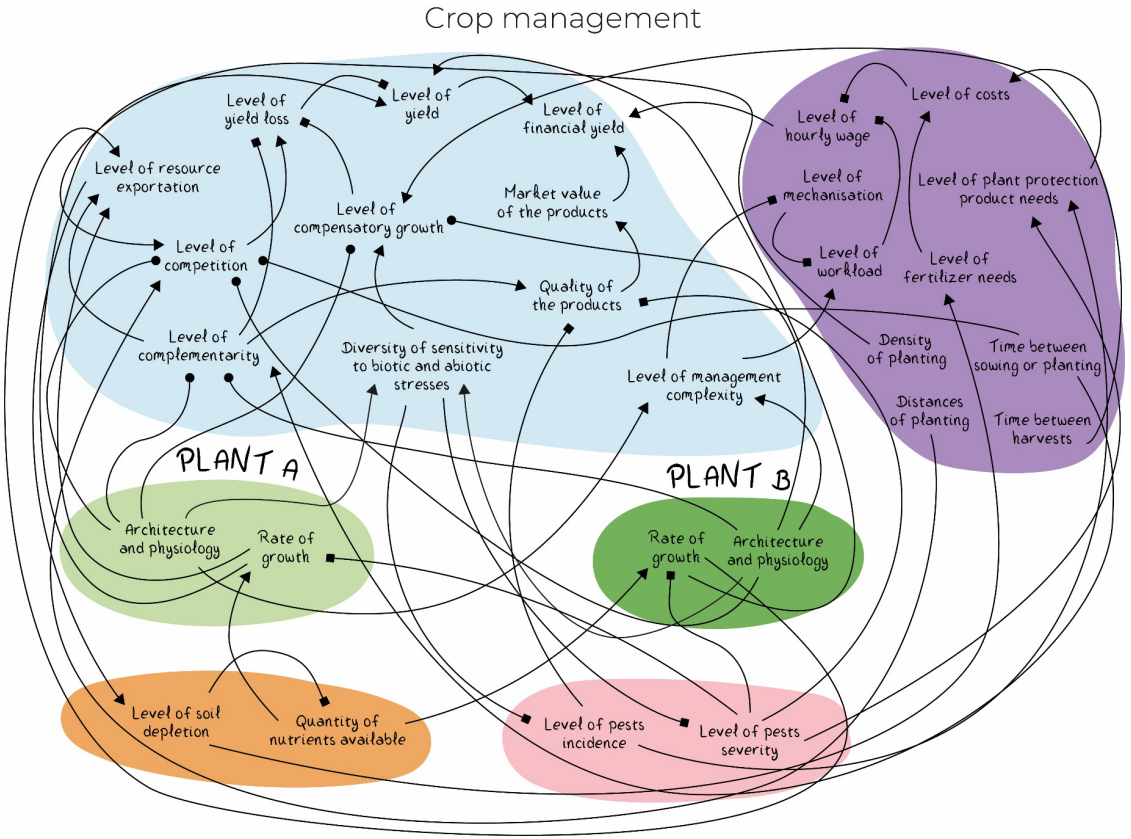
B.11 Impact of the abiotic environment



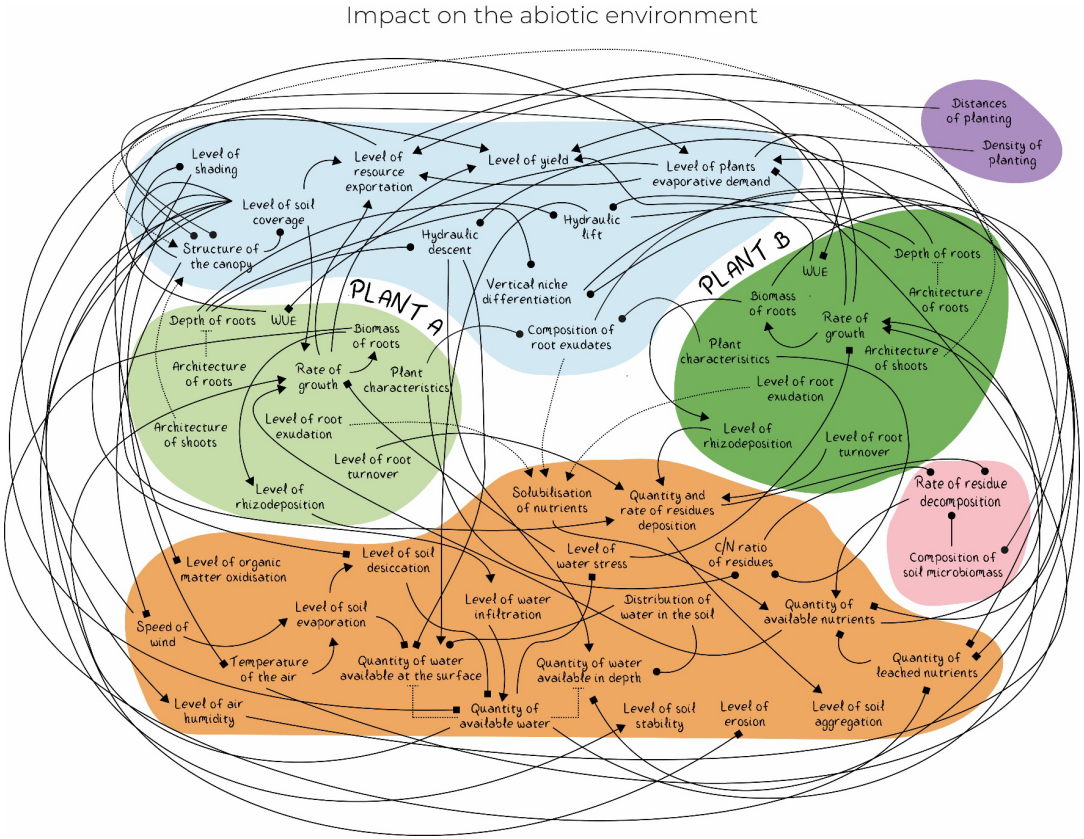
B.12 Impact of the biotic environment



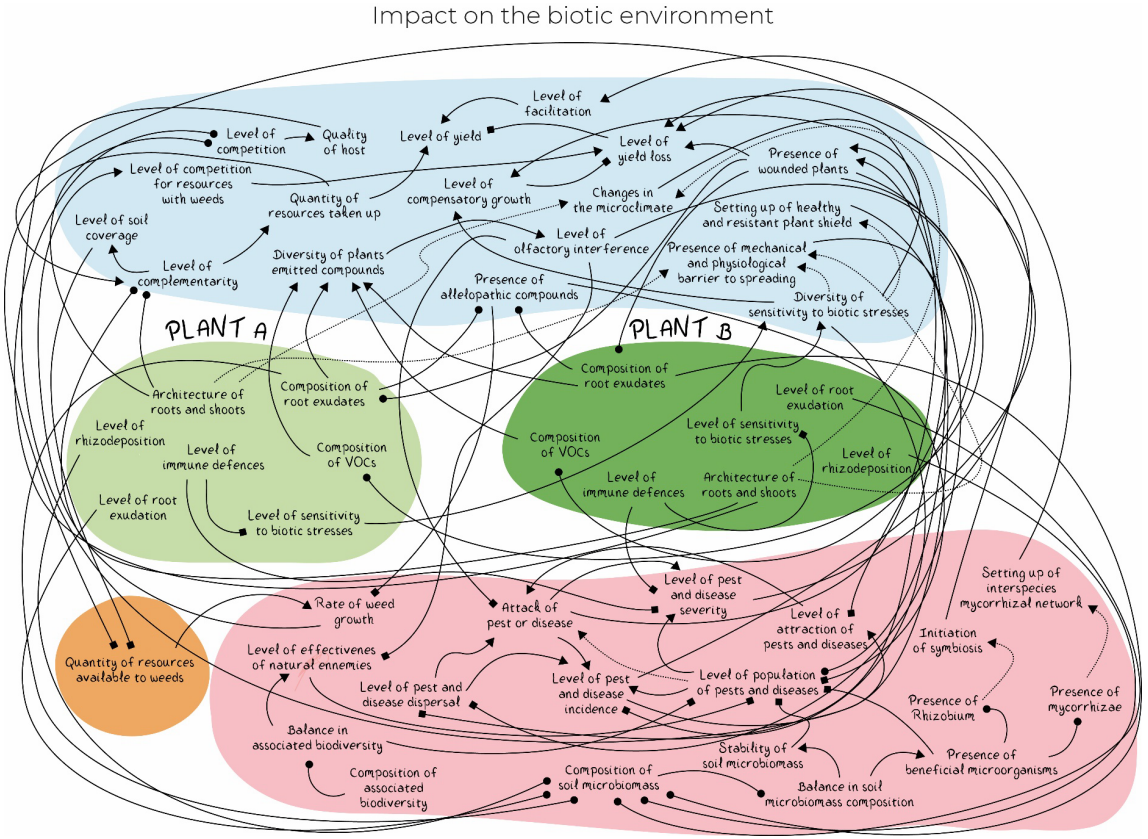
B.13 Crop management & impacts for farmers



B.14 Impact on the abiotic environment



B.15 Impact on the biotic environment



B.16 Index of the nodes from the interaction networks

	NODE	NETWORK(S)	COMPARTMENT(S)
1	Activity of roots	Competition, Root complementarity	Plant A, Plant B
2	Allocation of biomass	Competition, Impact of abiotic environment	Plant A, Plant B
3	Allocation of biomass to roots	Competition, Impact of abiotic environment	Plant A, Plant B
4	Allocation of biomass to shoots	Competition, Impact of abiotic environment	Plant A, Plant B
5	Angle of leaves	Competition, Light competition, Shoot complementarity	Plant A, Plant B
6	Architecture and physiology	Crop management	Plant A, Plant B
7	Architecture of roots	Competition, Competition for water & nutrients, Impact of abiotic environment, Impact of biotic environment, Impact on abiotic environment, Perception of neighbour, Root complementarity, Transfer of nutrients, Transfer of water	Plant A, Plant B
8	Architecture of roots & shoots	Impact on biotic environment	Plant A, Plant B
9	Architecture of shoots	Competition, Impact of abiotic environment, Impact on abiotic environment, Light competition, Perception of neighbour, Shoot complementarity, Temporal complementarity	Plant A, Plant B
10	Area of leaves	Competition, Light competition	Plant A, Plant B

	NODE	NETWORK(S)	COMPARTMENT(S)
11	Attack of pest or disease	Impact on biotic environment	Biotic environment
12	Balance in associated biodiversity	Impact on biotic environment	Biotic environment
13	Balance in soil microbiomass composition	Impact of biotic environment, Impact on biotic environment	Biotic environment
14	Balance in the distribution of resources	Transfer of nutrients	Interactions & emergent properties
15	Biomass of roots	Impact on abiotic environment	Plant A, Plant B
16	C/N ratio of residues	Impact on abiotic environment	Abiotic environment
17	Changes in the microclimate	Impact on biotic environment	Interactions & emergent properties
18	Closeness of roots	Perception of neighbour, Transfer of nutrients	Interactions & emergent properties
19	Competitive ability	Competition for water & nutrients	Plant A, Plant B
20	Competitive ability of roots	Competition	Plant A
21	Competitive ability of shoots	Competition	Plant B
22	Composition of associated biodiversity	Impact on biotic environment	Biotic environment

	NODE	NETWORK(S)	COMPARTMENT(S)
23	Composition of root exudates	Competition for water & nutrients, Impact of biotic environment, Impact on abiotic environment, Impact on biotic environment, Nutritive complementarity, Perception of neighbour, Transfer of nutrients	Interactions & emergent properties, Plant A, Plant B
24	Composition of soil microbiomass	Impact of biotic environment, Impact on abiotic environment, Impact on biotic environment	Biotic environment
25	Composition of VOCs	Impact on biotic environment, Perception of neighbour	Plant A, Plant B
26	Date of harvest	Temporal complementarity	Plant A, Plant B
27	Date of sowing	Temporal complementarity	Plant A, Plant B
28	Density of planting	Crop management, Impact on abiotic environment	Crop management
29	Density of root length	Transfer of water	Plant A, Plant B
30	Depth of roots	Impact on abiotic environment, Root complementarity, Transfer of water	Plant A, Plant B
31	Difference in competitive ability	Competition	Interactions & emergent properties
32	Difference in growth cycle length	Temporal complementarity	Interactions & emergent properties

	NODE	NETWORK(S)	COMPARTMENT(S)
33	Difference in growth rate	Temporal complementarity	Interactions & emergent properties
34	Difference in leaf angle	Shoot complementarity	Interactions & emergent properties
35	Difference in photosynthetic types	Shoot complementarity	Interactions & emergent properties
36	Difference in resource needs	Nutritive complementarity	Interactions & emergent properties
37	Difference in resource requirements over time	Temporal complementarity	Interactions & emergent properties
38	Difference in water availability between soil horizons	Transfer of water	Abiotic environment
39	Distance of nutrient transfer	Transfer of nutrients	Interactions & emergent properties

	NODE	NETWORK(S)	COMPARTMENT(S)
40	Distances of planting	Crop management, Impact on abiotic environment	Crop management
41	Distribution of water in soil	Impact of abiotic environment, Impact on abiotic environment, Transfer of water	Abiotic environment
42	Diversity of plants emitted compounds	Impact on biotic environment	Interactions & emergent properties
43	Diversity of sensitivity to biotic and abiotic stresses	Crop management	Interactions & emergent properties
44	Diversity of sensitivity to biotic stresses	Impact on biotic environment	Interactions & emergent properties
45	Fixation of atmospheric nitrogen	Impact of biotic environment, Nutritive complementarity	Biotic environment
46	Genetic identity	Perception of neighbour	Plant A, Plant B
47	Growth of shoots	Competition	Plant B
48	Harvest index	Competition	Plant A, Plant B
49	Height of shoots	Competition, Light competition, Shoot complementarity	Plant A, Plant B
50	Heterogeneity of the soil	Impact of abiotic environment	Abiotic environment

	NODE	NETWORK(S)	COMPARTMENT(S)
51	Hydraulic conductivity of roots	Transfer of water	Plant A, Plant B
52	Hydraulic conductivity of soil	Transfer of water	Abiotic environment
53	Hydraulic descent	Impact on abiotic environment, Transfer of water	Interactions & emergent properties
54	Hydraulic lift	Impact on abiotic environment, Transfer of water	Interactions & emergent properties
55	Identity of the exploitable forms of resources	Nutritive complementarity	Plant A, Plant B
56	Initiation of symbiosis	Impact of biotic environment, Impact on biotic environment, Nutritive complementarity	Biotic environment
57	Legume	Nutritive complementarity	Plant B
58	Length of growth cycle	Temporal complementarity	Plant A, Plant B
59	Length of internodes	Shoot complementarity	Plant A, Plant B

	NODE	NETWORK(S)	COMPARTMENT(S)
60	Level of air humidity	Impact on abiotic environment	Abiotic environment
61	Level of attraction of pests and diseases	Impact on biotic environment	Biotic environment
62	Level of biotic stresses	Impact of biotic environment	Biotic environment
63	Level of compensatory growth	Crop management, Impact on biotic environment, Temporal complementarity	Interactions & emergent properties
64	Level of competition	Crop management, Impact on biotic environment	Interactions & emergent properties
65	Level of competition for light	Impact of abiotic environment, Perception of neighbour, Temporal complementarity	Interactions & emergent properties
66	Level of competition for nutrients	Impact of abiotic environment, Nutritive complementarity, Perception of neighbour, Root complementarity, Temporal complementarity, Transfer of nutrients	Interactions & emergent properties
67	Level of competition for resources	Competition	Interactions & emergent properties

	NODE	NETWORK(S)	COMPARTMENT(S)
68	Level of competition for resources with weeds	Impact on biotic environment	Interactions & emergent properties
69	Level of competition for water	Impact of abiotic environment, Perception of neighbour, Root complementarity	Interactions & emergent properties
70	Level of competition for water and nutrients	Competition for water & nutrients	Interactions & emergent properties
71	Level of complementarity	Crop management, Impact on biotic environment	Interactions & emergent properties
72	Level of costs	Crop management	Crop management
73	Level of effectiveness of natural enemies	Impact on biotic environment	Biotic environment
74	Level of facilitation	Impact on biotic environment	Interactions & emergent properties
75	Level of fertilisation	Impact of abiotic environment	Crop management
76	Level of fertiliser needs	Crop management	Crop management
77	Level of financial yield	Crop management	Interactions & emergent properties

	NODE	NETWORK(S)	COMPARTMENT(S)
78	Level of height difference	Light competition, Shoot complementarity	Interactions & emergent properties
79	Level of hourly wage	Crop management	Crop management
80	Level of immune defences	Impact of biotic environment, Impact on biotic environment	Plant A, Plant B
81	Level of irrigation	Impact of abiotic environment	Crop management
82	Level of leaf overlapping	Impact of abiotic environment, Perception of neighbour	Interactions & emergent properties
83	Level of leaf saturation	Shoot complementarity	Plant A, Plant B
84	Level of management complexity	Crop management	Interactions & emergent properties
85	Level of mechanisation	Crop management	Crop management
86	Level of olfactory interference	Impact on biotic environment	Interactions & emergent properties
87	Level of organic matter oxidisation	Impact on abiotic environment	Abiotic environment
88	Level of overlap of depletion zones	Competition for water & nutrients	Interactions & emergent properties

	NODE	NETWORK(S)	COMPARTMENT(S)
89	Level of pest and disease dispersal	Impact on biotic environment	Biotic environment
90	Level of pest and disease incidence	Crop management, Impact of biotic environment, Impact on biotic environment	Biotic environment
91	Level of pest and disease severity	Crop management, Impact of biotic environment, Impact on biotic environment	Biotic environment
92	Level of plant protection product needs	Crop management	Crop management
93	Level of plants evaporative demand	Impact on abiotic environment	Interactions & emergent properties
94	Level of population of pests and diseases	Impact of biotic environment, Impact on biotic environment	Biotic environment
95	Level of resource exportation	Crop management, Impact on abiotic environment	Interactions & emergent properties
96	Level of resource needs	Nutritive complementarity	Plant A, Plant B
97	Level of resource requirements	Temporal complementarity	Plant A, Plant B

	NODE	NETWORK(S)	COMPARTMENT(S)
98	Level of rhizodeposition	Impact on abiotic environment, Impact on biotic environment	Plant A, Plant B
99	Level of root aggregation	Competition for water & nutrients, Impact of abiotic environment, Perception of neighbour, Root complementarity, Transfer of nutrients	Interactions & emergent properties
100	Level of root depth difference	Transfer of water	Interactions & emergent properties
101	Level of root exudation	Impact of biotic environment, Impact on abiotic environment, Impact on biotic environment, Perception of neighbour, Root complementarity	Plant A, Plant B
102	Level of root turnover	Impact on abiotic environment	Plant A, Plant B
103	Level of sensitivity to biotic stresses	Impact on biotic environment	Plant A, Plant B
104	Level of shading	Impact on abiotic environment	Interactions & emergent properties
105	Level of shading of plant A	Light competition, Shoot complementarity, Temporal complementarity	Interactions & emergent properties
106	Level of soil aggregation	Impact on abiotic environment	Abiotic environment

	NODE	NETWORK(S)	COMPARTMENT(S)
107	Level of soil coverage	Impact on abiotic environment, Impact on biotic environment, Shoot complementarity, Temporal complementarity	Interactions & emergent properties
108	Level of soil depletion	Crop management	Abiotic environment
109	Level of soil desiccation	Impact on abiotic environment	Abiotic environment
110	Level of soil evaporation	Impact on abiotic environment	Abiotic environment
111	Level of soil stability	Impact on abiotic environment	Abiotic environment
112	Level of VOCs emission	Perception of neighbour	Plant A, Plant B
113	Level of water infiltration	Impact on abiotic environment	Abiotic environment
114	Level of water stress	Impact on abiotic environment	Abiotic environment
115	Level of workload	Crop management	Crop management

	NODE	NETWORK(S)	COMPARTMENT(S)
116	Level of yield	Competition, Competition for water & nutrients, Crop management, Impact of abiotic environment, Impact of biotic environment, Impact on abiotic environment, Impact on biotic environment, Light competition, Nutritive complementarity, Perception of neighbour, Root complementarity, Shoot complementarity, Temporal complementarity, Transfer of nutrients, Transfer of water	Interactions & emergent properties, Plant A, Plant B
117	Level of yield loss	Crop management, Impact of biotic environment, Impact on biotic environment	Interactions & emergent properties
118	Level of yield of shallower plant	Transfer of water	Plant B
119	Market value of the production	Crop management	Interactions & emergent properties
120	Mobility of nutrients	Competition for water & nutrients	Abiotic environment
121	Nutritional status	Transfer of nutrients	Plant A, Plant B
122	Perception of neighbour	Perception of neighbour, Root complementarity	Interactions & emergent properties
123	Photosynthetic type	Shoot complementarity	Plant A, Plant B

	NODE	NETWORK(S)	COMPARTMENT(S)
124	Plant characteristics	Impact on abiotic environment	Plant A, Plant B
125	Position of nutrient rich patches	Competition for water & nutrients, Impact of abiotic environment	Abiotic environment
126	Preemption of resources by plant A	Temporal complementarity	Interactions & emergent properties
127	Presence of allelopathic compounds	Competition for water & nutrients, Impact of biotic environment, Impact on biotic environment	Interactions & emergent properties
128	Presence of beneficial microorganisms	Impact on biotic environment	Biotic environment
129	Presence of depletion zones	Competition for water & nutrients, Impact of abiotic environment, Perception of neighbour, Root complementarity	Abiotic environment
130	Presence of mechanical barrier to spreading	Impact on biotic environment	Interactions & emergent properties
131	Presence of mycorrhizae	Impact of biotic environment, Impact on biotic environment, Transfer of nutrients	Biotic environment
132	Presence of obstacles	Impact of abiotic environment	Abiotic environment

	NODE	NETWORK(S)	COMPARTMENT(S)
133	Presence of Rhizobium	Impact of biotic environment, Impact on biotic environment, Nutritive complementarity	Biotic environment
134	Presence of root exudates	Root complementarity	Abiotic environment
135	Presence of VOCs and allelopathic compounds	Perception of neighbour	Interactions & emergent properties
136	Presence of wounded plants	Impact on biotic environment	Interactions & emergent properties
137	Quality of distribution of light over leaves	Shoot complementarity	Interactions & emergent properties
138	Quality of host	Impact on biotic environment	Interactions & emergent properties
139	Quality of incident light	Impact of abiotic environment, Perception of neighbour	Abiotic environment
140	Quality of light incident to plant A	Light competition, Shoot complementarity	Abiotic environment
141	Quality of the products	Crop management	Interactions & emergent properties
142	Quantity and rate of residues deposition	Impact on abiotic environment	Abiotic environment

	NODE	NETWORK(S)	COMPARTMENT(S)
143	Quantity of available light	Impact of abiotic environment	Abiotic environment
144	Quantity of available nutrients	Competition for water & nutrients, Crop management, Impact of abiotic environment, Impact on abiotic environment, Nutritive complementarity, Root complementarity, Transfer of nutrients	Abiotic environment
145	Quantity of available water	Competition for water & nutrients, Impact of abiotic environment, Impact on abiotic environment, Root complementarity	Abiotic environment
146	Quantity of intercepted light	Impact of abiotic environment, Light competition, Shoot complementarity, Temporal complementarity	Interactions & emergent properties, Plant A, Plant B
147	Quantity of leached nutrients	Impact on abiotic environment	Abiotic environment
148	Quantity of light available to plant A	Light competition, Shoot complementarity, Temporal complementarity	Abiotic environment
149	Quantity of nutrient taken up	Transfer of nutrients	Plant A, Plant B

	NODE	NETWORK(S)	COMPARTMENT(S)
150	Quantity of nutrients and water taken up	Competition for water & nutrients	Plant A, Plant B
151	Quantity of nutrients available to plant A	Competition for water & nutrients, Impact of biotic environment, Transfer of nutrients	Abiotic environment
152	Quantity of nutrients available to plant B	Temporal complementarity, Transfer of nutrients	Abiotic environment
153	Quantity of nutrients taken up	Impact of abiotic environment, Impact of biotic environment, Nutritive complementarity, Root complementarity	Interactions & emergent properties, Plant A, Plant B
154	Quantity of resources available to plant A	Competition	Abiotic environment
155	Quantity of resources available to plant B	Competition	Abiotic environment
156	Quantity of resources available to weeds	Impact on biotic environment	Abiotic environment
157	Quantity of resources taken up	Competition, Impact on biotic environment, Perception of neighbour	Interactions & emergent properties, Plant A, Plant B
158	Quantity of water available at the surface	Impact on abiotic environment, Transfer of water	Abiotic environment

	NODE	NETWORK(S)	COMPARTMENT(S)
159	Quantity of water available in depth	Impact on abiotic environment, Transfer of water	Abiotic environment
160	Quantity of water available to plant A	Competition for water & nutrients	Abiotic environment
161	Quantity of water available to plant B	Temporal complementarity	Abiotic environment
162	Quantity of water available to shallower plant	Transfer of water	Abiotic environment
163	Quantity of water taken up	Impact of abiotic environment, Root complementarity	Interactions & emergent properties
164	Quantity of water taken up by shallower plant	Transfer of water	Plant B
165	Rate of germination	Transfer of nutrients	Plant A, Plant B

	NODE	NETWORK(S)	COMPARTMENT(S)
166	Rate of growth	Competition, Competition for water & nutrients, Crop management, Impact of abiotic environment, Impact of biotic environment, Impact on abiotic environment, Light competition, Nutritive complementarity, Root complementarity, Shoot complementarity, Temporal complementarity, Transfer of nutrients	Plant A, Plant B
167	Rate of residue decomposition	Impact on abiotic environment, Transfer of nutrients	Biotic environment
168	Rate of root proliferation	Competition, Competition for water & nutrients, Impact of abiotic environment, Perception of neighbour, Root complementarity	Plant A, Plant B
169	Rate of survival	Competition	Plant A, Plant B
170	Rate of weed growth	Impact on biotic environment	Biotic environment
171	Recognition of symbiotic microorganisms	Impact of biotic environment	Biotic environment
172	RUE	Shoot complementarity	Plant A, Plant B

	NODE	NETWORK(S)	COMPARTMENT(S)
173	Setting up of healthy and resistant plant shield	Impact on biotic environment	Interactions & emergent properties
174	Setting up of interspecies mycorrhizal network	Impact of biotic environment, Impact on biotic environment, Transfer of nutrients	Biotic environment
175	Size of roots	Transfer of water	Plant A, Plant B
176	Solubilisation of nutrients	Competition for water & nutrients, Impact on abiotic environment, Nutritive complementarity, Transfer of nutrients	Abiotic environment
177	Speed of canopy closure	Shoot complementarity, Temporal complementarity	Interactions & emergent properties
178	Speed of wind	Impact on abiotic environment	Abiotic environment
179	Stability of soil microbiomass	Impact on biotic environment	Biotic environment
180	Structure of the canopy	Impact on abiotic environment	Interactions & emergent properties
181	Temperature of the air	Impact on abiotic environment	Abiotic environment
182	Temperature of the air around plant A	Light competition	Abiotic environment

	NODE	NETWORK(S)	COMPARTMENT(S)
183	Thickness of leaves	Shoot complementarity	Plant A, Plant B
184	Time between harvests	Crop management, Temporal complementarity	Crop management, Interactions & emergent properties
185	Time between sowing or plantation	Crop management	Crop management
186	Transfer of allelopathic compounds	Impact of biotic environment	Interactions & emergent properties
187	Transfer of nutrients	Impact of biotic environment, Transfer of nutrients	Interactions & emergent properties
188	Turnover of roots	Competition, Transfer of nutrients	Plant A, Plant B
189	Vertical niche differentiation	Competition for water & nutrients, Impact on abiotic environment, Root complementarity	Interactions & emergent properties
190	Volume of soil explored	Impact of biotic environment, Root complementarity	Interactions & emergent properties
191	WUE	Impact on abiotic environment	Plant A, Plant B

Appendix C. VARIETIES, SOWING, PLANTATION AND HARVEST DATES, DENSITY AND SOWING/PLANTATION DISTANCES OF THE MODALITIES OF THE FIRST ON-FIELD TRIAL SET UP IN AGRICULTURAL EXPERIMENT STATION (CF. CHAPTER 3)

The densities of the crops in the intercrops are expressed based on the area of the plot and not on the area allocated to each crop within the plot. All crops from the first on-field trial set up in agricultural experiment station were sown/planted in 2019. A survival rate higher than 100% is linked to a bad thinning of the plants. Survival rate=ratio between the actual density at harvest and the expected density, Theoretical density ratio=ratio between the expected densities of the crop in intercropping and in pure crop, /=Not applicable, IC=intercropping, PC=pure crop.

C.1 Pure crops

CROP	VARIETY	SOWING OR PLANT-ATION	SOWING DATE	PLAN-TATION DATE	HARVEST DATE	DENSITY (PLANTS/M²)	MEAN SURVIVAL RATE (%)	ROW NUM-BER	INTER-ROWS DISTANCE (CM)	INTRA-ROWS DISTANCE (CM)
Beetroot	Alvro-Mono	P	19-05-08 19-05-17	19-06-12 19-06-21	19-08-08	33.33	86.81	6	15	20
Beetroot	Rhonda F1	P	19-05-08	19-06-12	19-08-08	33.33	165.28	6	15	20
Brussels sprout	Igor F1	P	19-05-08 19-05-17	19-06-12 19-06-21	19-11-08	2.8	62.50	2	60	60
Carrot	Jaune du Doubs	S	19-05-07 19-05-16	/	19-08-22	75	61.73	6	7	20
Chinese cabbage	Taisaï	P	19-05-08 19-05-17	19-06-12 19-06-21	19-08-09	6.25	61.11	3	40	40

CROP	VARIETY	SOWING OR PLANT-ATION	SOWING DATE	PLAN-TATION DATE	HARVEST DATE	DENSITY (PLANTS/M²)	MEAN SURVIVAL RATE (%)	ROW NUM-BER	INTER-ROWS DISTANCE (CM)	INTRA-ROWS DISTANCE (CM)
Fennel	Finale	P	19-05-08	19-06-12	19-08-09	11.11	95.83	4	30	35
Kohlrabi	Azur Star	P	19-05-08 19-05-17	19-06-12 19-06-21	19-08-08	8.33	69.44	3	35	40
Lamb's lettuce	Verte de Cambrai	S	19-05-07	/	19-08-09	225.69	NA	13	5	10
Parsnip	1/2 Long de Ger-nesey	S	19-05-07 19-05-16	/	19-08-23	21.92	87.88	3	10	40
Radish	Saxa 2	S	19-05-07	/	19-07-10	400	8.56	9	2	15
Rutabaga	Helenor	P	19-05-08		19-08-23	11.11	87.50	4	35	30
Savory	Annual	S	19-05-07 19-05-16	/	19-08-22	16.67	NA	4	20	30
Scorso-nera	Noir Géant de Russie	S	19-05-07 19-05-16	/	19-11-06	33.33	107.29	4	15	30
Scorso-nera	Enorma	S	19-05-07 19-05-16	/	19-11-06	33.33	65.63	4	10	30
Spinach	Escalade F1	S	19-05-07	/	19-07-10	81.25	80.91	9	10	15

CROP	VARIETY	SOWING OR PLANT-ATION	SOWING DATE	PLAN-TATION DATE	HARVEST DATE	DENSITY (PLANTS/M²)	MEAN SURVIVAL RATE (%)	ROW NUM-BER	INTER-ROWS DISTANCE (CM)	INTRA-ROWS DISTANCE (CM)
White onion	de Barletta	S	19-05-07 19-05-16	/	19-08-21	33.33	90.97	6	15	20
White onion	Glad-stone	S	19-05-07 19-05-16	/	19-08-21	33.33	22.92	6	15	20
Yellow onion	Hylander F1	S	19-05-07 19-05-16	/	19-10-11	33.33	70.83	6	15	20
Yellow onion	Sturon	S	19-05-07	/	19-10-11	33.33	95.14	6	15	20

C.2 Intercrops

CROP A	CROP B	ABBREVIATION	DIFFERENCE IN THE DATE OF SOWING/ PLANTING (DAYS)	DIFFERENCE IN THE DATE OF HARVEST (DAYS)	DENSITY (CROP A/CROP B) (PLANTS/M²)	THEORETICAL DENSITY RATIO (CROP A/CROP B)	MEAN SURVIVAL RATE (CROP A/CROP B) (%)	SPATIAL ORGANISATION	INTER-ROWS DISTANCE (CM)
Beetroot (Alvro-Mono)	**Yellow onion (Hylander F1)**	Bam & YOh	36	64	22.2 / 22.2	0.67 / 0.67	108.33 / 97.92	4 rows Bam 4 rows YOh ABABABAB	15
Beetroot (Rhonda F1)	**Rutubaga (Helenor)**	Br & RU	0	15	22.2 / 8.3	0.67 / 0.75	183.33 / 72.22	4 rows Br 3 rows RU ABABABA	17
Beetroot (Rhonda F1)	**Yellow onion (Sturon)**	BR & YOs	36	64	22.2 / 22.2	0.67 / 0.67	162.50 / 107.29	4 rows Br 4 rows YOh ABABABAB	15
Carrot (Jaune du Doubs)	**Yellow onion (Sturon)**	CA & YOs	0	50	50 / 22.2	0.67 / 0.67	114.81 / 42.71	4 rows CA 4 rows YOs ABABABAB	15
Carrot (Jaune du Doubs)	**Radish (Saxa 2)**	CA & RA	0	43	50 / 311.1	0.67 / 0.78	73.15 / 10.19	4 rows CA 7 rows RA BABABBBABAB	11
Chinese cabbage (Taisaï)	**Savory (Annual)**	ChC & SA	36	13	4.2 / 12.5	0.67 / 0.75	33.33 / NA	2 rows CC 3 rows SA BABAB	24

CROP A	CROP B	ABBREVIATION	DIFFERENCE IN THE DATE OF SOWING/ PLANTING (DAYS)	DIFFERENCE IN THE DATE OF HARVEST (DAYS)	DENSITY (CROP A/CROP B) (PLANTS/M²)	THEORETICAL DENSITY RATIO (CROP A/CROP B)	MEAN SURVIVAL RATE (CROP A/CROP B) (%)	SPATIAL ORGANISATION	INTER-ROWS DISTANCE (CM)
Fennel (Finale)	**Lamb's lettuce (Verte de Cambrai)**	F & L	36	0	8.3 / 173.6	0.75 / 0.77	81.94 / NA	3 rows F 10 rows L BBABBBABBBABB	9
Kohlrabi (Azur Star)	**Scorsonera (Noir Géant de Russie)**	K & SCbgr	36	90	5.6 / 16.7	0.67 / 0.75	95.83 / 70.83	2 rows K 3 rows SCbgr BABAB	24
Kohlrabi (Azur Star)	**White onion (Gladstone)**	K & WOg	36	13	5.6 / 22.2	0.67 / 0.67	91.67 / 72.92	2 rows K 4 rows WOg BABBAB	20
Kohlrabi (Azur Star)	**Yellow onion (Hylander F1)**	K & YOh	36	64	5.6 / 22.2	0.67 / 0.67	108.33 / 119.79	2 rows K 4 rows YOh BABBAB	20
Parsnip (1/2 Long de Gernesey)	**Rutubaga (Helenor)**	P & RU	36	0	15.3 / 8.3	0.67 / 0.75	116.67 / 97.22	2 rows P 3 rows RU BABAB	24
Parsnip (1/2 Long de Gernesey)	**Yellow onion (Sturon)**	P & YOs	0	49	15.3 / 22.2	0.67 / 0.67	124.24 / 80.21	2 rows P 4 rows YOs BABBAB	20

CROP A	CROP B	ABBREVIA-TION	DIFFERENCE IN THE DATE OF SOWING/ PLANTING (DAYS)	DIFFE-RENCE IN THE DATE OF HARVEST (DAYS)	DENSITY (CROP A/CROP B) (PLANTS/M²)	THEORE-TICAL DENSITY RATIO (CROP A/CROP B)	MEAN SURVIVAL RATE (CROP A/CROP B) (%)	SPATIAL ORGANISATION	INTER-ROWS DISTANCE (CM)
Spinach (Escalade F1)	**Brussels sprout (Igor F1)**	SP & BS	36	121	63.2 / 28	0.78 / 1	168.50 / 41.67	7 rows SP 2 rows BS AABAAABAA	13
Spinach (Escalade F1)	**Lamb's lettuce (Verte de Cambrai)**	SP & L	0	30	63.2 / 173.6	0.78 / 0.77	80.59 / NA	7 rows SP 10 rows L BABABBABABBABABAB	7
White onion (de Barletta)	**Scorsonera (Enorma)**	WOb & SCe	0	77	22.2 / 25	0.67 / 0.75	110.42 / 68.52	4 rows WOb 3 rows Sce ABABABA	17
Yellow onion (Sturon)	**Scorsonera (Noir Géant de Russie)**	YOs & SCbgr	0	26	22.2 / 16.7	0.67 / 0.75	77.08 / 79.17	4 rows YOs 3 rows SCbgr **ABABABA**	17

Appendix D. GROWTH CYCLE LENGTH AND ARCHITECTURAL CHARACTERISTICS OF THE CROPS OF THE FIRST ON-FIELD TRIAL SET UP IN AGRICULTURAL EXPERIMENT STATION (CF. CHAPTER 3).

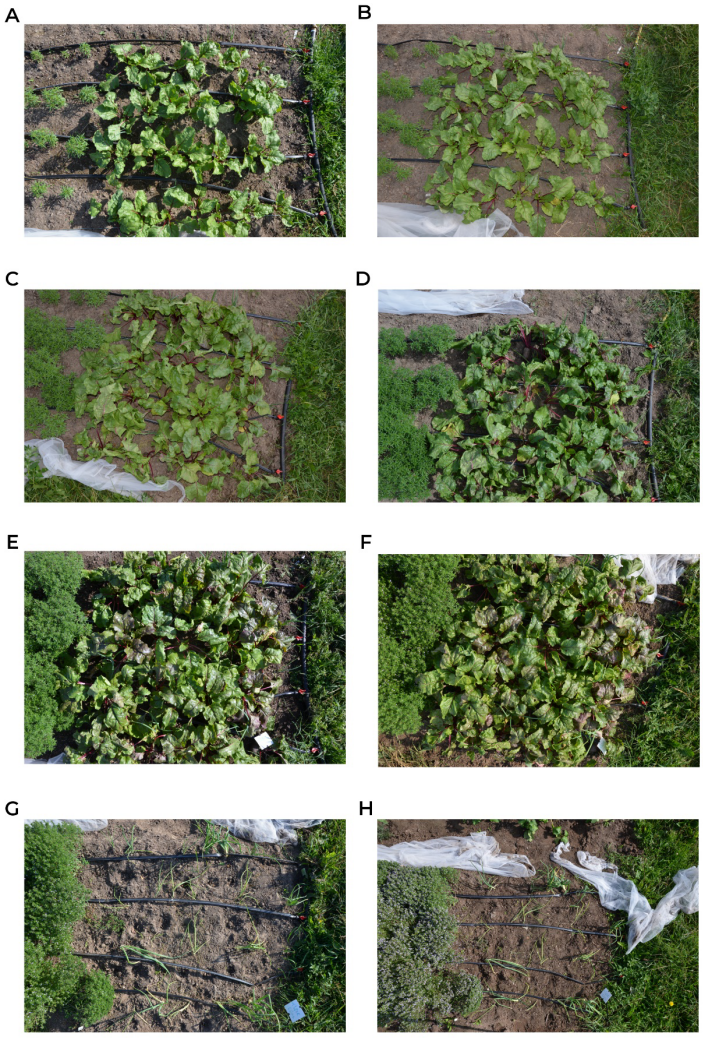
The data showed hereunder are derived from the book of Hervé-Gruyer & Hervé-Gruyer (2019), the website pages of the corresponding crop on the websites "Gerbeaud", "Ooreka", "Jardiner-malin", "Binette & Jardin" and "Wikipédia", from the technical sheets of the GAB/FRAB and of LPCbio, from the websites of the seeds retailers "Agrosemens" and "Semailles" and from Kutschera et al. (2009), Nishida (2011) and Weaver and Burner (1927). NA=Not available.

CROP	VARIETY	BOTANICAL FAMILY	TYPE OF VEGE-TABLE	AVERAGE GROWTH CYCLE LENGTH (DAYS)	ABOVE-GROUND GROWTH HABIT	HEIGHT (CM)	TYPE OF ROOT SYSTEM	ROOT DEPTH (CM)	ROOT SPREAD (CM)
Beetroot	Alvro-Mono	Chenopo-diaceae	Root	90	Spread	$38.75^{\pm 15.75}$	Taproot	$165.05^{\pm 68.11}$	$175.51^{\pm 48.96}$
	Rhonda F1	Chenopo-diaceae	Root	120	Spread	$38.75^{\pm 15.75}$	Taproot	$165.05^{\pm 68.11}$	$175.51^{\pm 48.96}$
Brussels sprout	Igor F1	Brassi-caceae	Leaf	200	Upright	$93.35^{\pm 29.01}$	Taproot	$91.07^{\pm 35.48}$	$146.96^{\pm 35.45}$
Carrot	Jaune du Doubs	Apiaceae	Root	180	Upright	$40.01^{\pm 19.99}$	Taproot	$115.19^{\pm 69.23}$	$95.38^{\pm 54.87}$
Chinese cabbage	Taisaï	Brassi-caceae	Leaf	45-55	Upright	$32.00^{\pm 10.95}$	Taproot	$74.96^{\pm 30.26}$	$147.84^{\pm 18.62}$
Fennel	Finale	Apiaceae	Leaf	90	Upright	$68.47^{\pm 21.53}$	Taproot	$81.75^{\pm 52.35}$	$108.12^{\pm 23.87}$
Kohlrabi	Azur Star	Brassi-caceae	Root	60-100	Spread	$36.31^{\pm 6.19}$	Taproot	$115.11^{\pm 86.28}$	$140.60^{\pm 34.72}$

CROP	VARIETY	BOTANICAL FAMILY	TYPE OF VEGE-TABLE	AVERAGE GROWTH CYCLE LENGTH (DAYS)	ABOVE-GROUND GROWTH HABIT	HEIGHT (CM)	TYPE OF ROOT SYSTEM	ROOT DEPTH (CM)	ROOT SPREAD (CM)
Lamb's lettuce	Verte de Cambrai	Valeria-naceae	Leaf	60-90	Spread	$24.86^{\pm 11.18}$	Taproot	$12.83^{\pm 4.51}$	$55^{/}$
Parsnip	1/2 Long de Gernesey	Apiaceae	Root	120	Upright	$67.47^{\pm 22.89}$	Taproot	$176.88^{\pm 59.97}$	$149.67^{\pm 34.94}$
Radish	Saxa 2	Brassi-caceae	Root	30-45	Upright	$19.68^{\pm 12.60}$	Taproot	$59.15^{\pm 43.96}$	92.28±49.24
Rutabaga	Helenor	Brassi-caceae	Root	110	Spread	$45.03^{\pm 24.63}$	Taproot	$78.76^{\pm 15.69}$	$86.66^{\pm 19.88}$
Savory	Annual	Lamia-ceae	Leaf	90	Upright	$31.25^{\pm 12.75}$	Taproot	$25.40^{/}$	NA
Scorso-nera	Noir Géant de Russie	Astera-ceae	Root	280	Upright	$65.25^{\pm 33.06}$	Taproot	$145.31^{\pm 34.92}$	$53.62^{\pm 23.16}$
	Enorma	Astera-ceae	Root	135-150	Upright	$70.00^{\pm 29.44}$	Taproot	170^{+NA}	70^{+NA}
Spinach	Escalade F1	Chenopo-diaceae	Leaf	60-75	Spread	$21.03^{\pm 8.75}$	Taproot	$69.24^{\pm 29.24}$	$62.70^{\pm 21.02}$
White onion	de Barletta	Alliaceae	Bulb	60	Upright	$80.27^{\pm 22.79}$	Fasciculate	$50.39^{\pm 26.75}$	$71.86^{\pm 23.66}$
	Gladstone	Alliaceae	Bulb	120	Upright	$80.27^{\pm 22.79}$	Fasciculate	$50.39^{\pm 26.75}$	$71.86^{\pm 23.66}$
Yellow onion	Hylander F1	Alliaceae	Bulb	172	Upright	$80.27^{\pm 22.79}$	Fasciculate	$50.39^{\pm 26.75}$	$71.86^{\pm 23.66}$
	Sturon	Alliaceae	Bulb	150	Upright	$80.27^{\pm 22.79}$	Fasciculate	$50.39^{\pm 26.75}$	$71.86^{\pm 23.66}$

Appendix E. EXAMPLE OF A SEQUENCE OF CANOPY PICTURES

The pictures presented hereunder were taken with a regular RGB camera, placed above the canopy, with the lens perpendicular to the ground. The pictures below were taken above a plot of beetroot + onion intercrop (Bam & YOh) from the trial set in agricultural experiment station in 2019 (cf. Chapter 3), on the 3rd of July (A), 8th of July (B), 17th of July (C), 22nd of July (D), 30th of July (E), 6th of August (F), 12th of August (G) and 20th of July (H).



Appendix F. Details of the statistical analyses of the first on-field trial set up in agricultural experiment station (cf. Chapter 3)

F.1 Outliers removal

Despite the anti-insect veils, Chinese cabbages suffered a lot of flea beetle damage. Therefore, the plots of pure crop of Chinese cabbage and intercrop of Chinese cabbage and savory were removed from the data, as well as the plots of pure crop of savory, as the savory was only intercropped with Chinese cabbage. Moreover, because of warm spring, radishes and spinaches developed faster than expected and went to seed before the germination or plantation of their companion crops. Therefore, we removed from the data the plots of pure crop of spinach, pure crop of radish, intercrop of radish and carrot, intercrop of spinach and lamb's lettuce, intercrop of spinach and Brussels' sprouts and pure crop of Brussels' sprouts. As carrots and lamb's lettuce were intercropped with other crops than radish and spinach, we kept the data from their pure crop.

F.2 Correction for differences in sowing/harvest dates

Because of a lack of seeds during the setting up of the trial, some of the plots were sown nine days after the others. To take into account this difference, we estimated, for each modality and each crop, the effect of the sowing date on each of our punctual variable, i.e. yield variables, mean weight per plant, harvest index, root-shoot ratio, vegetable size and leaf area, using a linear mixed model with "ModalityCrop", i.e. a variable gathering the crop and the modality, and "Sowing date" as fixed factors and "Block" as random factor. Then, we corrected the data of the plots sowed at the second sowing date using the estimate of the effect of the sowing date. These corrected data were used for the subsequent statistical analyses. Regarding the temporal data, i.e. soil coverage, percentage of iPAR, as there was no more differences between the curves of two repetitions of the same modality sown nine days apart than between the curves of two repetitions of the same modality sown at the same date, we considered that all modalities were set in place at the first sowing date.

F.3 Statistical analysis of time-series data

As the evolution curves of soil coverage and iPAR could not be simplified with a linear regression, we used a contingency table method. Firstly, for each variable, each modality and each measurement date, we attributed to each curve, i.e. the curves of the first pure crop, the second pure crop, the intercrop and the reference line[20], a rank, based on its value. Ranks were attributed in descending order, i.e. the higher value was attributed the rank "1". Secondly, we created contingency tables for each complementarity score component: columns represented the ranks – either 1, 2, 3 or 4 –, lines represented the levels of the score component – either "+" or "-" – and the intersection between one column and one row indicated the number of times an intercrop with a "+" or "-" – according to the line we considered – of the studied score component was in first, second, third or fourth rank – according to the column we considered –. For each score component, two contingency tables were created: one for the ranking of the intercrop curves before the harvest of the crop with the shortest cycle in each intercrop and one for the ranking of the intercrop curves after the harvest of this crop. The intercrops for which there were no time difference between the harvests of the two component crops were not taken into account in the second contingency tables. Finally, we tested the independency between the rows and the columns of each contingency table – eighteen in total: three score components, three variables, two parts of the growth cycle – using the *chisq.test* function in R v.3.4.1.

[20] The reference line was calculated, for each measurement date, by (i) multiplying the value of each pure crop at the same measurement date by the ratio between the density of the crop in intercrop and its density in pure crop and (ii) summing the corrected values of the two pure crops.

Appendix G. VARIETIES, SOWING, PLANTATION AND HARVEST DATES, DENSITY AND SOWING/PLANTATION DISTANCES OF THE MODALITIES OF THE SECOND ON-FIELD TRIALS SET UP IN AGRICULTURAL EXPERIMENT STATION (CF. CHAPTER 4)

The densities of the crops in the intercrops are expressed based on the area of the plot and not on the area allocated to each crop within the plot. All the crops from the second on-field trial set up in agricultural experiment station were sown/planted in 2020. A survival rate higher than 100% is linked to a bad thinning of the plants. Survival rate=ratio between the actual density at harvest and the expected density, Theoretical density ratio=ratio between the expected density of the crop in intercropping and in pure crop, /=Not applicable, IC=intercropping, PC=pure crop.

G.1 Pure crops

CROP	VARIETY	SOWING/ PLANTA-TION	SOWING DATE	PLAN-TATION DATE	HARVEST DATE(S)	DENSITY (PLANTS/M²)	MEAN SURVIVAL RATE (%)	NUM-BER OF ROWS	INTER-ROWS DISTANCE (CM)	INTRA-ROWS DISTANCE (CM)
Broccoli	Jets Vert Calabrais	P	20-05-28	20-07-03	20-09-28	3.6	88.89	2	70	45
Collard Cabbage	de Château-renard	P	20-05-28	20-07-03	20-10-12	3.6	91.67	2	50	50
Dwarf bean	Cupidon	S	20-06-10	/	20-08-06 20-08-07 20-08-10 20-08-18 20-08-24 20-09-15	21.4	99.07	3	40	10
Fennel	Finale	P	20-05-28	20-07-03	20-09-14	12.5	87.30	3	35	20
Kale	Westlandse winter	P	20-05-28	20-07-03	20-10-08	2.4	100.00	2	60	40
String bean	Vitalis	S	20-06-10	/	20-08-14 20-08-16 20-08-19 20-08-25 20-08-26 20-09-08 20-09-24	10.7	90.74	2	75	30
White onion	Gladstone	S	20-05-29	/	20-10-13	41.7	75.24	5	25	10

G.2 Intercrops

CROP A	CROP B	ABBREVIATION	DIFFERENCE IN THE DATE OF SOWING/PLANTING (DAYS)	DIFFERENCE IN THE DATE OF HARVEST (DAYS)	DENSITY (CROP A/CROP B) (PLANTS/M²)	THEORETICAL DENSITY RATIO (CROP A/CROP B)	MEAN SURVIVAL RATE (CROP A/CROP B) (%)	SPATIAL ORGANISATION	INTER-ROWS DISTANCE (CM)
Dwarf bean (Cupidon)	**Collard Cabbage (Château-renard)**	DB & CC	23	67	14.3 / 3.6	0.67 / 1	101.39 / 88.89	**2 rows DB 2 rows CC**	30
Dwarf bean (Cupidon)	**Broccoli (Jets Vert Calabrais)**	DB & B	23	53	14.3 / 3.6	0.67 / 1	98.61 / 100.00	**2 rows DB 2 rows B**	30
Dwarf bean (Cupidon)	**Fennel (Finale)**	DB & F	23	39	14.3 / 8.3	0.67 / 0.67	109.72 / 90.48	**2 rows DB 2 rows F**	30
Dwarf bean (Cupidon)	**Kale (Westlandse winter)**	DB & KA	23	63	14.3 / 2.4	0.67 / 1	97.22 / 91.67	**2 rows DB 2 rows KA**	30
Dwarf bean (Cupidon)	**String bean (Vitalis)**	DB & SB	0	8	14.3 / 10.7	0.67 / 1	98.67 / 100.00	**2 rows DB 2 rows SB**	30
Dwarf bean (Cupidon)	**White onion (Gladstone)**	DB & WOg	12	68	14.3 / 33.3	0.67 / 0.8	100.00 / 51.19	**2 rows DB 4 rows WOg**	20
Collard Cabbage (Château-renard)	**Broccoli (Jets Vert Calabrais)**	CC & B	0	14	3.6 / 3.6	1 / 1	61.11 / 88.89	**2 rows CC 2 rows B**	30

CROP A	CROP B	ABBREVIATION	DIFFERENCE IN THE DATE OF SOWING/PLANTING (DAYS)	DIFFERENCE IN THE DATE OF HARVEST (DAYS)	DENSITY (CROP A/CROP B) (PLANTS/M²)	THEORETICAL DENSITY RATIO (CROP A/CROP B)	MEAN SURVIVAL RATE (CROP A/CROP B) (%)	SPATIAL ORGANISATION	INTER-ROWS DISTANCE (CM)
Collard Cabbage (Châteaurenard)	**Fennel (Finale)**	CC & F	0	28	3.6 / 8.3	1 / 0.67	83.33 / 95.24	**2 rows CC 2 rows F**	30
Collard Cabbage (Châteaurenard)	**Kale (Westlandse winter)**	CC & KA	0	4	3.6 / 2.4	1 / 1	94.44 / 100.00	**2 rows CC 2 rows KA**	30
Collard Cabbage (Châteaurenard)	**String bean (Vitalis)**	CC & SB	23	59	3.6 / 10.7	1 / 1	83.33 / 109.26	**2 rows CC 2 rows SB**	30
Collard Cabbage (Châteaurenard)	**White onion (Gladstone)**	CC & WOg	35	1	3.6 / 33.3	1 / 0.8	94.44 / 54.17	**2 rows CC 4 rows WOg**	20
Broccoli (Jets Vert Calabrais)	**Fennel (Finale)**	B & F	0	14	3.6 / 8.3	1 / 0.67	94.44 / 100.00	**2 rows B 2 rows F**	30
Broccoli (Jets Vert Calabrais)	**Kale (Westlandse winter)**	B & KA	0	10	3.6 / 2.4	1 / 1	88.89 / 91.67	**2 rows B 2 rows KA**	30

CROP A	CROP B	ABBREVIATION	DIFFERENCE IN THE DATE OF SOWING/PLANTING (DAYS)	DIFFERENCE IN THE DATE OF HARVEST (DAYS)	DENSITY (CROP A/CROP B) (PLANTS/M²)	THEORETICAL DENSITY RATIO (CROP A/CROP B)	MEAN SURVIVAL RATE (CROP A/CROP B) (%)	SPATIAL ORGANISATION	INTER-ROWS DISTANCE (CM)
Broccoli (Jets Vert Calabrais)	**String bean (Vitalis)**	B & SB	23	45	3.6 / 10.7	1 / 1	61.11 / 112.96	**2 rows B 2 rows SB**	30
Broccoli (Jets Vert Calabrais)	**White onion (Gladstone)**	B & WOg	35	15	3.6 / 33.3	1 / 0.8	88.89 / 70.83	**2 rows B 4 rows WOg**	20
Fennel (Finale)	**Kale (Westlandse winter)**	F & KA	0	24	8.3 / 2.4	0.67 / 1	102.38 / 91.67	**2 rows F 2 rows KA**	30
Fennel (Finale)	**String bean (Vitalis)**	F & SB	23	31	8.3 / 10.7	0.67 / 1	66.67 / 109.26	**2 rows F 2 rows SB**	30
Fennel (Finale)	**White onion (Gladstone)**	F & WOg	35	29	8.3 / 33.3	0.67 / 0.8	92.86 / 76.79	**2 rows F 4 rows WOg**	20
Kale (Westlandse winter)	**String bean (Vitalis)**	KA & SB	23	55	2.4 / 10.7	1 / 1	83.33 / 107.41	**2 rows KA 2 rows SB**	30
Kale (Westlandse winter)	**White onion (Gladstone)**	KA & WOg	35	5	2.4 / 33.3	1 / 0.8	100.00 / 75.60	**2 rows KA 4 rows WOg**	20
String bean (Vitalis)	**White onion (Gladstone)**	SB & WOg	12	60	10.7 / 33.3	1 / 0.8	116.67 / 32.14	**2 rows SB 4 rows WOg**	20

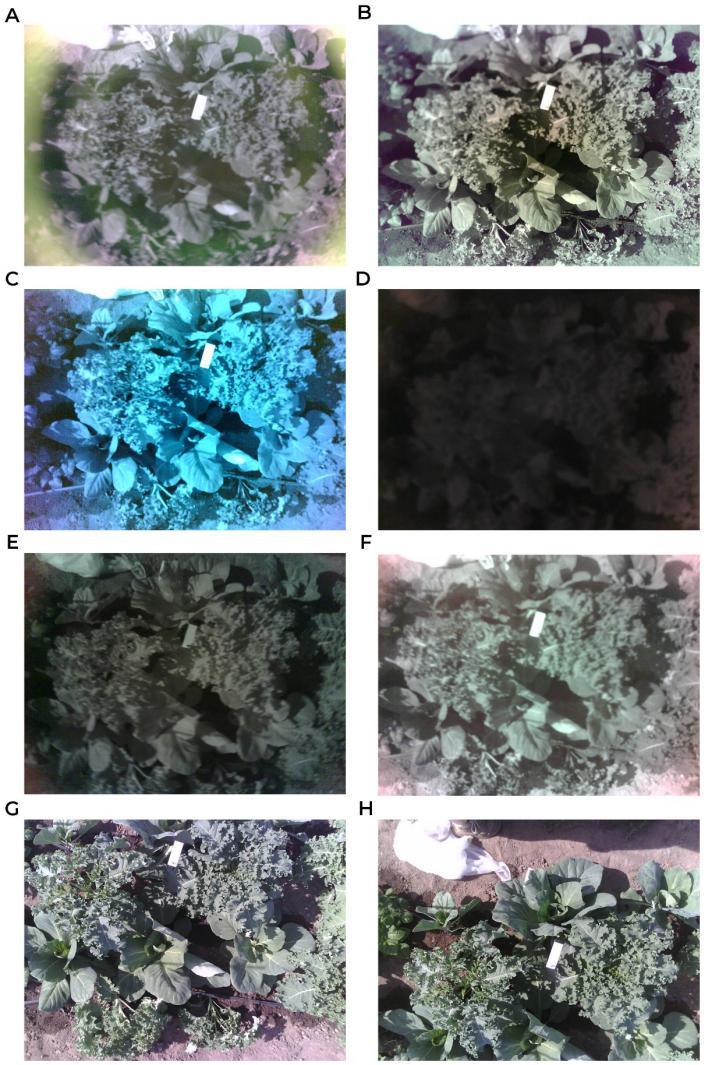
Appendix H. GROWTH CYCLE LENGTH AND ARCHITECTURAL CHARACTERISTICS OF THE CROPS OF THE SECOND ON-FIELD TRIALS SET UP IN AGRICULTURAL EXPERIMENT STATION (CF. CHAPTER 4)

The data shown hereunder are derived from the book of Hervé-Gruyer & Hervé-Gruyer (2019), the website pages of the corresponding crop on the websites "Gerbeaud", "Ooreka", "Jardiner-malin", "Binette & Jardin" and "Wikipédia", from the technical sheets of the GAB/FRAB and of LPCbio, from the websites of the seeds retailers "Agrosemens" and "Semailles" and from Kutschera et al. (2009), Nishida (2011) and Weaver and Burner (1927).

CROP	VARIETY	BOTANICAL FAMILY	TYPE OF VEGETABLE	AVERAGE GROWTH CYCLE LENGTH (DAYS)	ABOVE-GROUND GROWTH HABIT	HEIGHT (CM)	TYPE OF ROOT SYSTEM	ROOT DEPTH (CM)	ROOT SPREAD (CM)
Broccoli	Jets Vert Calabrais	Brassicaceae	Flower	75-90	Spread	$66.42^{\pm 28.56}$	Taproot	$75.06^{\pm 25.46}$	$120.15^{\pm /}$
Collard cabbage	De Château-renard	Brassicaceae	Leaf	120	Spread	$52.03^{\pm 24.30}$	Taproot	$109.79^{\pm 91.88}$	$162.57^{\pm 51.57}$
Dwarf bean	Cupidon	Fabaceae	Fruit	60-75	Spread	$43.97^{\pm 9.42}$	Taproot	$76.82^{\pm 25.66}$	$124.11^{\pm 22.48}$
Fennel	Finale	Apiaceae	Leaf	90	Upright	$68.47^{\pm 21.53}$	Taproot	$81.75^{\pm 52.35}$	$108.12^{\pm 23.87}$
Kale	Westlandse winter	Brassicaceae	Leaf	120-150	Spread	$74.40^{\pm 57.12}$	Taproot	$56.34^{\pm 32.49}$	$105.9^{\pm NA}$
String bean	Vitalis	Fabaceae	Fruit	60-90	Upright	$195.26^{\pm 96.29}$	Taproot	$82.38^{\pm 24.70}$	$122.73^{\pm 23.62}$
White onion	Gladstone	Alliaceae	Bulb	120	Upright	$80.27^{\pm 22.79}$	Fasciculate	$50.39^{\pm 26.75}$	$71.86^{\pm 23.66}$

Appendix I. EXAMPLE OF A SET OF EIGHT PICTURES TAKEN WITH THE MULTISPECTRAL CAMERA

The eight picture presented hereunder were taken in the second trial set in agricultural experiment station (cf. Chapter 4) on the 6th of August 2020. Pictures are from a plot of collard cabbage + kale intercrop. Each one of the picture was taken by one of the eight camera installed on the device. Six of them were equipped with optical bandpass filters (pictures A to F) and two were usual RGB cameras (pictures G and H). The bandpass filters we used were the following : 445-455 nm (A), 563-573 nm (B), 671-681 nm (C), 687.5-712.5 nm (D), 725-735 nm (E) and 837.5-862.5 nm (F).



Appendix J. Details of the statistical analyses of the second on-field trials set up in agricultural experiment station (cf. Chapter 4)

J.1 Correction for differences in sowing/harvest dates

The first harvest of dwarf beans and string beans was spread over two (string beans, 14th and 16th of June) to three (dwarf beans, 7th, 8th and 10th of June) days. As the date of the harvest had a significant effect on both the weight of harvested beans and the number of harvested beans, we applied a correction to our data. For each bean type, we estimated the effect of each harvest date on the harvested weight and the number of harvested beans using a linear mixed model (*lmer* function in R v.3.4.1) with "Harvest date", used as a factor variable, as fixed factor and "Block" as random factor. Then, we subtracted this effect from the harvested weight and the number of harvested beans of the latest harvests (16th of June for string beans, 8th and 10th of June for dwarf beans). These corrected data were used for the subsequent statistical analyses and for the calculation of the marketable harvested biomass of beans.

Appendix K. DESCRIPTION OF THE DESIGN OF THE 2019 PARTICIPATORY TRIAL FOR MARKET GARDENERS

Document describing the 2019 participatory trial and summarising the decisions taken during the preparation meeting with market gardeners (cf. Chapter 6). It was sent to every market gardener interested in taking part in the trial.

Essai participatif sur les associations de cultures

Guide pratique à destination des maraîcher(e)s

1. Contexte

Les associations de cultures sont une pratique prônée par certains modèles agricoles alternatifs (ex. : agroécologie, permaculture) dont les avantages, nombreux, ont déjà été largement démontrés : augmentation du rendement, réduction de l'érosion, amélioration de la fertilité du sol, diminution de l'impact des organismes nuisibles, etc. Leur intérêt n'est donc plus à prouver. Toutefois, la compréhension que l'on a des associations de cultures est actuellement très limitée : si elles peuvent fonctionner parfaitement dans un certain contexte, elles peuvent tout aussi bien rater complètement dans un autre contexte, sans que l'on sache très bien pourquoi. Les agriculteur(trice)s prennent donc des risques importants en en mettant en place. Par ailleurs, l'intérêt d'une association de cultures étudiée dans le cadre d'une recherche scientifique est généralement déterminée sans tenir compte des critères d'évaluation propres aux agriculteurs(trice)s (facilité de mise en place ? demande en travail ? etc.). Son intérêt productif peut donc être prouvé, mais pas sa pertinence pour les agriculteurs(trice)s.

Sur base de ces constats, nous avons décidé de mettre en place une recherche participative pour étudier les associations de cultures en maraîchage en Belgique et de réaliser un essai expérimental participatif. L'essai participatif qui sera mis en place cette année est un premier test et nous permettra d'avoir des premiers résultats et de modifier notre méthodologie, si nécessaire, pour mettre au point un second essai participatif l'année prochaine en collaboration avec, on l'espère, un plus grand nombre de maraîcher(e)s. En participant à ce premier essai vous serez donc, en quelque sorte, des pionnier(e)s !

2. Objectif

Lors de la réunion précédente (29/11/2018) plusieurs problèmes relatifs aux associations de cultures sont ressortis. Parmi ceux-ci, le problème de la variabilité des résultats d'une même association en fonction des années et, plus généralement, en fonction des conditions environnementales. Cette question est particulièrement importante car c'est la variabilité de comportement d'une même association qui empêche les résultats obtenus à son sujet dans certaines conditions d'être généralisés à d'autres conditions. Nous avons donc décidé de nous pencher sur ce sujet. La thèse est malheureusement trop courte pour espérer pouvoir évaluer la stabilité d'une association au cours du temps. Cependant, le travail en collaboration avec vous, maraîcher(e)s, qui venez de diverses zones de la Belgique nous permet d'aborder la question de la variabilité spatiale : le résultat d'une même association est-il différent selon la zone dans laquelle on se trouve et, si oui, quelles pourraient être les causes de ces différences ?

En testant une même association A-B, et les cultures pures correspondantes A et B, chez chacun(e) d'entre vous, nous espérons pouvoir obtenir des premiers éléments de réponse à cette question et mieux comprendre les causes de la variabilité des résultats en association.

Un second thème d'intérêt qui est ressorti lors de la réunion précédente est celui de l'organisation spatiale des associations. Il n'existe en effet aucune référence concernant les densités et les distances de plantations préconisées en association. Lorsque l'on associe des cultures, deux modèles d'organisation spatiale sont prédominants :

- Le modèle dit « additif » : l'association A-B a une densité égale à la somme des densités de la culture pure A et de la culture pure B (Fig. 1),

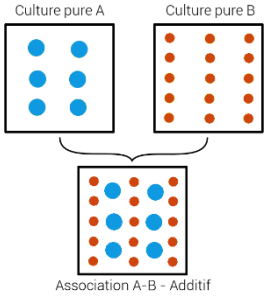


Figure 1 - Schéma du modèle additif.

- Le modèle dit « de remplacement » : l'association A-B a une densité égale à 50 % de la densité de la culture pure A + 50 % de la densité de la culture pure B (Fig. 2).

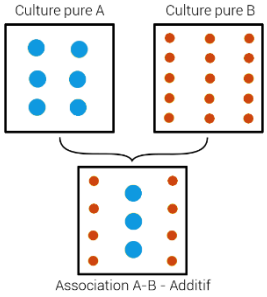


Figure 2 - Schéma du modèle de remplacement.

Même si la logique laisse penser que le modèle additif ne fonctionne que lorsque la différence de durée de cycle entre les cultures est importante et que le modèle de remplacement s'impose dans les autres cas, il n'existe pas d'informations claires à ce sujet, et encore moins en ce qui concerne l'impact des conditions environnementales sur le résultat de ces deux modèles. Nous avons donc mis au point un dispositif expérimental qui permet d'aborder à la fois la question de la variabilité des résultats et celle de l'organisation spatiale.

3. Dispositif expérimental

a. Cultures testées

Les cultures étudiées lors de l'essai seront :

- L'oignon ciboule (culture A)
- La carotte botte (culture B)

b. Modalités

Si vous souhaitez participer à l'essai participatif, vous devrez tester, sur votre exploitation :

- L'association A-B en modèle additif,
- L'association A-B en modèle de remplacement,
- La culture pure A,
- La culture pure B.

Ces quatre types de cultures sont appelés les « modalités » de l'essai. Chacune de ces modalités devra être répétée trois fois sur chaque exploitation. Les répétitions sont très importantes dans un essai scientifique car elles permettent d'avoir des données sur le comportement moyen de chaque modalité. En ne basant ses résultats que sur une seule répétition, on peut dresser des conclusions erronées car la répétition que l'on a étudiée peut avoir eu un comportement exceptionnel et ne pas refléter le comportement habituel de cette modalité.

Dans notre cas, nous avons donc trois répétitions, chaque répétition comprenant quatre modalités (A, B, A-B additif, A-B remplacement).

Chaque modalité devra être testée sur une longueur de planche de 2 mètres. La largeur des planches a été fixée à 1,20 m. Entre chaque modalité sera mise en place une zone tampon de 50 cm. Au total, une répétition devrait donc prendre une longueur d'environ 10 mètres (Fig. 3). Les différentes modalités sont réparties de manière aléatoire sur ce segment de 10 mètres. Les trois répétitions vont nécessiter 30 mètres de planche (3*10m).

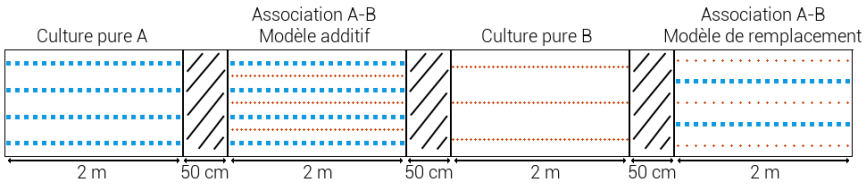


Figure 3 - Schéma d'une répétition comprenant les quatre modalités : les deux cultures pures et les deux modèles d'association.

c. Répartition dans l'exploitation

Les répétitions (blocs de quatre modalités) doivent être placées à la suite les unes des autres. En effet, au sein d'une même exploitation, il peut y avoir des variations d'environnement. On souhaite limiter les sources de variabilité en répétant toutes les modalités au même endroit. Les quatre modalités d'une même répétition doivent impérativement être placées les unes à la suite des

autres. Les trois figures ci-dessous (Fig. 4) représentent la répartition des modalités et des répétitions au sein d'une exploitation. La première est un exemple de bonne répartition, les deux suivantes sont des exemples de mauvaises répartitions.

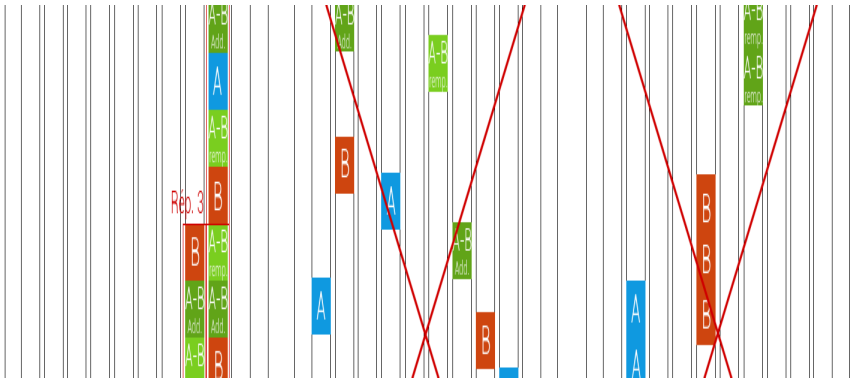


Figure 4 - Exemples de bonne (gauche) et mauvaises (milieu et droite) répartitions des modalités et répétitions dans une exploitation.

4. Aspects pratiques

a. Cultures testées

Les cultures choisies pour être testées lors de l'essai sont la carotte botte et l'oignon ciboule. Les quatre modalités de l'essai sont donc :

- Une culture pure de carottes botte,
- Une culture pure d'oignons ciboules,
- Une association de carottes botte et d'oignons ciboules en modèle additif,
- Une association de carottes botte et d'oignons ciboules en modèle de remplacement.

b. Préparation du sol

La préparation du sol se fait comme le(la) maraîcher(e) en a l'habitude. La seule restriction est que **les planches doivent avoir une largeur de 1,20 mètres**.

Le(la) maraîcher(e) peut décider de faire une planche entièrement surélevée (butte) ou entièrement plate. Toutefois, nous souhaiterions, dans la mesure du possible, avoir deux groupes équilibrés entre les deux options.

L'installation d'un paillage est également laissée à l'appréciation des maraîcher(e)s. À nouveau, nous souhaiterions avoir deux groupes équilibrés entre les deux options (avec ou sans paillage).

c. Distances de plantation et date de mise en place

Les distances de plantation et les dates de mise en place ont été décidées en concertation avec un petit groupe de maraîchers et maraîchères. Ces distances et dates de plantation sont imposées à tou(te)s les maraicher(e)s participant à l'essai pour permettre une comparaison entre eux(elles).

Dates de mise en place :

- La carotte botte sera semée lors de la deuxième quinzaine d'avril. Une date plus précise sera fixée dans cet intervalle en fonction des conditions climatiques du moment. Cette date sera décidée par concertation entre les différent(e)s participant(e)s à l'essai. Une fois les carottes semées, un voile P17 devra être installé par tou(te)s les participant(e)s sur les planches de l'essai.
- L'oignon ciboule sera repiqué trois semaines après le semis de la carotte (vers mi-mai). La date exacte dépendra de la date choisie pour le semis des carottes. En décalant les mises en place, on laisse aux carottes le temps de germer et on laisse la possibilité de faire un premier désherbage à la binette avant d'implanter l'oignon.

Il est important que, dans chaque exploitation, **chaque culture soit semée/repiquée le même jour sur pour les différentes modalités et les différentes répétitions**.

Distances de plantation :

Le nombre de rangs est donné pour une largeur de planche de 1,20 m, largeur choisie pour l'essai. Les **distances de plantation sont imposées** pour chacune des modalités. Elles doivent être identiques pour toutes les répétitions et chez tou(te)s les participant(e)s.

- *Carotte botte en culture pure* : semées en trois lignes, distantes de 40 cm. Pour éviter de devoir tenir compte de l'impact des différences d'éclaircissage entre les participant(e)s et pour favoriser la standardisation des distances de plantation, des rubans seront utilisés pour le semis des carottes (Fig. 5).



Figure 5 - Organisation spatiale des carottes en culture pure.

- *Oignon ciboule en culture pure* : repiqués en quatre lignes, distantes de 30 cm; plants distants de 10 cm dans la ligne (Fig. 6).

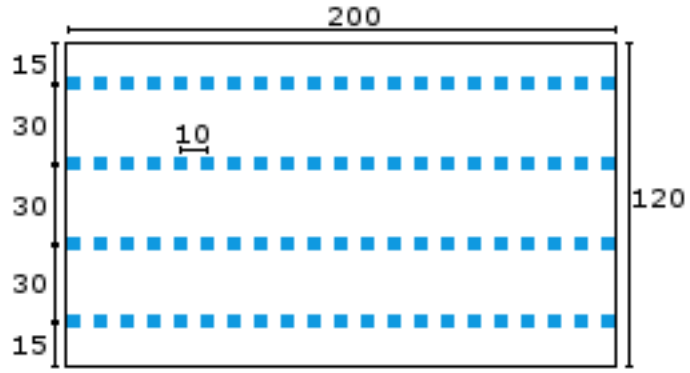


Figure 6 - Organisation spatiale des oignons en culture pure.

- *Association oignon-carotte en modèle additif* : sept lignes (trois lignes de carotte, quatre lignes d'oignon) distantes de 15 cm ; les distances dans les lignes restent identiques aux cultures pures (10 cm pour l'oignon ciboule, distance du ruban pour la carotte). Les lignes de carottes et d'oignons sont alternées (o.-c.-o.-c.-o.-c.-o.), de sorte que la distance entre deux lignes de la même culture est de 30 cm (Fig. 7). → 100 % carotte en culture pure, 100 % oignon en culture pure → Densité totale=200 %

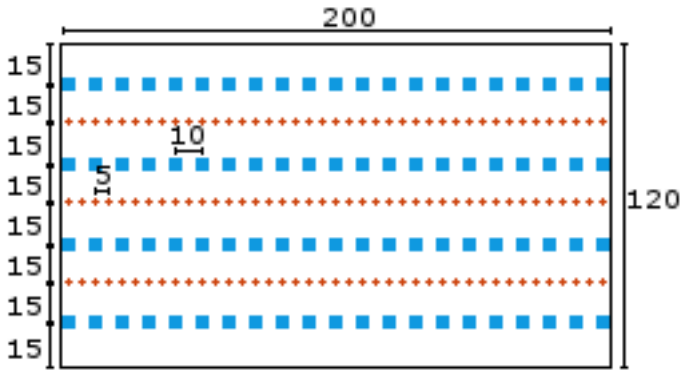


Figure 7 - Organisation spatiale de l'association carottes-oignons dans le modèle additif.

- *Association oignon-carotte en modèle de remplacement* : trois lignes de carotte et deux lignes d'oignon, distantes de 25 cm. Le but du modèle de remplacement est de diviser par deux la densité de chacune des cultures par rapport aux cultures pures. Pour les oignons, la distance dans la ligne reste de 10 cm. Pour les carottes, par contre, nous vous demanderons de les éclaircir une fois germées, en enlevant une carotte sur deux, afin d'obtenir une densité de 50% par rapport à la densité de la culture pure. → 50 % carotte en culture pure, 50 % oignon en culture pure. → Densité totale=100 %

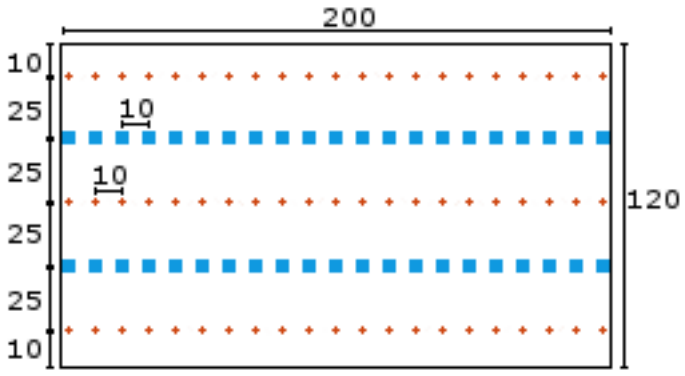


Figure 8 - Organisation spatiale de l'association carottes-oignons dans le modèle de remplacement.

d. Fertilisation

La fertilisation est laissée à l'appréciation des maraîcher(e)s, mais tout ajout en prévision de ou durant l'essai doit être noté et décrit.

Pour permettre une comparaison, la même fertilisation doit être appliquée pour toutes les modalités et toutes les répétitions de l'essai.

e. Désherbage

La fréquence et le mode de désherbage sont laissés à l'appréciation des maraîcher(e)s, mais toute action de désherbage doit être notée et décrite. Dans la mesure du possible, le temps nécessaire à l'action de désherbage pour chaque modalité dans chaque répétition devra être indiqué. De cette façon, nous pourrons par la suite comparer les demandes en désherbage des différentes modalités de l'essai.

f. Gestion des pestes

Certain(e)s maraîcher(e)s ont marqué leur intérêt pour la présence potentielle d'un effet phytosanitaire positif dans l'association « oignon-carotte ». L'oignon repousserait en effet la mouche de la carotte. Pour pouvoir étudier cet effet chez certain(e)s des participant(e)s, deux modes de gestion des pestes sont proposés :

- L'utilisation d'un voile anti-insectes pour ceux ne souhaitant pas prendre de risques,
- L'absence de voile anti-insectes pour ceux souhaitant étudier l'effet phytosanitaire,

Cependant, ne pas mettre de voile anti-insectes nous fait prendre le risque de perdre des points de comparaison pour notre essai (si toutes les carottes d'une exploitation sont perdues à cause de la mouche de la carotte, nous n'aurons pas de résultats pour cette exploitation et nous aurons donc un point de comparaison en moins). Pour éviter les pertes, nous vous demandons donc, si vous ne souhaitez pas mettre de voile, soit :

- D'utiliser des moyens sûrs pour empêcher les pertes (produits phytos) – on pourra alors observer la différence de fréquence de pulvérisation nécessaire entre la culture pure de carottes et les associations,
- De faire quatre répétitions pour chaque modalité plutôt que trois ; de placer un voile sur deux d'entre elles et pas de voile sur les deux autres. De cette façon, on s'assure de ne pas perdre un point de comparaison à cause de la mouche.
- Dans le cas où aucune de ces trois options (voile (3rep.), pas de voile + phytos (3rep.), voile (2rep.) + pas de voile

(2rep.)) ne vous convient, il est envisageable que vous fassiez trois répétitions sans voile, mais nous souhaiterions dans la mesure du possible éviter cette option.

g. Irrigation

Tou(te)s les participant(e)s s'engagent à fournir aux cultures de l'essai suffisamment d'eau pour qu'elles ne soient pas influencées par ce facteur. Toute action d'arrosage doit être notée pour chaque modalité et chaque répétition avec, si possible, une estimation de la quantité d'eau appliquée. A nouveau, veuillez à traiter les différentes modalités et les différentes répétitions de la même façon.

Dans chaque exploitation sera installé un tensiomètre (outil permettant de mesurer l'humidité du sol). Nous vous demandons, avant chaque irrigation, de relever les données du tensiomètre. De cette façon, nous pourrons évaluer jusqu'où est descendue la quantité d'eau dans le sol entre deux irrigations. Si vous en avez le temps/l'envie/l'occasion, vous pouvez relever plus fréquemment les données du tensiomètre (en notant toujours la date), ces données pourront nous être utiles !

h. Récolte

L'aspect de la récolte est relativement compliqué car nous avons besoin, pour pouvoir comparer les modalités et les répétitions, qu'un échantillon de chaque soit prélevé au même moment. Toutefois, nous sommes conscients que récolter chaque jour par partie de sous-parcelle n'est pas très efficient et que récolter tout en une fois ne convient pas pour la commercialisation. Nous avons donc essayé de trouver une solution intermédiaire :

- Je viendrai en début de période de récolte chez chacun(e) de vous pour récolter un échantillon de chacune des deux cultures dans chacune des modalités et chacune des répétitions. A priori, cet échantillon devrait être de 10 plantes de chaque culture pour chaque modalité et répétition, soit 90 plantes d'oignons et 90 plantes de carottes. Le reste de la récolte est à votre disposition et peut être commercialisé selon vos canaux habituels.
- Pour le reste de la récolte, nous vous demandons de récolter répétition par répétition. Cela ne signifie pas que toute la répétition (= les quatre modalités, culture pure d'oignons, culture pure de

carottes, association oignon-carotte en modèle additif et association oignon-carotte en modèle de remplacement) doit être récoltée au même moment mais que vous devez finir de récolter la répétition 1 avant de récolter la répétition 2 et finir de récolter la répétition 2 avant de récolter la répétition 3. Vous pouvez échelonner dans le temps la récolte d'une même répétition.

En ce qui concerne les mesures à prendre pendant la récolte :

- A chaque récolte, la date de récolte doit être indiquée, de même que le nombre de légumes récoltés dans chacune des sous-parcelles (modalité*répétition). Ces légumes doivent ensuite être pesés. Il est impératif, lorsque vous pèserez les légumes, de séparer les légumes récoltés sur des sous-parcelles différentes. Vous pouvez par contre peser en une fois tous les légumes récoltés le même jour sur la même sous-parcelle, en indiquant le nombre de légumes pesés en même temps.
  Ex. : Pour les carottes, vous indiquez le nombre de carottes récoltées dans chacune des sous-parcelles :
  - Culture pure – répétition 1
  - Culture pure – répétition 2
  - Culture pure – répétition 3
  - Association modèle additif – répétition 1
  - Association modèle additif – répétition 2
  - Association modèle additif – répétition 3
  - Association modèle de remplacement – répétition 1
  - Association modèle de remplacement – répétition 2
  - Association modèle de remplacement – répétition 3

  Pour chacune des neuf sous-parcelles indiquées ci-dessus, vous indiquez ensuite le poids total des carottes récoltées sur une même journée.

5. <u>Mesures…</u>

a. …que je réaliserai

Tout au long de l'essai, des mesures seront effectuées pour suivre la croissance, l'interception de lumière et le prélèvement des nutriments par les plantes dans les différentes modalités. Ces mesures seront principalement des mesures optiques, donc non-destructives. Pour ceux et

celles que cela intéresse, un document résumant les mesures qui seront prises sera créé.

Je me déplacerai toutes les deux semaines chez chacun(e) de vous pour réaliser ces mesures. Nous conviendrons ensemble d'un jour et d'une heure de passage approximative chez chacun(e) de vous, en fonction de vos disponibilités, de mes disponibilités et de la proximité de vos différentes exploitations.

b. …que vous réaliserez

Nous allons également avoir besoin de votre aide pour réaliser certaines mesures lors de cet essai. Pour que nous puissions comparer efficacement les résultats que vous aurez chacun(e) obtenus et dresser des conclusions à partir de ces comparaisons, nous vous demandons de noter, avec précision, plusieurs informations :

- Toute action (fertilisation, désherbage, gestion des pestes, irrigation, paillage, taille, etc.) que vous réalisez sur l'essai. Pour chaque action, nous vous demandons de :
    - Décrire l'action (quantité et type de fertilisation, quantité ou durée d'irrigation, produits et quantités pour la gestion des pestes, outils pour le désherbage, etc.),
    - Indiquer la partie de l'essai sur laquelle a été faite l'action (modalité (A, B, A-B add. ou A-B remp.), répétition (1, 2 ou 3)),
    - Indiquer la date à laquelle l'action a été réalisée,
    - Indiquer, pour la récolte et le désherbage, pour chaque partie de l'essai (traitement*répétition), le temps passé à réaliser cette action. Nous sommes conscients que noter le temps passé à chaque action est très contraignant, mais cela nous permettra par la suite de comparer le temps passé sur l'association et sur les cultures pures pour chacun(e) de vous. Bien sûr, l'idée n'est pas du tout de vous juger sur le temps que vous aurez passé sur chaque partie du traitement.
- Toute observation qui vous semble intéressante, toute difficulté rencontrée,
- Pour chaque légume récolté, nous vous demandons de :

- Indiquer la partie de l'essai d'où provient le légume récolté (traitement*répétition),
- Indiquer la date à laquelle le légume a été récolté,
- Peser le légume récolté et noter son poids (les légumes provenant d'une même partie de l'essai et récolté le même jour peuvent être pesés ensemble mais le nombre de légumes correspondant au poids devra alors être indiqué).

Afin de faciliter l'encodage de ces données, à la fois pour vous et pour moi, des fichiers Excel à compléter vous serons envoyés (cf. Annexes). Vous trouverez en annexe de ce document un exemple de fiche à compléter. Par ailleurs, pour me permettre d'analyser les données en cours d'essai, je vous demanderai de m'envoyer ces fichiers plusieurs fois au cours de l'essai (dates à définir).

6. Engagements…

Pour assurer la bonne réussite de cette recherche participative et obtenir des résultats exploitables à la fin, plusieurs engagements doivent être pris, par vous et par moi.

a. …auxquels je m'engage

De mon côté, je m'engage à :

- Organiser des moments de partage et de discussion collectifs de manière plus ou moins régulière selon vos et mes besoins et disponibilités,
- Partager les connaissances que j'acquerrai tout au long de la thèse,
- Être disponible pour répondre à toute question/problème que vous auriez sur l'essai ou sur la thèse en général,
- Assurer une continuité dans le temps (trois ans restants de la thèse et peut-être plus via Philippe Baret),
- Faciliter les échanges entre les différent(e)s participant(e)s via la création d'une plateforme de discussion ou d'une chaîne de mails,
- Assurer l'anonymat des données récoltées si vous le souhaitez.

Nous nous engageons également à organiser un évènement à la fin de l'essai pour vous partager les résultats que nous aurons obtenus lors de l'essai participatif et de l'essai que nous mettons en place en parallèle à la Ferme de Lauzelle et les premières conclusions que nous pouvons en tirer.

Je ferai, par ailleurs, tout mon possible pour assurer le bon déroulement de l'essai en :

- Me déplaçant chez chacun(e) d'entre vous pour réaliser la majorité des mesures,
- Vous envoyant des fichiers Excel structurés pour faciliter l'encodage des informations (cf. Annexes),
- Vous fournissant les graines/plants nécessaires à la mise en place de l'essai.

Nous nous engageons également à vous payer un dédommagement financier, dont le montant doit encore être défini, pour votre participation à cet essai et le temps que cela vous prendra.

b. …auxquels vous vous engagez

i. Collectifs

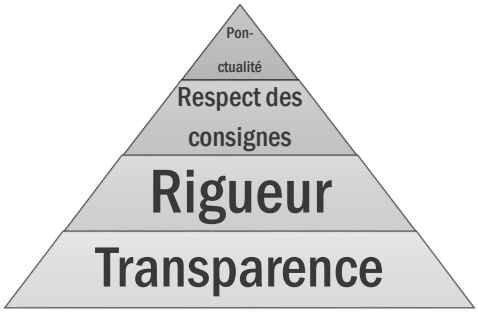
D'un point de vue collectif, trois réunions principales seront mises en place :

- Réunion de mise en place : explication de l'essai, définition du cadre → **06 février 2019 de 18h à 20h** ;
- Réunion de « mi-essai » : premier ressenti concernant l'essai, difficultés rencontrées, points positifs → Date à définir ;
- Réunion de fin d'essai : discussion sur l'essai et son organisation, ressenti → Date à définir.

Nous vous demandons, dans la mesure du possible, d'être présent(e)s lors de ces réunions. Nous sommes cependant conscients que vous avez des journées très chargées en pleine saison et qu'il peut être compliqué pour vous de venir. Toutefois, si la date choisie correspond à une date pour laquelle vous avez mis « Présent(e) » sur le Doodle, nous comptons sur vous. Les prochaines réunions auront probablement lieu à Gembloux, dans le local d'Agricovert.

ii. Individuels

Comme je l'ai déjà expliqué plusieurs fois, nous souhaitons pouvoir établir une comparaison entre les résultats que chacun(e) de vous obtiendra lors de cet essai participatif. Pour pouvoir



faire une telle comparaison et identifier les éléments qui pourraient être la cause des différences observées, nous avons besoin de connaître le mieux possible vos pratiques habituelles et l'historique de votre exploitation mais aussi toutes les actions que vous aurez faites sur les différent(e)s traitements et répétitions de l'essai. Votre transparence est l'élément capital de l'essai, de même que votre rigueur dans le recensement et l'encodage de vos actions. Si l'un(e) de vous ne joue pas le jeu à 100%, nous perdons un point de comparaison et le travail des autres participant(e)s perd, suite à ça, un peu de sa valeur. Les quatre engagements principaux que nous vous demandons sont donc :

- La transparence et l'honnêteté : notez tout ce que vous faîtes sur l'essai, peu importe si cela s'avère par la suite être une erreur de l'avoir fait ; notre but n'est aucunement de vous juger sur vos pratiques mais simplement d'avoir une bonne idée de ce qui a été fait sur chaque culture pour mieux comprendre les causes des différences de résultats que nous pourrions observer entre vous,
- La rigueur : soyez précis dans vos observations et vos prises de notes,
- Le respect du dispositif expérimental que nous avons choisi et du cadre de gestion défini lors de la réunion du 06/02,
- La ponctualité : essayez, dans la mesure du possible, de me renvoyez les fichiers Excel à compléter (cf. Annexes) aux dates qui auront été convenues.

Je souhaiterais également avoir l'opportunité de faire un entretien privé avec chacun(e) de vous (durée : 1h) avant la mise en place de l'essai pour pouvoir caractériser au mieux vos exploitations et vos pratiques et à la fin de l'essai pour avoir votre ressenti sur cette expérience.

Il est également très important que vous m'autorisiez à venir prendre des mesures toutes les deux semaines chez vous et que vous respectiez, tout comme moi, le jour et l'heure approximative fixés au début de l'essai. Il sera compliqué pour moi de gérer mon temps et mes trajets si le jour et l'heure auxquels je viens chez chacun(e) de vous changent toutes les semaines… Si, lors de la prise de mesure, vous avez le temps que l'on discute un peu ensemble, c'est encore mieux !

Enfin, d'un point de vue pratique, nous vous demandons de vous engager à :

- Gérer les associations et les cultures pures de l'essai expérimental « en bon père de famille », avec le même soin que celui que vous apportez à vos autres cultures,
- Demander l'avis du réseau en cas de difficultés,
- Poser toute question que vous pourriez avoir, même si elle semble stupide.

7. Calendrier

A titre informatif, voici une idée de la forme que pourrait prendre le calendrier (Fig. 10). Un calendrier plus précis vous sera envoyé sous peu.

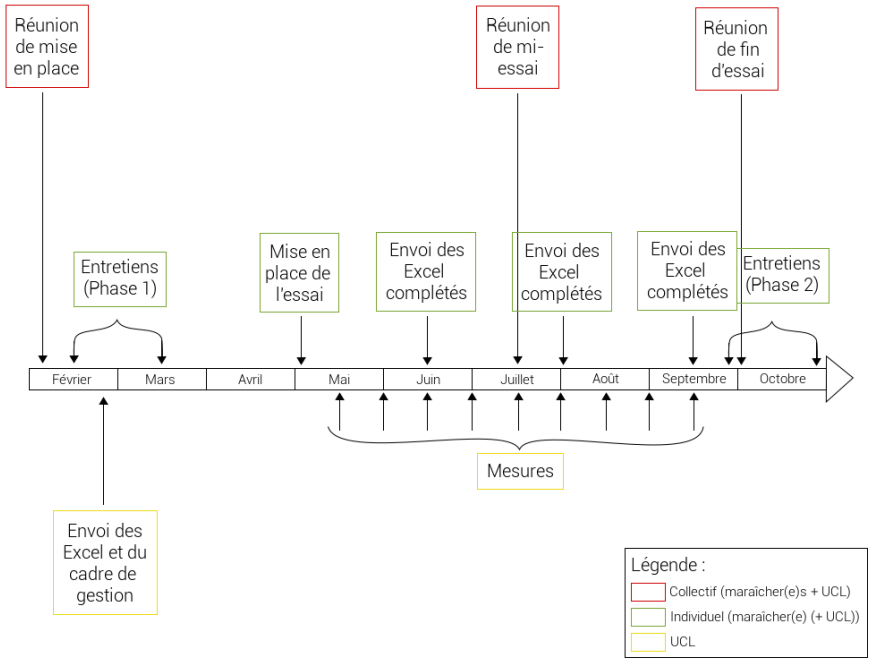
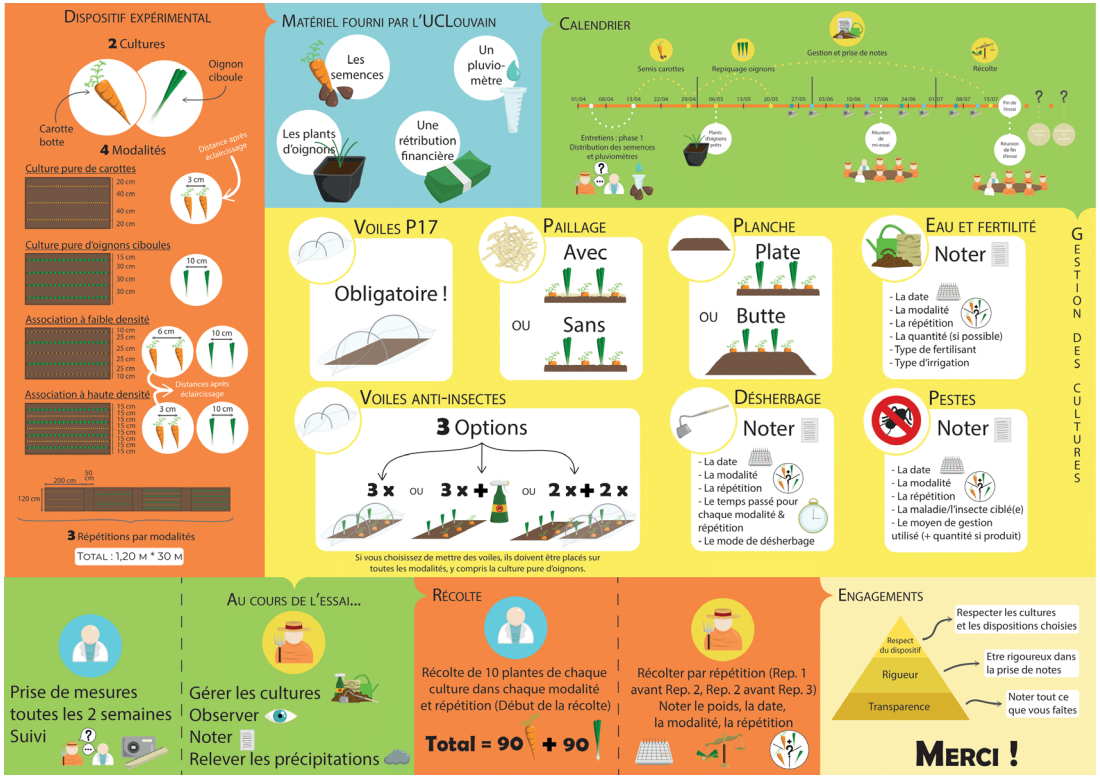


Figure 10 - Calendrier fictif de l'essai participatif.

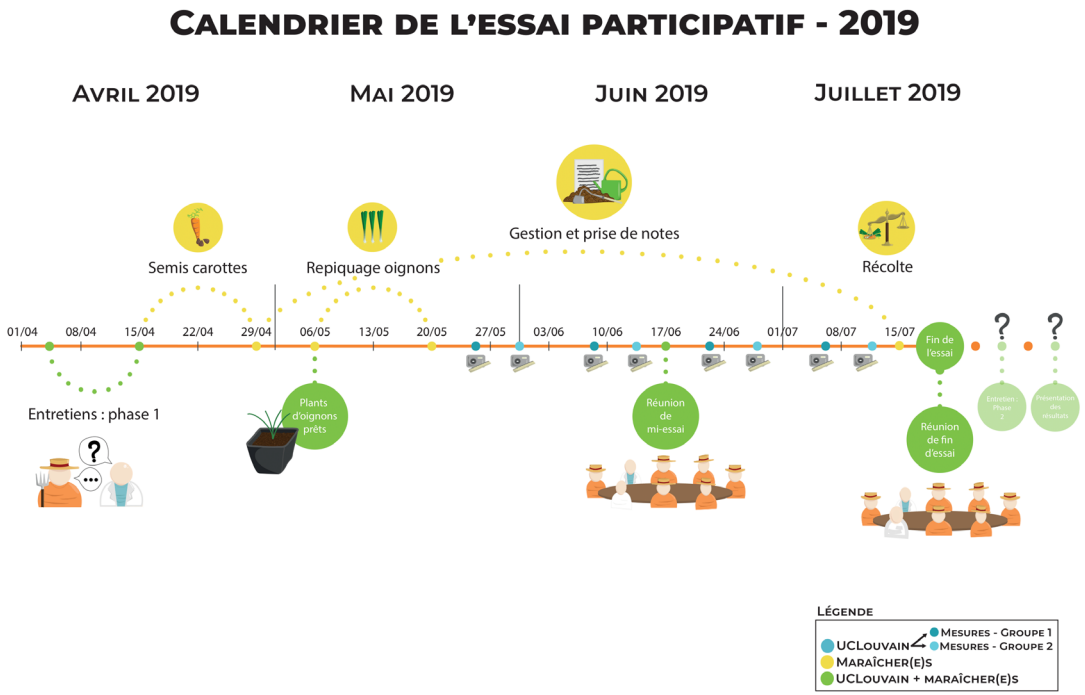
Appendix L. "PRACTICAL ASPECTS" SHEET OF THE 2019 PARTICIPATORY TRIAL

Sheets summarising the practical aspects of the 2019 participatory trial, which we distributed to each participant.



Appendix M. "CALENDAR" SHEET OF THE 2019 PARTICIPATORY TRIAL

Initial schedule of the 2019 participatory trial, given to each market gardener.



Appendix N. EXPLANATORY SHEET OF THE 2020 PARTICIPATORY TRIAL

Explanatory sheet of the 2020 participatory trial, which we printed on laminated A4 sheet and distributed to each one of the participants. This sheet included information about the objective of the trial, the vocabulary used, the design and the organisation of the trial and the commitments of each participant.

Essai participatif 2020 – Fiche explicative

• **Le principe**

L'essai a pour but de comparer une association de cultures (laitue romaine – haricot nain) avec les deux cultures pures correspondantes chez différent·es maraîcher·es réparti·es un peu partout en Wallonie. Nous souhaitons comparer les trois modalités (l'association et les deux cultures pures) entre elles chez chacun des maraîcher·es et comparer les résultats des différent·es maraîcher·es entre eux pour déterminer si les conditions environnementales et les pratiques culturales influencent les résultats d'une même association.

• **Le vocabulaire**

Plusieurs mots reviendront assez souvent au cours de l'essai, il est important que vous les compreniez bien.

- *Planche d'essai* : la planche sur laquelle est mis en place l'essai expérimental ;
- *Parcelle* : chacune des subdivisions de la planche d'essai. Les parcelles mesurent 1,10m*3m ;
- *Modalités* : les modalités de l'essai sont les différentes choses que l'on souhaite étudier. Ici, il y en a trois : la culture pure de laitues, la culture pure de haricots nains et l'associations laitues-haricots nains.
- *Répétition* : Pour tenir compte de la variabilité naturelle et de potentiels problèmes, chaque modalité sera répétée trois fois. Cela signifie que sur la planche d'essai, chaque modalité sera cultivée sur trois parcelles différentes. Lorsqu'on parle d'une répétition d'une modalité, il s'agit d'une des trois parcelles sur laquelle cette modalité est cultivée.

• **Le design** (voir feuille « Plan de l'essai »)

Culture pure de laitues	Culture pure de haricots nains	Associations laitues-haricots
		
Distance dans la ligne : 30 cm	Distance dans la ligne : 10 cm	Distance dans la ligne H : 10 cm Distance dans la ligne L : 30 cm



• **L'organisation**

- Les plants et semences sont fourni·es la semaine du 15 juin ;
- La plantation des laitues doit se faire entre le mardi 16 juin et le mardi 23 juin ;
- Le semis des haricots doit se faire la semaine du 29 juin ;
- Au cours du premier mois, je passerai toutes les semaines pour prendre des mesures. Le jour de passage vous sera communiqué. Vous ne devez pas forcément être présent au moment où je passerai ;

- Après la récolte de laitues, je ne passerai plus qu'une fois toutes les deux semaines, jusqu'à la récolte des haricots.
- A chacun de mes passages, je récupèrerai les différents formulaires (gestion de la planche d'essai, irrigation, précipitations, temps de travail) et vous en laisserai de nouveaux. Cela évitera la perte d'informations.

Les mesures que je prendrais sont essentiellement des mesures non destructives. Toutefois, il est possible de je prélève quelques plants de laitues et de haricots au cours de la saison. Par ailleurs, lors des périodes de récolte, je viendrai prélever un petit échantillon de laitues et de haricots chaque chacun·e. Le nombre de plants prélevés reste à déterminer mais restera dans tous les cas assez bas. Le reste de la récolte vous appartient et peut être commercialisé comme on vous semble.

- **Les engagements**

➔ **Nous nous engageons à :**
  - Vous fournir les plants et les semences ;
  - Vous fournir un pluviomètre et un débitmètre ;
  - Vous fournir des formulaires à compléter pour faciliter vos prises de notes ;
  - Vous accompagner tout au long de l'essai et répondre à toutes les questions que vous auriez ;
  - Mettre en place des mesures le moins destructif possible afin d'influencer le moins possible sur votre récolte finale ;
  - Vous fournir vos résultats individuels à la fin de l'essai ;
  - Organiser une restitution des résultats collective à la fin de l'essai ;
  - Vous dédommager financièrement (250 €) pour le temps passé sur l'essai et les prélèvements de plantes que nous effectuerons.

➔ **En participant à l'essai, vous vous engagez à :**
  - Gérer la parcelle d'essai « en bon père de famille » ;
  - Nous avertir en cas de problème ;
  - Respecter les périodes de semis et de plantation définies ;
  - Peser tout ce qui est récolté et différencier ce qui est récolté dans chacune des parcelles d'essai (= chacune des répétitions des différentes modalités).
  - Compléter les formulaires de suivi de :
    - La gestion de la planche d'essai (Désherbage, fertilisation, traitements phytos) ;
    - L'irrigation (via les débitmètres) ;
    - La pluviométrie (via les pluviomètres) ;
    - La récolte.

➔ **ATTENTION : Nous sommes conscients que compléter les formulaires de suivi peut être laborieux et chronophage, mais ils sont essentiels pour permettre un bon suivi de l'essai et une bonne interprétation des résultats ! Ces formulaires sont disponibles en version papier (plastifié) ou en ligne.**

➔ **OPTION** : Cette année, nous avons également mis en place un système de mesure du temps de travail à l'aide de petites fiches de couleurs à compléter (voir ci-dessous). Si vous souhaitez y prendre part, dîtes-le-moi et je vous distribuerai les fiches en question !

Exemple de fiche de mesure du temps de travail :

Association laitues & haricots - Répétition 1

Prénom & nom :…… **Exploitation :……**

Date :……

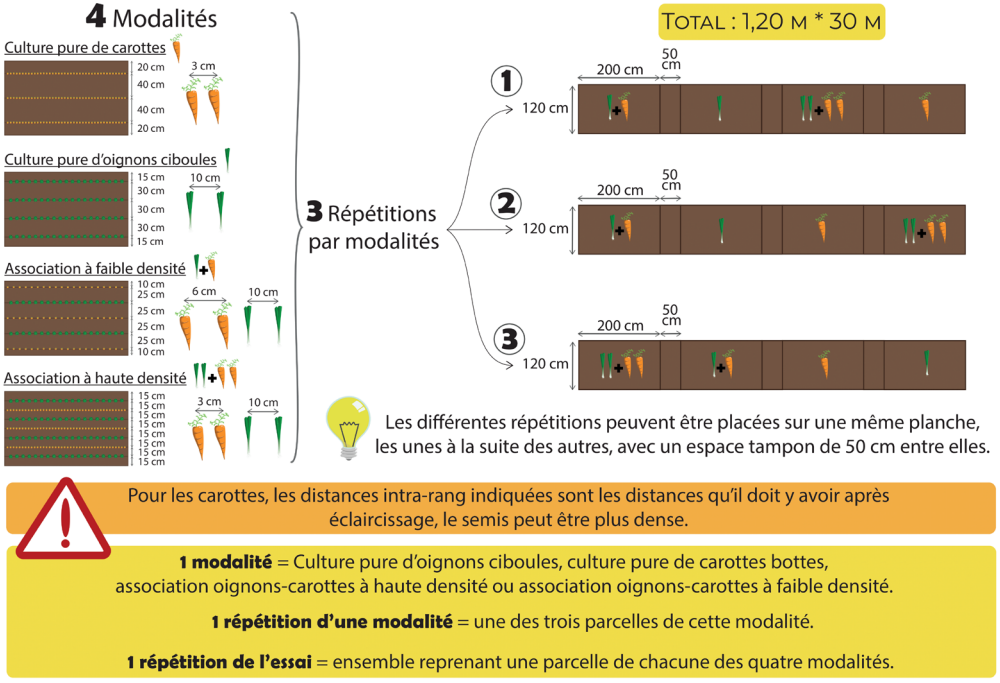
Heure de début :……H……min **Heure de fin :……H……min**

Opération : ☐ **Désherbage** ☐ **Irrigation** ☐ **Traitements phytos**

☐ **Fertilisation** ☐ **Récolte** ☐ **Autre :……**

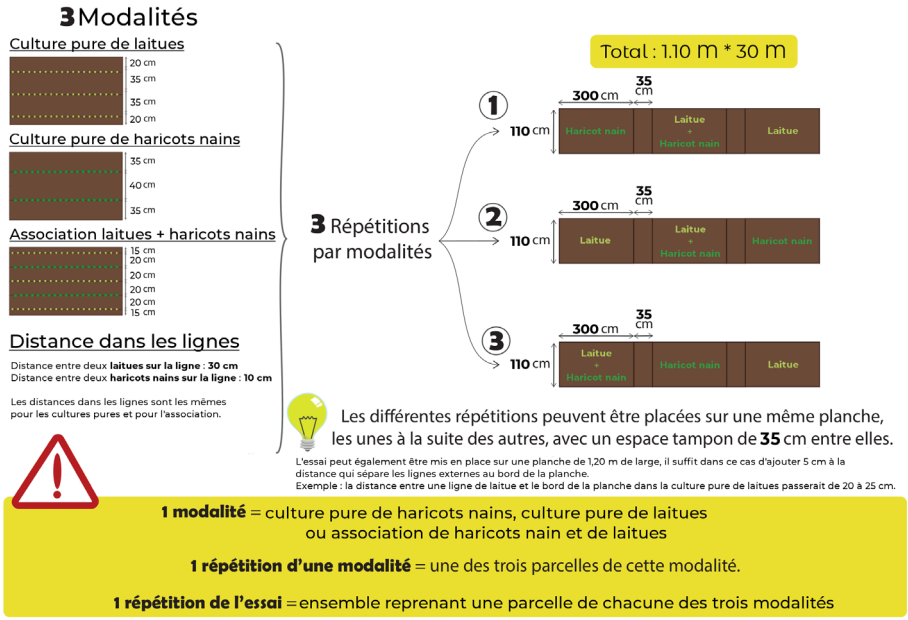
Appendix O. "DESIGN" SHEET OF THE 2019 PARTICIPATORY TRIAL

The "Design" sheet was printed and given to each market gardener at the beginning of the trial. It included information about the spatial organisation of each modality, the spatial organisation of the whole plot and the definitions of "modality" and "repetition".



Appendix P. "DESIGN" SHEET OF THE 2020 PARTICIPATORY TRIAL

In 2020, we provided an A3 laminated sheet with the design of the trial to each market gardener. It included information about the spatial organisation of each modality, the spatial organisation of the whole plot and the definitions of "modality" and "repetition".



Appendix Q. "CROP MANAGEMENT" LAMINATED SHEET OF THE 2020 PARTICIPATORY TRIAL

We distributed a new "Crop management" sheet to each market gardener each time we visited, i.e. every week, and collected the completed sheet from the previous week. Market gardeners were provided with a permanent marker and with a plastic sleeve in which to keep all the laminated sheets at the beginning of the plot.

Essai participatif 2020 – Fiche à remplir

Maraîcher·e : Ferme de Lauzelle

Semaine du …… au ……

Voici la fiche de suivi de l'essai que vous devrez compléter, si possible, chaque semaine. Je les récupèrerai au fur et à mesure, à chacun de mes passages. Afin de favoriser l'encodage, pourriez-vous respecter les notations suivantes :

- Culture pure de laitue : L
- Culture pure de haricot : H
- Association laitue-haricot : H+L
- Toute la planche : T
- Si vous n'avez effectué l'opération que sur l'une ou l'autre répétition d'une modalité, faites suivre l'abréviation de la modalité du numéro de la répétition (1, 2 ou 3 ; voir plan de l'essai).

DESHERBAGE

Date/jour de la semaine	Parcelle(s) concernée(s)	Durée (min)

TRAITEMENTS PHYTOSANITAIRES

Date/jour de la semaine	Parcelle(s) concernée(s)	Maladie(s)/insecte(s) ciblé·e(s) ?

FERTILISATION

Date/jour de la semaine	Parcelle(s) concernée(s)	Quantité (kg)	Type de fertilisant (compost, fumier, etc.)

AUTRE

Date/jour de la semaine	Parcelle(s) concernée(s)	Description de l'action

Appendix R. "IRRIGATION" LAMINATED SHEET OF THE 2020 PARTICIPATORY TRIAL

One "Irrigation" sheet was distributed to each market gardener. We asked them to complete it every time they irrigated the plot and to use the flowmeter we gave them to measure the quantity of water they used. We did not asked them the quantity of water per plot but only for the whole trial field. When they only irrigated part of the trial field, we asked them to indicate which plot(s) they irrigated on the irrigation sheet.

Essai participatif 2020 – Relevé de l'irrigation

Maraîcher·e : Ferme de Lauzelle

Utiliser la fonction « Auto » du débitmètre, pour connaitre la quantité totale d'eau administrée sur la parcelle à chaque arrosage. N'oubliez pas de relever le chiffre du compteur avant d'arroser une autre planche que la planche d'essai ! Afin de permettre un encodage des données plus faciles, merci de ne noter que le chiffre indiqué par le débitmètre, sans unité. Merci !

Si vous avez arrosé uniquement certaines modalités, ou plus certaines modalités que d'autres, veuillez le préciser dans la colonne « Modalités ». Dans le cas contraire, laissez la colonne vide. Cela voudra dire que vous avez arrosé de façon égale toute la parcelle d'essai.

Date	Quantité d'eau administrée à la parcelle (L)	Modalités ?

Appendix S. "RAINFALL" LAMINATED SHEET OF THE 2020 PARTICIPATORY TRIAL

One "Rainfall" sheet was distributed to each market gardener. We asked them to complete it every time it rained using the rain gauge we gave them.

Essai participatif 2020 – Relevé des précipitations

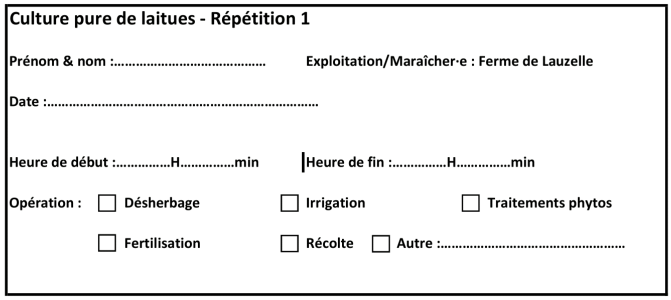
Maraîcher·e : Ferme de Lauzelle

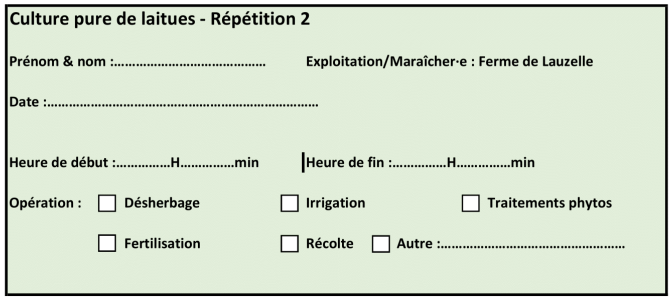
Afin de permettre un encodage des données plus faciles, merci de ne noter que le chiffre indiqué par le pluviomètre, sans unité. Merci !

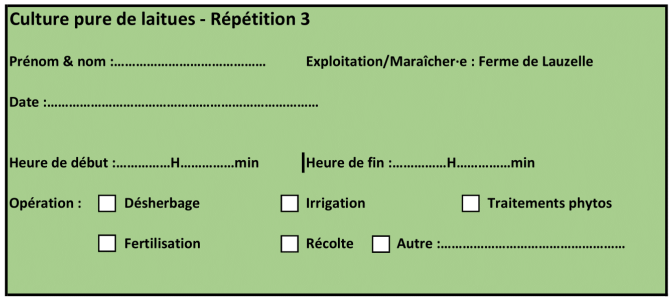
Date	Pluie (mm)

Appendix T. "WORK TIME" LAMINATED CARDS OF THE 2020 PARTICIPATORY TRIAL

Hereunder are presented the cards used for the evaluation of the work time. Each colour corresponded to one repetition of one modality. Each individual card was printed on an A6 laminated sheet. We installed a bamboo stake with a plastic pouch containing the corresponding work time card at the beginning of each plot in each site.







Culture pure de haricots - Répétition 1

Prénom & nom :..... Exploitation/Maraîcher·e : Ferme de Lauzelle

Date :.....

Heure de début :.....H.....min Heure de fin :.....H.....min

Opération : ☐ Désherbage ☐ Irrigation ☐ Traitements phytos

☐ Fertilisation ☐ Récolte ☐ Autre :.....

Culture pure de haricots - Répétition 2

Prénom & nom :..... Exploitation/Maraîcher·e : Ferme de Lauzelle

Date :.....

Heure de début :.....H.....min Heure de fin :.....H.....min

Opération : ☐ Désherbage ☐ Irrigation ☐ Traitements phytos

☐ Fertilisation ☐ Récolte ☐ Autre :.....

Culture pure de haricots - Répétition 3

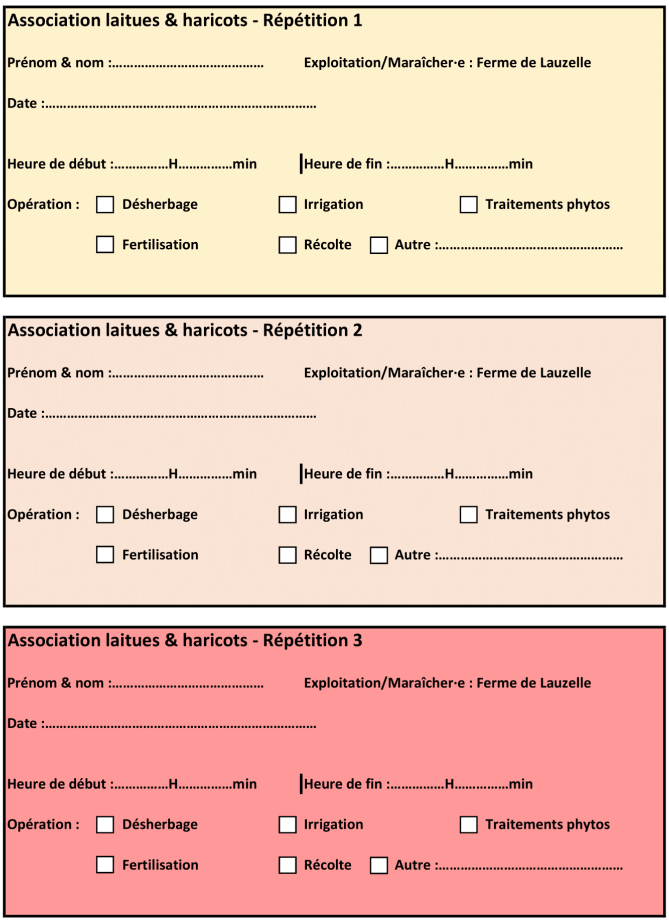
Prénom & nom :..... Exploitation/Maraîcher·e : Ferme de Lauzelle

Date :.....

Heure de début :.....H.....min Heure de fin :.....H.....min

Opération : ☐ Désherbage ☐ Irrigation ☐ Traitements phytos

☐ Fertilisation ☐ Récolte ☐ Autre :.....


Association laitues & haricots - Répétition 1
Prénom & nom :.....
Exploitation/Maraîcher·e : Ferme de Lauzelle
Date :.....
Heure de début :.....H.....min
Heure de fin :.....H.....min
Opération :
Désherbage
Irrigation
Traitements phytos
Fertilisation
Récolte
Autre :.....
Association laitues & haricots - Répétition 2
Prénom & nom :.....
Exploitation/Maraîcher·e : Ferme de Lauzelle
Date :.....
Heure de début :.....H.....min
Heure de fin :.....H.....min
Opération :
Désherbage
Irrigation
Traitements phytos
Fertilisation
Récolte
Autre :.....
Association laitues & haricots - Répétition 3
Prénom & nom :.....
Exploitation/Maraîcher·e : Ferme de Lauzelle
Date :.....
Heure de début :.....H.....min
Heure de fin :.....H.....min
Opération :
Désherbage
Irrigation
Traitements phytos
Fertilisation
Récolte
Autre :.....

Appendix U. "HARVEST" LAMINATED SHEET OF THE 2020 PARTICIPATORY TRIAL

Every market gardener was provided with one "Harvest" laminated sheet per crop and repetition of each modality. They had to complete it every time they harvested lettuces or beans from the trial plot. Harvests from different plots had to be weighed separately.

Essai participatif 2020 – Récolte

Maraîcher·e : Ferme de Lauzelle

Le fichier récolte ci-dessous est organisé par parcelles. Veillez à bien noter les données dans le tableau qui correspond à la parcelle que vous êtes en train de récolter.

CULTURE PURE DE LAITUES – REPETITION 1

Date	Nombre de laitues récoltées	Poids total des laitues récoltées (kg)

1

Appendix V. CROP MANAGEMENT & FARM CHARACTERISTICS OF THE SITES FROM THE 2019 PARTICIPATORY TRIAL

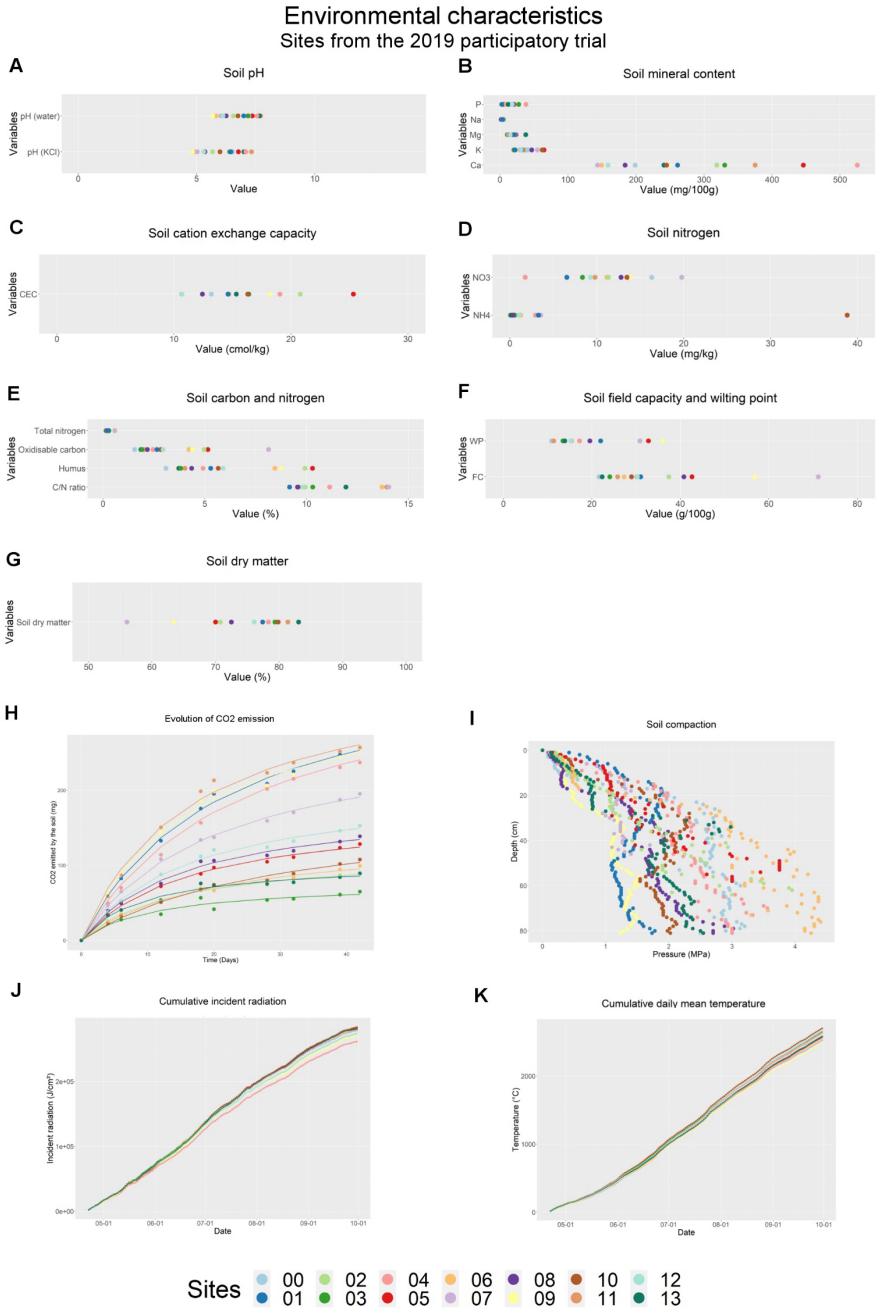
The main characteristics of the sites and the crop management of the market gardeners from the 2019 participatory trial (cf. Chapter 7) are gathered in the table hereunder. All data comes from the semi-directive interview performed with each participating market gardener. No information about weeding was included, as weeding was manual at all sites for the experimental plot during the trial. “High” is used in the “Number of crops” column when the market gardener insisted on the fact that his/her farm was diversified but that he/she was unable to approximate the number of different crops. The “Type of farming” column is based on the description of their practices by market gardeners themselves. The “Soil management”, “Mulching”, “Fertilisation” and “Irrigation” columns correspond to what was used by market gardeners in the experimental field. The “Pests management” column corresponds to the general orientation of each farm regarding pests. The “Previous crop” column indicates the crops that were cultivated on the experimental field the year before the trial. Finally, the “Anti-insect veil” column shows if the market gardener used an anti-insect veil on the experimental field or not. The letters in the “Site” column correspond neither to the letters used in Figure 33 nor to the numbers used in Chapter 6, Chapter 7 and Chapter 8 to ensure farmers’ anonymity. NA=Not available.

SITE	TYPE OF FARMING	CULTIVATED AREA (HA)	GREENHOUSES AREA (HA)	NUMBER OF CROPS	SOIL MANAGEMENT
A	Organic farming	9	0,2	High	Ploughing
B	Organic farming	0,5	0,037	40	Cultivator
C	Market gardening on living soil	0,5	0	3	Cultivator
D	Organic farming	0,48	0	40	Milling
E	Agroecological	0,55	0,072	90	Tarp
F	Market gardening on living soil	0,3	0,0296	68	Cultivator
G	Market gardening on living soil	0,44	0	0	Cultivator
H	Permaculture	0,15	0,052	High	Grelinette
I	Market gardening on living soil	0,0453	0,0154	30	Grelinette
J	Natural agriculture	0,3	0,045	60	None
K	Organic farming	3	0	NA	Ploughing
L	Responsible farming	1,63	0,042	20	Ploughing & cutter
M	Organic farming	1,2	0,05	60	Ploughing
N	Agroecological	0,55	0,072	90	None

SITE	MULCHING	FERTILISATION	IRRIGATION	PEST MANAGEMENT	PREVIOUS CROP	ANTI-INSECT VEIL
A	No	Manure	Sprinkler	Organic	NA	No
B	No	Green manure	Sprinkler	Integrated	Onions, shallots	No
C	Yes (Hemp)	Manure	Sprinkler	Integrated	None	No
D	No	Dead leaves	Drip feed	Organic	Grassland	Yes
E	No	Hay + wood	Drip feed	None	Onions	No
F	Yes (Miscanthus, tarp)	Compost	Watering can	Integrated	Mustard, turnip, cabbage, broccoli	Yes
G	Yes (Hemp)	Manure + fragmented wood	Watering can	Integrated	Grassland	No
H	Yes (Straw-mulching)	Manure	Watering can	Integrated	Potato	Yes
I	Yes (Straw-mulching)	Green waste compost	Watering can	Organic	Grassland	Yes
J	Yes (Hay)	Green waste compost	Drip feed + watering can	Integrated	Grassland	Yes
K	No	Green manure + manure + compost	Sprinkler	Organic	Green manure	No
L	No	None	Sprinkler	Chemical	Grassland	No
M	No	None	Drip feed + sprinkler	Organic	Potato, cauliflower, broccoli	No
N	Yes (Bokashi)	Bokashi + Biochar	Drip feed	None	Potato, cards, cabbage, asparagus	No

Appendix W. ENVIRONMENTAL CHARACTERISTICS OF THE SITES FROM THE 2019 PARTICIPATORY TRIAL

Environmental characteristics of the 14 sites from the 2019 participatory trial (cf. Chapter 7): soil pH (A), soil mineral content (P, Na, Mg, K, Ca) (B), soil cation exchange capacity (C), soil nitrogen (NO_3, NH_4^+) (D), soil carbon and nitrogen (% of total nitrogen, % of oxidisable carbon, % of humus, C/N ratio) (E), soil field capacity (FC) and wilting point (WP) (F), soil dry matter (G), evolution of CO_2 emission by the soils as an estimation of soil biological activity (H), evolution of pressure needed to go deeper in the soil with soil depth as an indicator of soil compaction (I), cumulative incident radiation (J) and cumulative daily mean temperature (K). Due to the difficulty for market gardeners to record data in the Excel sheet provided in 2019, no data is available for rainfall and irrigation. Data of soil characteristics (A, B, C, D, E, G) are based on the analysis of soil samples taken in each site, on the experimental plot, before the beginning of the trial, in the 20 first centimeters of the soil. Soil field capacity and wilting point (F) are based respectively on structured and unstructured samples taken from the surface horizon of the soil in each site before the beginning of the trial and put in pressure plate extractors. Evolution of CO_2 emission (H) is based on respirometry measurement and soil compaction (I) was measured using a penetrometer. Data of radiation (J) and temperature (K) are based on data from the weather stations of the Pameseb network. All data is presented using graphs – to see the distribution of the sites – and in a table – to see minimum, maximum, mean and median values –. In addition, soil texture and drainage of the sites, derived from the map of the main soil types in Wallonia (SPW, 2005), are presented in the second table. CEC=Cation exchange capacity, FC=Field capacity, WP=Wilting point.



Graphical representation of the environmental characteristics of the fourteen sites of the 2019 participatory trial.

Mean, median, minimum and maximum of the measured/estimated environmental characteristics in the fourteen sites of the 2019 participatory trial.

VARIABLES	MEAN	MEDIAN	MINIMUM	MAXIMUM
Soil characteristics				
Soil dry matter (%)	74.58	77.42	56.04	83.07
Wilting point (g/100g)	20.34	16.31	10.88	36.01
Field capacity (g/100g)	35.02	30.22	21.59	71.15
pH (H2O)	6.74	6.75	5.68	7.71
pH (KCl)	6.01	5.99	4.83	7.32
NO_3^- (mg/kg)	10.83	11.15	1.75	19.77
NH_4^+ (mg/kg)	4.08	0.68	0.38	38.81
K (mg/100g)	37.08	32.16	20.03	64.73
P (mg/100g)	13.97	11.90	2.29	38.27
Na (mg/100g)	2.94	2.51	1.75	5.28
Mg (mg/100g)	19.16	19.53	10.78	37.95
Ca (mg/100g)	278.80	246.89	143.35	525.21
Cation exchange capacity (cmol/kg)	15.73	15.02	10.64	25.34
Humus (%)	7.03	5.66	3.72	16.26
Total nitrogen (%)	0.32	0.30	0.14	0.58
Oxydisable carbon (%)	3.52	2.83	1.86	8.13
C/N ratio	10.99	10.29	9.16	14.03
Maximal pressure from penetrometry (MPa)	1.91	1.87	0.91	3.39
Depth of maximal pressure from penetrometry (cm)	30.00	32.00	16.00	41.00
Weather characteristics				
Number of rainy days	24.18	23.21	5.36	44.92
Cumulative incident radiation (J/cm^2)	2768.71	2786.86	2616.53	2838.46
Cumulative mean temperature (°C)	2608.98	2632.80	2491.60	2699.90

Number of sites, among the fourteen sites of the 2019 participatory trial, with each combination of soil texture and soil drainage. Data is not available for three of the sites.

		SOIL TEXTURE			
		Silty	Silty and stony	Sandy loam	Sandy or loamy sand
SOIL DRAINAGE	Favourable	4	0	0	0
	Moderate or imperfect	0	0	1	2
	Moderate to fairly poor	2	1	0	0
	Poor to very poor	1	0	0	0

Appendix X. CROP MANAGEMENT & FARM CHARACTERISTICS OF THE SITES FROM THE 2020 PARTICIPATORY TRIAL

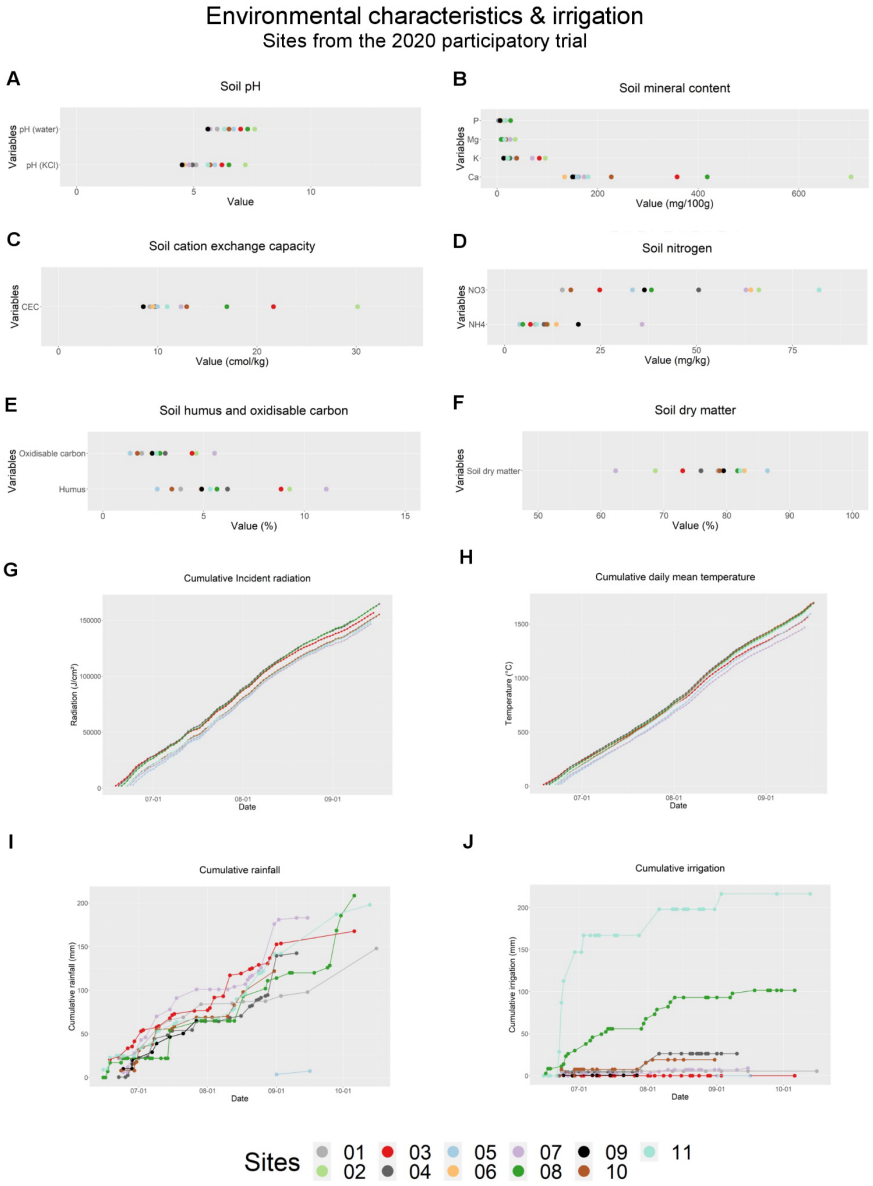
The main characteristics of the sites and the crop management of the market gardeners from the 2020 participatory trial (cf. Chapter 7) are gathered in the table hereunder. All data comes from the semi-directive interview performed with each participating market gardener. No information about weeding was included, as weeding was manual at all sites for the experimental plot during the trial. “High” is used in the “Number of crops” column when the market gardener insisted on the fact that his/her farm was diversified but that he/she was unable to approximate the number of different crops. The “Type of farming” column is based on the description of their practices by market gardeners themselves. The “Soil management”, “Mulching”, “Fertilisation”, “Irrigation” and “Weeding occurrences” columns correspond to what was used by the market gardeners in the experimental plot. The “Pests management” column correspond to the general orientation of the each farm regarding pests. The “Previous crop” column shows the crops that were cultivated on the experimental plot the year before the trial. The letters in the “Site” column correspond neither to the letters used in Figure 33 nor to the numbers used in Chapter 6, Chapter 7 and Chapter 8 to ensure farmers’ anonymity.

SITE	TYPE OF FARMING	CULTIVATED AREA (HA)	GREENHOUSES AREA (HA)	NUMBER OF CROPS	SOIL MANAGEMENT
A	Market gardening on living soil	3,5	0,127	High	Cultivator
B	Agroecological	0,55	0,072	90	Tarp
C	Organic farming	0,5	0,037	40	Cultivator
D	Permaculture	0,12	0	High	Grelinette
E	Organic farming	9	0,2	High	Ploughing
F	Organic farming	1,2	0,05	60	Ploughing
G	Natural agriculture	0,7	0,012	High	None
H	Organic farming	0,48	0	40	Mill
I	Responsible farming	1,63	0,042	20	Ploughing & cutter
J	Permaculture	0,15	0,052	High	Grelinette
K	Agroecological	0,55	0,072	90	None

SITE	MULCHING	FERTILISATION	IRRIGATION	PEST MANAGEMENT	WEEDING OCCURRENCES	PREVIOUS CROP
A	No	Manure	Sprinkler	Integrated	3	Grassland
B	No	Bokashi + Biochar	Drip feed	None	1	Onions
C	No	None	Sprinkler	Integrated	2	Onions, shallots
D	Yes	Compost	Watering can	Integrated	6	Grassland
E	No	Manure	Sprinkler	Organic	1	NA
F	No	None	Drip feed & sprinkler	Organic	4	Potato, cauliflower, broccoli
G	Yes (Hay)	NA	Perforated hose + watering can	Integrated	NA	Grassland
H	No	Dead leaves	Drip feed	Organic	3	Grassland
I	No	None	Chemical	Chemical	NA	Grassland
J	Yes (Straw-mulching)	Manure	Integrated	Integrated	1	Potato
K	Yes (Bokashi)	Hay	None	None	1	Potato, cards, cabbage, asparagus

Appendix Y. ENVIRONMENTAL CHARACTERISTICS OF THE SITES FROM THE 2020 PARTICIPATORY TRIAL

Environmental characteristics of the 11 sites of the 2020 participatory trial (cf. Chapter 7): soil pH (A), soil mineral content (P, Na, Mg, K, Ca) (B), soil cation exchange capacity (C), soil nitrogen (NO_3, NH_4^+) (D), soil oxidisable carbon and soil humus (E) soil dry matter (F), cumulative incident radiation (G), cumulative daily mean temperature (H), cumulative rainfall (I) and cumulative irrigation (J). Data of soil characteristics (A, B, C, D, E, F) are based on the analysis of soil samples taken in each site, on the experimental field, before the beginning of the trial, in the 20 first centimeters of the soil. Data of radiation (G) and temperature (H) are based on data from the weather stations of the Pameseb network. Data of rainfall (I) and irrigation (J) are based respectively on the "Rainfall" and "Irrigation" laminated sheets filled in by market gardeners (cf. Appendix S, Appendix R). All data is presented using graphs – to see the distribution of the sites – and in a table – to see minimum, maximum, mean and median values –. In addition, soil texture and drainage of the sites, derived from the map of the main soil types in Wallonia (SPW, 2005), are presented in the second table. CEC=Cation exchange capacity.



Graphical representation of the environmental characteristics of the eleven sites of the 2020 participatory trial.

Mean, median, minimum and maximum of the measured/estimated environmental characteristics in the eleven sites of the 2020 participatory trial.

VARIABLES	MEAN	MEDIAN	MINIMUM	MAXIMUM
Soil characteristics				
Soil dry matter (%)	77.27	78.85	62.33	86.47
pH (H_2O)	6.36	6.30	5.60	7.60
pH (KCl)	5.55	5.60	4.50	7.20
NO_3^- (mg/kg)	44.61	38.26	15.03	81.92
NH_4^+ (mg/kg)	12.08	10.27	3.94	35.80
K (mg/100g)	40.41	25.50	13.00	96.00
P (mg/100g)	10.28	8.10	2.70	26.70
Ca (mg/100g)	256.32	173.00	134.00	704.00
Mg (mg/100g)	17.82	17.00	8.00	36.00
CEC (cmol/kg)	13.81	10.94	8.54	30.15
Humus (%)	6.01	5.32	2.70	11.08
Oxidisable carbon (%)	3.00	2.66	1.35	5.54
Weather characteristics				
Cumulative rainfall (mm)	141.09	157.85	7.50	208.50
Cumulative incident radiation (MJ/m^2)	1555.31	1559.41	1465.71	1646.13
Cumulative mean temperature (°C)	1606.27	1600.95	1467.60	1697.50
Crop management				
Cumulative irrigation (mm)	37.84	7.30	0.00	216.33

Number of sites, among the eleven sites of the 2020 participatory trial, with each combination of soil texture and soil drainage. Data is not available for one of the sites.

		SOIL TEXTURE			
		Silty	Silty and stony	Sandy loam	Sandy or loamy sand
SOIL DRAINAGE	Favourable	2	1	0	0
	Moderate or imperfect	0	0	1	2
	Moderate to fairly poor	2	1	0	0
	Poor to very poor	1	0	0	0