

Role of exogenous organic matter in the transfer of trace elements in the soil-plant system

Contribution of metal isotopes, rare earth
elements, and organic matter characterization

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December 2024



This thesis was funded by the *Fonds de la Recherche Scientifique (FNRS)*.
Additional funding has been granted by the *Fonds Baillet Latour*.

“Well, I guess this is growing up”

blink-182, *Dammit*

Remerciements

L'achèvement de cette thèse de doctorat marque la fin d'un long voyage de quatre ans qui n'aurait pas été possible sans l'aide, le soutien et les encouragements de nombreuses personnes. A travers ces quelques lignes, je tiens à leur exprimer ma profonde et sincère gratitude.

Tout d'abord, je souhaite remercier mon promoteur de thèse, le Professeur Yannick Agnan. Il déteste être dénommé par son titre mais hé, c'est ma thèse, je fais ce que je veux après tout. Je lui suis profondément reconnaissant pour la confiance qu'il m'a accordée dès le début. Merci pour son encadrement précieux, sa disponibilité et son soutien constant tout au long de cette thèse. Son expertise et ses encouragements ont grandement contribué à la réalisation de ce travail. Je tiens à saluer Yannick non seulement pour ses compétences professionnelles et son expertise inestimable, mais aussi pour son côté profondément humain. Tout au long de ce parcours, j'ai été touché par sa bienveillance, son écoute attentive et son empathie. Son soutien ne s'est pas limité aux aspects techniques ou académiques de cette thèse, mais a également été une véritable source de réconfort dans les moments de doute et de difficulté. Yannick a toujours su allier rigueur scientifique et qualités humaines, sa générosité, sa patience et son souci du bien-être des autres ont été un exemple inspirant, et c'est un privilège d'avoir pu compter sur son accompagnement tout au long de cette aventure.

Je tiens à exprimer toute ma gratitude aux membres du jury de ma thèse, qui ont accepté d'évaluer mon travail et de participer à cette soutenance. Mes sincères remerciements vont aux professeurs Mélanie Davranche, Nadine Mattielli, Sophie Opfergelt, Katell Quénéa pour avoir pris le temps de lire minutieusement cette thèse, pour leur participation, leurs questions stimulantes, leurs suggestions et leurs commentaires éclairés qui ont grandement contribué à la qualité de la discussion lors de la soutenance privée et permis d'enrichir et de perfectionner ce travail. Je remercie également tout particulièrement le Professeur Marnik Vanclooster pour avoir présidé cette soutenance et pour ses remarques constructives.

Je remercie chaleureusement tous les membres de l'équipe SOLS pour l'environnement stimulant et collaboratif qu'ils m'ont offert pendant quatre ans. Merci à Arnaud, Arthur, Aubry, Benoît, Catherine, Clélia, Elisabeth,

Eléonore, Fidèle, François, Hind, Hugo, Joachim, Juliette, Maëlle, Marlon, Maxime B., Maxime D., Maxime T., Nathan, Noa, Philippe, Pierre, Romain, Sébastien, Sophie M., Sophie O., Yannick et Zimin pour leur amitié, leur soutien et les nombreux moments enrichissants que nous avons partagés.

Je tiens à exprimer mes plus sincères remerciements à chacun des mémorants que j'ai eu la chance d'encadrer au cours de ma thèse. Merci à Adil, Adrien, Julie, Lancelot et Marie pour leur engagement, leur sérieux et leur passion tout au long de leur mémoire. Leur implication, leur persévérance face aux défis et leur désir constant d'apprendre ont été une véritable source de motivation pour moi. Ce fut un plaisir de les accompagner dans cette aventure académique et de voir leurs idées et compétences évoluer. Merci pour leurs efforts et pour la qualité du travail accompli qui a grandement contribué à l'amélioration de ma thèse.

Un grand merci à ma famille, et en particulier à mes parents, Christian et Catherine, et mes sœurs, Louise et Valentine pour leur amour, leur patience et leur soutien indéfectible tout au long de ces années. Leurs encouragements m'ont donné la force de persévérer, même dans les moments les plus difficiles. Je souhaite également remercier mes amis et proches en dehors de la recherche qui ont toujours été présents pour me soutenir et me permettre de garder un équilibre entre travail et vie personnelle.

L'achèvement de cette thèse n'aurait pas été possible sans le soutien financier et appui structurel et logistique de plusieurs institutions et plateformes, que je tiens à remercier chaleureusement.

Je souhaite exprimer ma profonde gratitude à « Le Fonds de la recherche scientifique » (FNRS) pour le financement « fonds pour la formation à la recherche dans l'industrie et dans l'agriculture » (FRIA) qui m'a permis de mener à bien mes recherches durant quatre ans. Ce soutien a été essentiel pour l'avancement de mes travaux, ainsi que participation à des conférences et séminaires internationaux, qui ont considérablement enrichi ma perspective scientifique. Je suis reconnaissant de la confiance qui m'a été accordée. Je remercie également le Fonds Baillet Latour pour le financement mis à ma disposition au cours de ce projet. Grâce à leur appui, j'ai pu accéder aux équipements nécessaires pour mener à bien les différentes étapes liées aux analyses isotopiques qui ont contribué de manière significative à l'avancée de mes recherches.

Je souhaite également remercier profondément l'ensemble du personnel de la plateforme MOCA pour leur aide précieuse et leur soutien tout au long de ce projet de recherche. Je remercie particulièrement Anne, Brice, Claudine, Elodie, Etienne, François, Hélène, Karine, Laurence, Matthieu pour leur expertise technique, leur disponibilité et leur aide dans la gestion des équipements, ainsi que pour leurs précieux conseils qui ont facilité le déroulement de mes expériences. Leur professionnalisme et leur efficacité ont été d'une grande aide pour surmonter les défis techniques de ce travail.

Je tiens à exprimer ma profonde gratitude aux responsables de la plateforme SEFY, particulièrement Marc Migon, pour leur soutien logistique et technique tout au long de mes recherches. Leur expertise, leur disponibilité et leur implication ont été essentiels au bon déroulement de mes expériences dans les serres universitaires de l'UCLouvain. Merci pour leur accueil chaleureux et leur assistance précieuse, qui ont grandement facilité la réalisation de ce projet.

Je souhaite également remercier chaleureusement l'équipe de la Ferme universitaire de Marbaix, particulièrement Hugues Falys et Rémy Desmet pour m'avoir permis d'accéder à leurs infrastructures agricoles et pour leur aide plus que précieuse sur le terrain. Leur disponibilité, leur professionnalisme et leur passion pour leur travail ont été une véritable source de motivation pour moi. Leur collaboration a largement contribué à la réussite de cette thèse, et je leur en suis très reconnaissant.

Je tiens à exprimer toute ma gratitude à Cécilia, Geneviève, Jeroen et Wendy de l'ULB pour leur précieuse collaboration. Leur expertise a été essentielle au développement et à l'optimisation du protocole expérimental dans la mise en place et l'adaptation des méthodes d'analyses isotopiques. Aussi, je tiens à remercier grandement Christelle et François de Sorbonne Université pour leur expertise et leur disponibilité pour les analyses de caractérisation de la matière organique, qui ont été essentielles au bon déroulement de mes recherches. Je leur suis sincèrement reconnaissant pour leur accompagnement scientifique et leurs précieux conseils, qui ont grandement enrichi ce travail.

Enfin, je suis reconnaissant envers l'équipe administrative, notamment Jasmine et Sabine, pour leur soutien logistique et leur aide dans les démarches administratives. Leur assistance a permis à ce projet de se dérouler dans les meilleures conditions possibles. Leur contribution discrète mais essentielle a été un pilier de la réussite de cette thèse.

Scientific publications

- (6) **Arbalestrie B.**, Mattielli N., Opfergelt S., Debouge W., De jong J., Agnan Y. Isotopic fractionation of Cu, Zn, Fe and Pb in soil-plant agroecosystems: influence of organic matter application. **(in prep)**.
- (5) **Arbalestrie B.**, Van de Castele A., Quénéa K., Baudin F., Anquetil C., Bemelmans N., Agnan Y. Influence of organic matter application on the transfer of potentially harmful elements from soil to plant. **(in prep)**.
- (4) **Arbalestrie B.**, Thami A., Dedoyard M., Bemelmans N., Agnan Y. Challenges in assessing trace element transfer from soil to plant: contribution of environmental compartments for uncontaminated and contaminated agricultural soils. **(in prep)**.
- (3) Bemelmans N., Dejardin R., **Arbalestrie B.**, Agnan Y. (2024). Glyphosate application may influence the transfer of trace elements from soils to both soil solutions and plants. *Chemosphere*, Vol. 143603, no. 1, p. 1. doi: 10.1016/j.chemosphere.2024.143603.
- (2) Bemelmans N., **Arbalestrie B.**, Dailly H., Bodart E., Agnan Y. (2023). Influence of glyphosate and aminomethylphosphonic acid on the mobility of trace elements in uncontaminated and contaminated agricultural soils. *Environmental Science and Pollution Research*, 30: 103983–103995. doi: 10.1007/s11356-023-29660-w.
- (1) **Arbalestrie B.**, Falys J., Bemelmans N., Thami A., Monin L., Devos E., Agnan Y. (2022). Rare earth elements in an intercropping cover crop to evaluate the trace element transfer from soil to plant. *Biogeochemistry*, 161: 373–387. doi: 10.1007/s10533-022-00989-7.

Scientific conferences

(12) Bemelmans N.*, Dejardin R., **Arbalestrie B.**, Agnan Y. (2024). Glyphosate application modifies the transfer of trace elements from soils to soil solutions and plants. Centennial IUSS, Florence, 19–21 May 2024 [oral].

(11) **Arbalestrie B.***, Van de Castele A., Quénéa K., Baudin F., Anquetil C., Bemelmans N., Agnan Y. (2024). Qualitative characterization and influence of organic matter on the transfer of potentially harmful trace elements in the soil-plant system. Centennial IUSS, Florence, 19–21 May 2024 [poster].

(10) Bemelmans N.*, Dejardin R., **Arbalestrie B.**, Agnan Y. (2023). Glyphosate application increases or decreases the mobility of trace elements in agricultural soils depending on the contamination level. ICOBTE/ICHMET, Wuppertal, 6–10 Sep. 2023 [poster].

(9) **Arbalestrie B.***, Thami A., Bemelmans N., Agnan Y. (2023). Influence of organic matter application on the transfer of potentially harmful elements from soils to plant: an isotopic approach. ICOBTE/ICHMET, Wuppertal, 6–10 Sep. 2023 [oral].

(8) Agnan Y.*, **Arbalestrie B.**, Falys J., Dedoyard M., Bemelmans N. (2023). Rare earth elements in agroecosystems: insight for understanding the trace element transfer from soil to plant. ICOBTE/ICHMET, Wuppertal, 6–10 Sep. 2023 [oral].

(7) Bemelmans N.*, **Arbalestrie B.**, Agnan Y. (2023). Impact of glyphosate and aminomethylphosphonic acid on the mobility of trace elements in uncontaminated and contaminated agricultural soils. Goldschmidt, Lyon, 9–14 Jul. 2023 [oral].

(6) **Arbalestrie B.***, Thami A., Bemelmans N., Agnan Y. (2023). Transfer evaluation of potentially harmful elements from uncontaminated and contaminated soils to plant. <https://doi.org/10.7185/gold2023.13874>. Goldschmidt, Lyon, 9–14 Jul. 2023 [oral].

(5) Bemelmans N.*, **Arbalestrie B.**, Agnan Y. (2022). Dynamics of trace elements in uncontaminated and contaminated soils: influence of glyphosate and AMPA. ELIday, Louvain-la-Neuve, 19 May 2022 [poster].

- (4) **Arbalestrie B.***, Falys J., Bemelmans N., Thami A., Agnan Y. (2022). Understanding trace element dynamics in the soil–plant continuum using rare earth elements. ELIday, Louvain-la-Neuve, 19 May 2022 [poster].
- (3) Bemelmans N.*, **Arbalestrie B.**, Agnan Y. (2022). Influence du glyphosate et de l’AMPA sur l’extractibilité des éléments traces dans les sols contaminés et non contaminés. GFP, Namur, 18–20 May 2022 [oral].
- (2) Bemelmans N.*, **Arbalestrie B.**, Agnan Y. (2022). Influence of glyphosate and AMPA on the extractability of trace elements from contaminated and uncontaminated soils. DYSS, Brussels, 31 Mar. 2022 [poster].
- (1) **Arbalestrie B.***, Falys J., Bemelmans N., Thami A., Agnan Y. (2022). Use of rare earth elements as tracers for soil–plant transfer of trace elements. DYSS, Brussels, 31 Mar. 2022 [poster].

* speaker

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I. General overview

1. Motivation

Trace elements are chemical elements present in low concentrations in the environment, foodstuffs and all living organisms. While some are essential for various biochemical processes in organisms, all trace elements can become toxic when concentrations exceed certain thresholds. Elevated levels of toxic elements or insufficient quantities of essential elements in food products can pose significant risks to human health, representing a critical global concern. In agricultural soils, trace elements primarily originate from the parent material but human activities contribute significantly to elevated trace element levels in soils. Over time, the concentration of trace elements in soils worldwide has been steadily increasing, largely driven by these anthropogenic inputs (industrial and agricultural activities), posing potentially greater threats to ecosystems and human health. But, the complex physicochemical properties of trace elements combined with their diverse sources, make it challenging to study their distribution and behavior across different environmental compartments. In particular, their dynamics within the soil–plant system, which form the foundation of human nutrition, remain poorly understood, especially regarding the factors that govern their retention or transfer in agroecosystems. Among the factors influencing trace element availability and transfer in agroecosystems, soil organic matter appears to be a key parameter to investigate, as it provides a reactive surface that facilitates the retention of trace elements in the soil. However, declining organic matter levels in European agricultural soils are reducing this retention capacity, leading to the migration of these elements out of the soil-plant system, which can lead to potential deficiencies in essential trace elements, a trend that is tending to accelerate with current climate change according to projection results. However, agricultural practices such as the application of exogenous organic matter in agricultural soils, often practiced to improve soil chemical and physical fertility, can significantly influence the dynamics of these trace elements, which are levers for environmental and health issues. Consequently, it is essential to assess the impact of organic matter on trace element behavior, considering retention processes that may lead to

deficiencies and transfer processes that could promote contamination. This evaluation is crucial for the appropriate selection and use of organic matter across diverse agricultural contexts. In this context, the aim of this thesis is to investigate the influence of applying exogenous organic matter on the fate of trace elements in the soil-plant system, with a focus on the specific processes that govern the availability and mobility of these elements. To address the anticipated challenges of low trace element concentrations in certain soils and the limited duration of the experimental setups for this research, this thesis proposes the use of rare earth elements and stable isotopes of non-conventional elements as geochemical tracers.

2. State of the art

2.1. Dynamics of trace elements in natural and anthropogenic environments

2.1.1. Difficulties in defining trace elements

The term "trace elements", opposed to major elements, refers to chemical elements present in low concentrations in the environment and/or living organisms and can be found in different chemical families such as transition metals (Cd, Cr, Cu, Mn, Ni, Pb, Ti, V, Zn), metalloids (As and Sb) and non-metals (Se; Figure I.1). But, a series of terms considered synonymous with trace elements have emerged over time, such as toxic metals, essential metals, trace metals, heavy metals, micronutrients, microelements, and minor elements. These various terms, often imprecise and inconsistently used, group elements according to various chemical properties and characteristics, such as density, atomic mass, biological functions, or toxicity associated with pollution and whether or not they are necessary for living organisms (Adriano, 2001; Duffus, 2002). In this document, we used the term "trace elements" referring to elements in small quantities in natural and disturbed environments and which may present a risk of deficiency or toxicity to living organisms when present in insufficient bioavailable quantity or above a toxic threshold value, respectively.

To define trace elements, a threshold for element concentration must be established, which varies depending on the specific scientific discipline considered. For example, in geochemistry, trace elements have content below 0.1% (i.e., 1000 mg kg⁻¹) in natural media, while in biochemistry, the threshold is 0.01% (i.e., 100 mg kg⁻¹) in plant or animal tissues. In the context of food nutrition, trace element contents rarely exceeds 20 mg kg⁻¹ in consumed foodstuffs (Adriano, 2001; Kabata-Pendias, 2011).

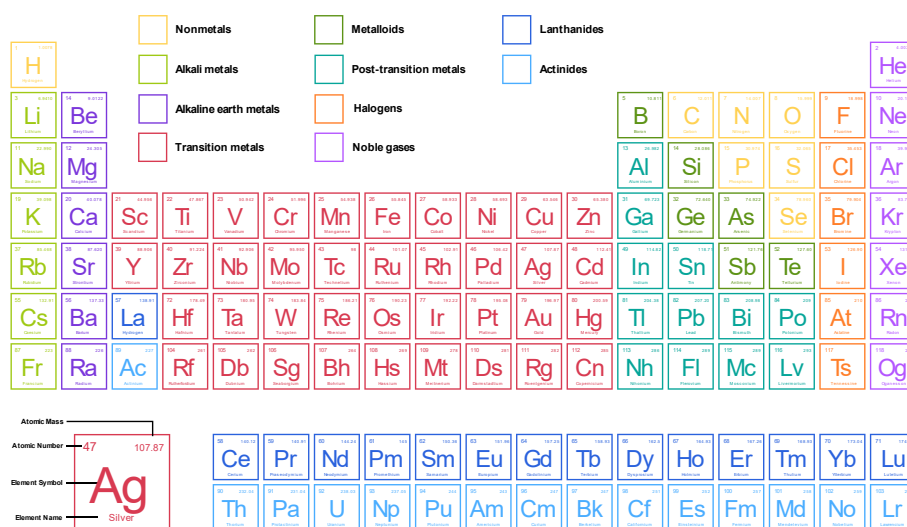


Figure I.1 - Distribution of trace elements in the different element families in the periodic table.

2.1.2. Environmental distribution and implications for ecosystem and human health

Trace elements are found ubiquitously in all compartments of the geosphere (atmosphere, hydrosphere, lithosphere, and cryosphere), as well as in the biosphere (including animals and plants; Rauch and Pacyna, 2009), but certain elements have a tendency to accumulate in specific ones. For example, mercury (Hg), due to its semi-volatility, is more prevalent in the atmosphere (Adriano, 2001), while Cd, highly mobile in water, is readily detected in the hydrosphere (Wright and Welbourn, 1994). Their distribution is influenced by a diversity of factors, such as anthropogenic activities, natural geological processes, climatic conditions, and biotic interactions (Nriagu, 1989a, 1989b; Pacyna and Pacyna, 2001). Their content in the environment has a direct influence on the ecosystems health and, by extension, on human health, given their accumulation into plant and animal tissues that modifying their vital cycles (Prasad et al., 2006). Indeed, trace elements play crucial roles in a multitude of biogeochemical processes. For instance, elements such as Co, Cu, and Zn are essential in minute quantities for the proper functioning of biological processes, including plant growth and animal metabolism (Hooda, 2010; Kabata-Pendias, 2011). Conversely, toxic trace elements like As, Cd, Hg,

and Pb can have deleterious effects on living organisms, even at low concentrations. However, all trace elements have the potential to become toxic if their concentrations exceed a certain threshold (Alloway, 2012). This is particularly concerning given the increasing environmental concentrations due to anthropogenic activities over recent decades. Therefore, understanding their distribution, behavior, and impact on ecosystems is crucial for addressing the complexities associated with environmental contamination and food safety.

2.1.3. Natural and anthropogenic sources

The primary natural sources of trace elements in the environment include the weathering of parent rocks, volcanic activity, soil erosion, and biogenic sources (such as volatile compounds or particles like pollen and spores). Wildfires and marine aerosols (sea spray) can also contribute, to a lesser extent, to natural trace element emissions into the environment. The contribution of these emission sources varies significantly depending on the specific trace elements. For instance, soil erosion and atmospheric suspension of soil particles account for an average of 50% of the natural atmospheric emissions of Cr, Mn, and V, 20-30% for Pb, Sb, and Zn, but less than 10% for Hg and Se (Nriagu, 1989a). Volcanic activity, however, is responsible for 40-50% of the emissions of Cd and Hg, and 20-40% of the emissions of As, Cr, Ni, Pb, and Sb. Biogenic emissions contribute to 50% of the emissions of Se and Mo and 30-50% of the emissions of As, Cd, Cu, Mn, Pb, Sb, and Zn (Nriagu, 1989a). In contrast, marine aerosols and wildfires have a lower impact, each contributing less than 10% to the emissions of trace elements (Nriagu, 1989a).

Over the past few decades, human society has dramatically altered the biogeochemical cycles of various chemicals through anthropogenic activities, significantly increasing the levels of trace elements in the air, water, and soil (Pacyna and Pacyna, 2016). The primary anthropogenic sources of trace elements in the environment include the metallurgical and mining industries, as well as energy production, particularly through the combustion of fossil fuels and biomass. Transportation also plays a significant role, with vehicle emissions contributing to the dispersion of trace element, as well as particles resulting from abrasion of break and tire wear (Lopez et al., 2023). Additionally, the improper management of waste, particularly electronic waste, represents another substantial source, as well as the use of pesticides

and fertilizers in agriculture. Fossil fuel combustion for energy production accounts for more than 85% of anthropogenic atmospheric emissions of Ni, Pb, Sb, Se, Sn, V and is responsible for approximately 15% of As and Cu emissions (Nriagu and Pacyna, 1988; Pacyna and Pacyna, 2001). The metallurgical sector is the leading source of As, Cd, Cu, Mn, and Zn emissions, contributing to 40-65% of the total and transportation accounts for 75% of Pb emissions for instance (Nriagu and Pacyna, 1988; Pacyna and Pacyna, 2001).

The initial quantitative global assessment of annual industrial emissions of trace elements into the air, soil, and water was published by Nriagu and Pacyna (1988). Subsequent updates to this global emission inventory were provided by Pacyna and Pacyna (2001), with the emission data representing conditions at the start of the 1990s (Table I-1). Although these data are based on some of the most comprehensive studies to date, they were collected in the late 20th century and may no longer reflect current conditions due to technological advancements aiming at reducing trace element emissions and the emergence of new pollutants, such as Sb (Filella et al., 2009). The data presented highlighted that anthropogenic trace element emissions to soil are higher compared to emissions of these elements to aquatic ecosystems, the atmosphere, and natural sources (Table I-1).

Table I-1 - Global emissions of trace elements to the environment (10^3 t yr^{-1} ; Pacyna and Pacyna, 2016).

Trace element	Natural emissions ^a	Anthropogenic emissions				Anthro. ^a /nat. ratio (-)
		Air	Water	Soil	Total	
As	12.0	5.0	41.0	82.0	128.0	0.4
Cd	1.3	3.0	9.4	22.0	34.4	26.5
Cr	44.0	14.7	142.0	896.0	1053.7	24.0
Cu	28.0	25.9	112.0	955.0	1092.9	0.9
Hg	2.5	4.6	6.3	4.0	14.9	5.9
Mo	3.0	2.6	11.0	88.0	101.6	8.6
Ni	30.0	95.3	113.0	325.0	533.3	3.2
Pb	17.0	119.3	138.0	796.0	1053.3	62.0
Sb	2.4	1.6	18.0	26.0	45.6	19.0
Se	9.3	4.6	41.0	32.0	86.6	9.0
V	26.0	240.0	12.0	132.0	384.0	2.4
Zn	45.8	57.0	226.0	1372.0	1655.0	1.2

^aatmospheric emissions

2.1.4. Biogeochemical cycles of trace elements

The biogeochemical cycles of trace elements are critical processes that regulate the distribution and transformation of chemical elements in the environment. These cycles involve complex interactions among atmospheric, terrestrial, oceanic, and biological compartments, and are directly influenced by the sources and fluxes of trace elements (Adriano, 2001; Figure I.2).

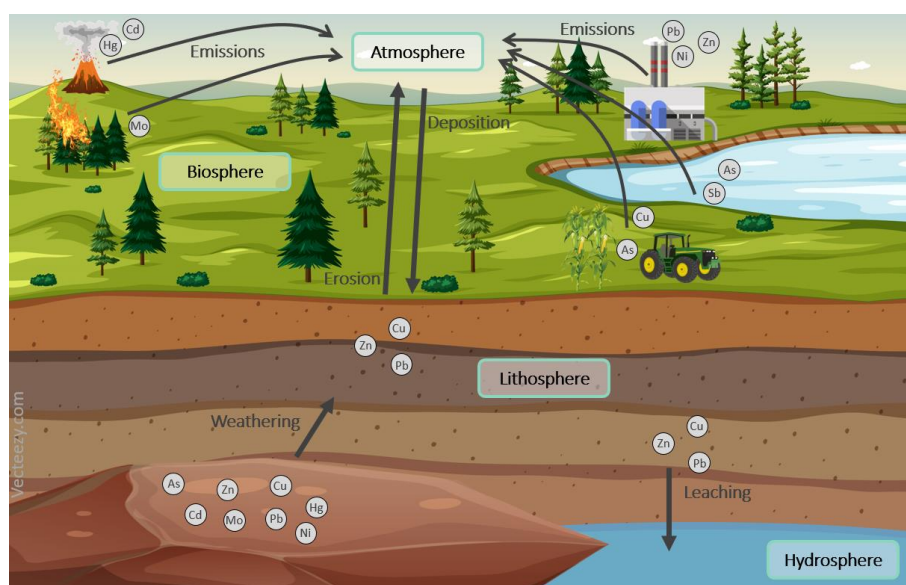


Figure I.2 - Schematic representation of the major fluxes within the biogeochemical cycle of trace elements.

The strong correlation between parent material and the soil it forms suggests that trace element content in soil are largely determined by the composition and characteristics of the parent material, as well as by the processes of chemical weathering, physical disintegration, and biological activity that occur during pedogenesis (Kabata-Pendias, 2011; Prabhakaran Nair and Cottenie, 1971). Indeed, depending on the weatherability of trace element-bearing minerals, the trace element concentrations in soils can vary considerably. For instance, minerals such as olivine and biotite are likely to release higher amounts of trace elements (e.g., Ni, Co, Zn, Cu, Mo) compared to less weatherable or nearly inert minerals like magnetite and quartz (Bradl, 2005). Tu et al. (2013) further demonstrated, for instance, that topsoil derived from carbonate rock tends to have elevated trace element content. But, trace elements can be introduced into the soil through other pathways than weathering, and their behavior and fate in the soil are influenced by both their source and chemical form (Senesil et al., 1999).

The mobility of trace elements across different environmental compartments is primarily determined by their speciation. In soils, chemical reactions (e.g., redox processes, complexation, dissolution), physicochemical interactions (e.g., sorption), and biological activities (e.g., biomethylation) critically influence the behavior and bioavailability of trace elements (Pacyna and

Pacyna, 2016). Notably, trace elements of anthropogenic origin are often more bioavailable than their lithogenic counterparts (Kabata-Pendias, 2011; Tremel-Schaub and Feix, 2005). Through rock weathering and soil leaching, trace elements are released as ions and transported into aquatic systems, including both groundwater and surface waters. Microbial and other biological processes may also play significant roles in modulating these transfers. In aqueous environments, trace elements typically occur in three main forms: as free ions, in complexes (e.g., organometallic compounds), or associated with colloids (i.e., adsorbed onto organic or mineral particles; Kabata-Pendias, 2011). Plants serve as intermediate reservoirs, facilitating the transfer of trace elements from soils—some of which may originate from water and air—into the food chain, eventually reaching humans and other animals (Kabata-Pendias, 2011).

In the atmosphere, trace elements are present either as aerosols—associated with organic or mineral particles suspended in the air—or in gaseous form for more volatile elements, such as As, Hg, and Se (Adriano, 2001; Kabata-Pendias, 2011; Pacyna and Pacyna, 2016). The atmospheric residence time and deposition rate of these trace elements are inversely related to the particle size and density. In their gaseous state, trace elements can be transported over much greater distances. The atmosphere plays a critical role in the long-range transport of trace elements, which are eventually deposited through wet or dry deposition processes into other environmental compartments such as soils, aquatic systems, and vegetation (Kabata-Pendias, 2011).

As mentioned, human activities play a significant role in the biogeochemical cycles of trace elements by disrupting natural fluxes on spatial and temporal scales. The annual mobilization of elements through anthropogenic activities exceeds that of natural mobilization. However, when considering all global compartments, the total mass fluxes within the natural system (e.g., Earth's crust formation, subduction, erosion, oceanic deposition, etc.) surpass the mass fluxes of anthropogenic origin (e.g., mining, metal production, and consumption; Rauch and Pacyna, 2009). The temporal scale of these fluxes is also critical: anthropogenic activities tend to disturb biogeochemical cycles over the short term, while natural fluxes occur over much longer time scales (Kabata-Pendias, 2011).

2.2. Trace elements in the soil-plant system

The transfer from soil to plants is a critical process in biogeochemical cycling of trace elements. Both environmental and human health risks associated with trace elements are largely determined by their mobility and bioavailability within the soil-plant system. However, the mechanisms governing this transfer are highly complex and influenced by various factors, both natural and anthropogenic. These include geochemical, climatic, and biological variables through the regulation of trace element mobility and bioavailability (Antoniadis et al., 2017). Consequently, predicting the uptake of trace elements by plants from a given growth medium requires a comprehensive understanding of the biotic and abiotic factors that control their behavior in soils (Kabata-Pendias, 2004).

2.2.1. Trace element in soil

Trace elements in soils are predominantly distributed among the solid, liquid, and, to a lesser extent, the gaseous phases (Tack, 2010). They can be classified into three primary categories of trace element species (Figure I.3): (1) species bound within the mineral fraction, (2) species associated with mineral (oxides, carbonates) or organic solid phases, and (3) species dissolved in the soil solution. The distribution among these different categories depends on the trace element considered and is governed by the variability in the physicochemical characteristics of the element and the physical, chemical, and biological processes in the soil that determine the speciation, redistribution, mobility, and ultimately the bioavailability of trace elements. For instance, in a podzolic loamy sand soil, Cd is predominantly associated with the mineral (residual) fraction, whereas Mo is mainly retained by organic matter (Kabata-Pendias, 2011).

In the solid phase, trace elements can be occluded into soil mineral structures. Although not immediately available, these elements may be released over extended timescales through the gradual weathering of minerals. Additionally, trace elements are distributed between the mineral and organic fractions, where they are superficially adsorbed or complexed with components, such as clay minerals, iron and manganese oxyhydroxides, carbonates, or organic compounds (organic matter; Figure I.3), and are more

or less exchangeable with the soil solution (Kabata-Pendias, 2011; Tack, 2010).

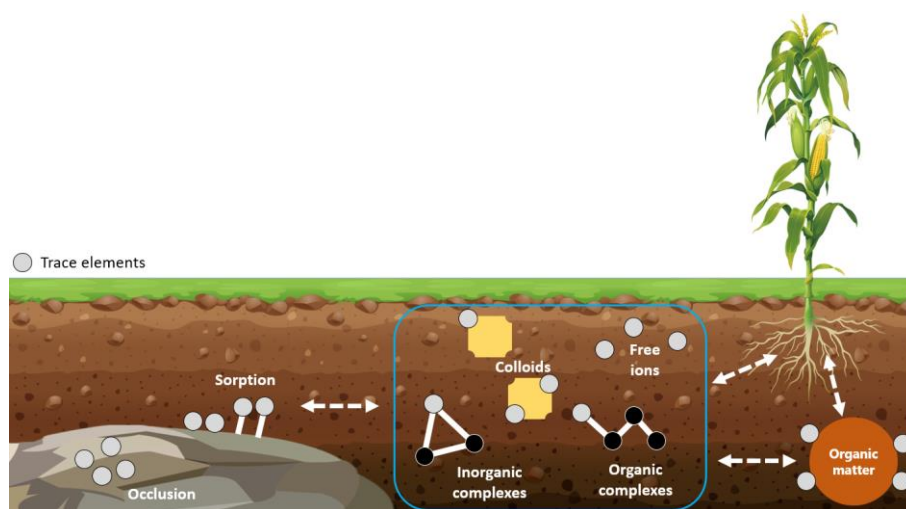


Figure I.3 - Schematic representation of the various trace element pools in the soil (adapted from Thami, 2022).

In the liquid phase, trace elements are found in various forms, primarily as hydrated species (e.g., Zn^{2+} , Cu^{2+} , etc.), which are simplified representations of their actual presence in solution as hexa-hydrated forms (e.g., $\text{Zn}(\text{H}_2\text{O})_6^{2+}$; Tack, 2010). However, certain elements may also be present as oxyanions, such as molybdate (MoO_4^{2-}), arsenate (AsO_4^{3-}), and chromate (CrO_4^{2-}). Moreover, trace elements can exist in both organic and inorganic complex forms. An organic complex involves the chemical bonding between a trace element and a carbon atom, either directly or through a heteroatom (e.g., O, N) from an organic group (Hooda, 2010). This type of complex is particularly common with As, which can form compounds such as monomethylarsonate ($\text{CH}_3\text{AsO}_2^{3-}$) and dimethylarsonate [$(\text{CH}_3)_2\text{AsO}_2^{3-}$]. In addition to this variety of organic complexes, inorganic complexes are formed through the interaction of metal cations with inorganic anions and ligands, such as hydroxide (OH^-) in ZnOH^+ , carbonate (CO_3^{2-}) in CuCO_3 , or chloride (Cl^-) in CdCl_2 (Tack, 2010). Lastly, trace elements can be adsorbed onto colloidal particles present in soil solution and transported to surface waters through runoff. It has been shown that the application of organic residues to structured soils may promote the transport of trace elements via particulate movement. For instance, it has been demonstrated that the mobility of Pb associated with colloids is significant, concluding that colloid-facilitated transport plays a significant role,

particularly for contaminants that exhibit strong sorption behavior (Carrillo-González et al., 2006).

2.2.2. Trace element in plant

Kabata-Pendias (2011) identified 17 trace elements (Al, B, Br, Cl, Co, Cu, F, Fe, I, Mn, Mo, Ni, Rb, Si, Ti, V, and Zn) as essential for plant growth. However, some of these elements are required only by specific plant species, while others have been observed to enhance growth, though their exact physiological roles remain unclear. Transition metals, in particular, play critical roles in enzymatic systems, primarily functioning as electron carriers. Notable examples include Cu, Fe, Mn, and Zn, which are integral to various metabolic processes (Awasthi et al., 2022; Bowen, 1979). The involvement of trace elements spans a wide range of metabolic pathways, including respiration, photosynthesis, and the fixation and assimilation of key macronutrients such as N and S (Sahu et al., 2020).

Elemental uptake by plant roots

Higher plants absorb most elements in their bioavailable chemical forms from the soil solution (Wiggenhauser et al., 2022). These elements enter the root apoplast primarily via water mass flow, which is driven by the transpiration stream. Once in the root apoplast, the elements are either retained within root cells or radially translocated from the root cortex to the root stele. From there, they are loaded into the xylem and phloem tissues (for further root-to-shoot transport) through two distinct pathways (Figure 1.4): the apoplastic and symplastic pathways, which correspond to passive and active transport, respectively (Gupta et al., 2019). The apoplastic pathway involves the movement of elements through the extracellular spaces without directly entering the cells. This mode of transport is often faster, as it does not require the crossing of cell membranes. However, in roots, the Casparian strip, a waxy barrier located in the endodermis, blocks the apoplastic passage, forcing elements to enter the symplast to continue their journey toward the xylem (Marschner and Marschner, 2012). The symplastic pathway, in contrast, involves the movement of substances through the cytoplasmic continuum of cells via connections known as plasmodesmata that are small intercellular channels allowing the direct passage of substances from one cell to another. This pathway is more selective, as elements must cross the plasma membrane

to enter a cell, enabling more precise control over transport. Although distinct, these two pathways are complementary, working together to ensure the efficient and regulated distribution of resources within the plant in their bioavailable chemical forms (Barberon and Geldner, 2014; Taiz et al., 2015).

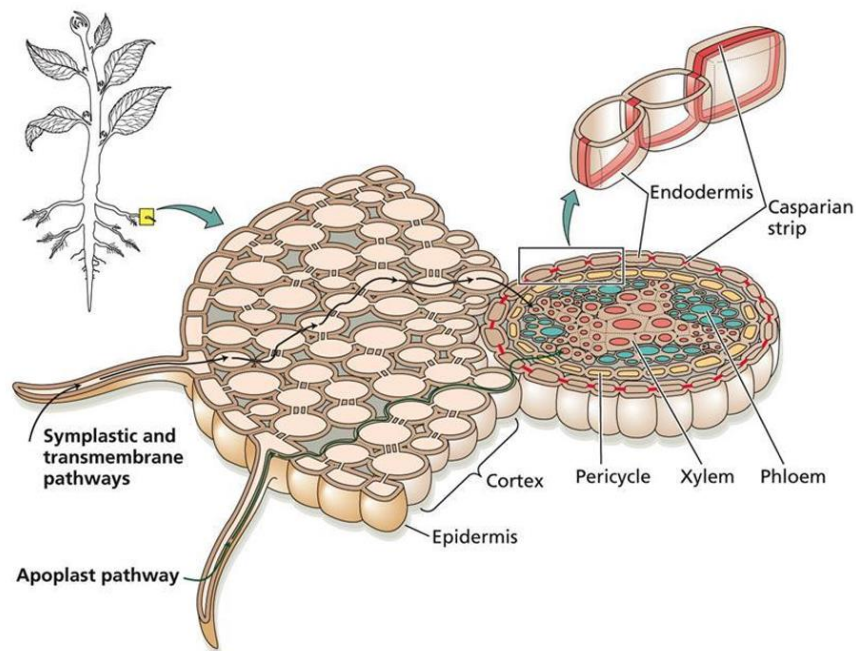


Figure I.4 - Visualization of symplastic and apoplastic pathways in the root of higher plant (Taiz et al., 2015).

Elemental transport in plants

Once in the xylem, the elements are transported unidirectionally by transpiration stream to the shoots (translocation), where they can be allocated to the aerial tissues and distributed to almost all subcellular compartments, such as mitochondria or chloroplasts (Figure I.5). As some transition metals are highly reactive, chelation is necessary to avoid oxidative stress and to facilitate ion translocation through the vascular system. These metals can be chelated by association with amino acids or organic acids. In addition, plants are also characterized by another vascular tissue, the phloem (bidirectional transport), which runs parallel to the xylem and translocates and redistributes photosynthetic products and elements throughout the plant body between source and sink organs (re-translocation), even returning elements to the roots. This cycle is important for the redistribution of

nutrients and it has been shown that certain trace element, such as Cu, Zn, Fe, Co, Ni, and Cd, can undergo a transfer from the xylem to the phloem and also a cycle in the phloem (DalCorso et al., 2014; Wiggerhauser et al., 2022).

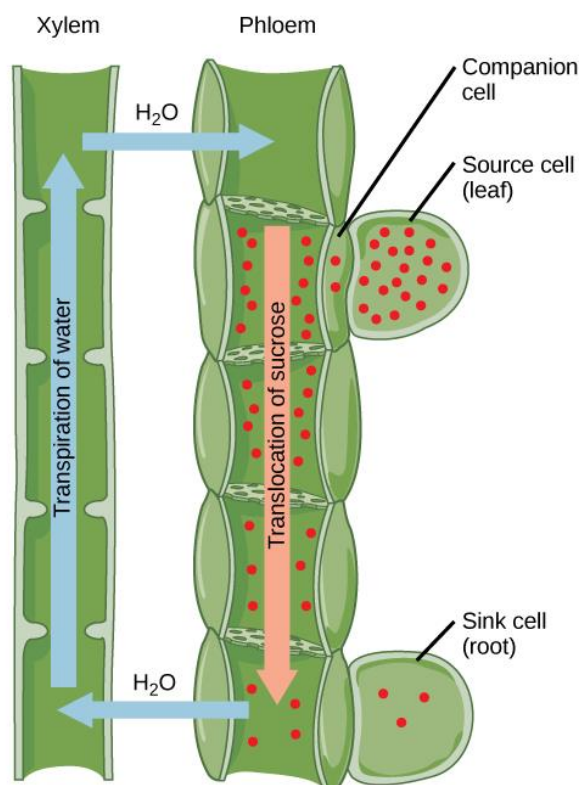


Figure I.5 - Visualization of translocation pathways in xylem and phloem (Rye et al., 2016).

Assessing transfer in the soil-plant system

The transfer of trace elements from soil to plants is a primary pathway through which these elements enter the food chain, making it a critical aspect of assessing risks to both animal and human health. To evaluate the ability of plants to absorb trace elements from the soil, as well as to quantify the transfer of these elements within different plant parts, various authors employ distinct transfer indices called transfer factors (TF; Antoniadis et al., 2017; Buscaroli, 2017). This type of index serves two key purposes: (1) it allows for the assessment of the potential transfer of trace elements into the food chain, particularly in relevant plant parts; (2) it aids in identifying phytoremediating plants in polluted environments (Buscaroli, 2017).

Various terms are used to describe the transfer of elements from soil to plants, including the transfer coefficient (TC), bioconcentration factor (BCF), bioaccumulation factor (BAF), and others (Antoniadis et al., 2017; Buscaroli, 2017). These transfer factors all represent the ratio between the concentration of elements in the aerial parts (shoot) of the plant (denoted as C_{plant}^1 or C_{shoot}) and the concentration of elements in the soil (C_{soil}) where the plant is growing (Antoniadis et al., 2017).

$$TF_{\text{soil-plant}} = \frac{C_{\text{plant}}}{C_{\text{soil}}}$$

This type of index depends both on the plant properties (its ability to absorb and translocate trace elements within the plant) and on the soil characteristics. Additionally, the nature of the element being studied can influence these values, given their specific biological functions (Antoniadis et al., 2017).

Other indices can be used to assess the ability of plants to transfer trace elements from the roots to the shoot (Antoniadis et al., 2017). The shoots typically include the stems and leaves, but this index can be adapted to individual parts (C_{stems} or C_{leaves} , respectively). It is important to note that the choice of the aerial part is significant, as trace elements are not uniformly distributed within the plant.

$$TF_{\text{root-shoot}} = \frac{C_{\text{shoot}}}{C_{\text{root}}}$$

Elemental uptake by leaves

Foliar absorption, though less significant than root absorption, is influenced by the surface properties of leaves, and the atmospheric deposition of trace elements on the leaf surface. In cases of atmospheric pollution (e.g., from agriculture, industry, etc.), a substantial proportion of trace elements can penetrate plant tissues. Certain trace elements (e.g., Pb) tend to be leached from plant foliage to the soil, particularly by acid rain, while others (e.g., Cd, Cu, Zn) appear to be preferentially absorbed by the leaves. Once absorbed, these trace elements can be translocated via the phloem to other plant tissues, including the roots (Gupta et al., 2019; Kabata-Pendias, 2011).

¹ The term 'plant' is sometimes used to refer to the entire organism, encompassing all its parts, including the roots.

2.2.3. Factors affecting trace element mobility

The transfer of trace elements from soil to plants is directly dependent on their mobility within the soil. Numerous factors can influence the mobility of trace elements. Among the most critical parameters are soil pH, redox potential (Eh), and the cation exchange capacity of both soil and organic matter (Carrillo-González et al., 2006).

pH and redox potential

The pH and redox potential (Eh) of soil solutions directly and indirectly influence all physicochemical processes within the soil and determine the behavior of trace elements. The effects of pH and redox potential are specific to individual trace elements. For instance, the solubility of trace elements, present in cationic forms (e.g., Cu^{2+} , Zn^{2+}), generally increases as pH decreases, whereas elements in anionic forms (e.g., AsO_4^{3-} , CrO_4^{2-}) exhibit greater mobility under alkaline conditions (Figure 1.6; Tack, 2010).

Indeed, a decrease in pH leads to an increase in the activity of Fe^{3+} and Al^{3+} ions, as well as their respective positively charged hydroxides. These positively charged ions then compete with cationic trace elements for negatively charged binding sites. But, a reduction in pH also results in a decrease in the number of available binding sites because the high abundance of protons (H^+) in the environment causes the protonation of functional groups, which are initially negatively charged but become neutral or even positively charged, particularly in the case of Fe and Mn hydroxides. Additionally, a drop in pH promotes increased sorption of various anions. As the net charge of the binding sites becomes positive, a significant proportion of anionic species, such as As, Mo, and Cr, can be adsorbed (Adriano, 2001). Simultaneously, a decrease in pH induces instability and dissociation of certain compounds, particularly Mn and Fe oxides, which dissociate at pH 5.5 and 3.5, respectively, thereby releasing trace elements into the environment.

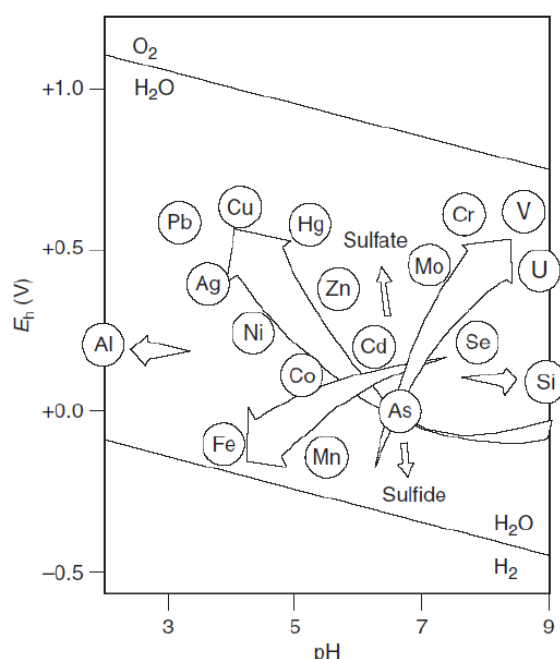


Figure I.6 - Schematic representation of the main trends in the increasing mobility (broadening arrows) of elements in soils as a function of redox potential and pH (Förstner, 1993).

Within the pH range typically encountered in soils (pH 4-8), the surfaces of phyllosilicates and organic matter generally exhibit a net negative charge and behave as cation exchangers (Sadiq, 1997; Tack, 2010). In contrast, Fe oxyhydroxides tend to carry a net positive charge and therefore adsorb oxyanions from the soil solution (Sadiq, 1997). The net surface charge of a soil constituent depends on the mineral's point of zero charge (pH_{PZC}), which is defined as the pH at which the overall net surface charge of the solid is zero (Tschapek et al., 1974). Other mechanisms, such as chemisorption or ligand exchange, may also explain the adsorption of trace elements onto the solid phase of the soil (Tack, 2010).

In soils, most trace elements, such as Cd, Pb, and Zn, exist in a single oxidation state, whereas elements like As, Cr, and Se can occur in multiple oxidation states (Tack, 2010). Changes in redox conditions result in modifications to the speciation of trace elements, thereby influencing their behavior and mobility in the soil. Typically, trace elements are less mobile under reducing conditions than under oxidizing conditions (Figure I.6; Tack, 2010). For example, Cr exists in two oxidation states, with the reduced form Cr^{3+} being relatively insoluble

in water, whereas the oxidized form Cr^{6+} is highly soluble and bioavailable (Gupta et al., 2019). Biological activity (microorganisms, plants) induces reducing conditions when the environment becomes anaerobic or anoxic. Under these conditions, for instance, Fe and Mn are present in their reduced, more soluble forms (Fe^{2+} and Mn^{2+}) compared to their oxidized forms, which occur as Fe(III) and Mn(III-IV) hydroxides. The dissolution of these hydroxides can lead to the release of trace elements adsorbed on their surfaces or occluded within the hydroxide matrix (Tack, 2010). Oxidizing and aerobic conditions also promote the mineralization of organic matter, releasing associated trace elements such as Cu, Cd, Hg, Pb, and Zn (Förstner, 1993).

Cation exchange capacity

The cation exchange capacity (CEC) of a soil sample represents the total amount of cations that can be adsorbed onto its exchange complexes at a specific pH (Baize, 2000a) and is directly related to its texture (Kabata-Pendias, 2011). Indeed, the clay fraction ($<2\ \mu\text{m}$) has a greater specific surface area and surface reactivity, and therefore a higher CEC compared to silt ($2\ \mu\text{m} - 20\ \mu\text{m}$) and sand ($20\ \mu\text{m} - 2\ \text{mm}$). Moreover, depending on the type of mineral present in the clay fraction, the CEC of the soil can vary significantly, i.e., secondary minerals (such as phyllosilicates and Fe and Mn oxyhydroxides) typically exhibit a higher CEC than primary minerals. For example, montmorillonite has a CEC ranging from 80-150 $\text{cmol}_\text{c}\ \text{kg}^{-1}$, whereas kaolinite has a CEC of approximately 3-22 $\text{cmol}_\text{c}\ \text{kg}^{-1}$ (Kabata-Pendias, 2011).

Organic matter content can significantly influence CEC of the soil. With a CEC ranging from 100 to 300 $\text{cmol}_\text{c}\ \text{kg}^{-1}$, soil organic matter serves as a source of negative charges, contributing substantially to the soil CEC (about 20 to 90%; Kabata-Pendias, 2004; Tack, 2010). Organic matter consists of: (1) macromolecules such as polysaccharides and proteins; and (2) simpler molecules like sugars and amino acids. Its interactions with trace elements involve not only sorption reactions but also the formation of organometallic complexes in solution, ion exchange, and surface complexation (Gupta et al., 2019; Tack, 2010). At a pH above 6–7, organic matter tends to form complexes in solution, primarily with divalent cations (Tack, 2010). The general order of affinity of organic matter for complexing cations is: $\text{Cu}^{2+} > \text{Cd}^{2+} > \text{Fe}^{2+} > \text{Pb}^{2+} > \text{Ni}^{2+} > \text{Mn}^{2+} > \text{Co}^{2+} > \text{Zn}^{2+}$ (Adriano, 2001). When the cation concentration is sufficiently high, flocculation occurs, and the complex behaves like a colloid.

Among the key factors influencing trace element availability and transfer in agroecosystems, soil organic matter stands out as a critical parameter. The application of exogenous organic matter (EOM), particularly in agricultural practices aimed at enhancing soil fertility, may significantly influence the dynamics of trace elements. These practices may serve as both an environmental lever and a public health concern. Therefore, it is crucial to evaluate the effects of organic matter on trace element behavior, considering retention processes that may contribute to deficiencies, as well as transfer mechanisms that could increase the risk of contamination.

2.3. Organic matter fundamentals

To improve agricultural practices, organic amendments such as compost, manure, cover crop residues, sewage sludge, etc. present cost-effective and environmentally friendly alternatives to chemical inputs (Huang et al., 2016). These organic amendments offer several benefits, including enhancing soil structure and fertility, promoting microbial activity, and increasing soil biomass and crop growth. Their decomposition and transformation by soil microorganisms and enzymes into CO₂, H₂O, mineral ions, and organic acids can lead to interaction with trace elements in the soil, providing potential solutions to control trace element availability and transfer in agroecosystems. In the Walloon Region, the annual production of organic materials amounts to approximately 2.5 million tons of dry matter. Of this total, 60% originates from livestock effluents (e.g., manure), while 5% consists of green waste potentially compostable (Culot, 2005).

2.3.1. Definition of organic matter

Although minor compared to the mineral fraction, the organic fraction of soils plays a crucial role in maintaining ecosystems by performing a wide range of essential functions at the physical, chemical, and biological levels (Wander, 2004). Soil organic matter is predominantly found in solid form, with a liquid contribution coming from dissolved organic matter (Ondrasek et al., 2019). Organic matter consists primarily of carbon (50%), along with other elements such as oxygen (38%), hydrogen and nitrogen (5% each), and sulfur and phosphorus (1% each). Despite its designation as organic, soil organic matter

may also contain an inorganic fraction, which includes trace elements complexed with various functional groups. These groups, such as carboxyl, carbonyl, and phenolic groups, can retain trace elements through a variety of chemical interactions (Huang et al., 2016; Ondrasek et al., 2019).

Soil organic matter can originate from both animal and plant residues. In the case of plant residues, organic matter is derived from compounds associated with intracellular materials and structural components of plant cells. Among these, proteins (polymers of amino acids) play various metabolic roles within plants and contribute to their structural integrity (Kögel-Knabner, 2002). Other intracellular compounds serve as energy reserves, notably starch, which is composed of amylose and amylopectin, two glucose polymers (Gallois, 2008). In addition, a second category includes compounds that form the structural components of plant cell walls. This group contains a significant proportion of polysaccharides, both cellulosic and non-cellulosic, each contributing approximately 15% to the composition of organic residues (Kögel-Knabner, 2002). Cellulose (linear glucose polymer) plays a major structural role by forming fibrils interconnected via hydrogen bonds, which gives it substantial structural properties (Gallois, 2008). In contrast, non-cellulosic polysaccharides, commonly grouped under the term hemicelluloses, are polymers composed not of glucose but of various sugars such as pentoses, hexoses, or amino sugars (Kögel-Knabner, 2002). These polysaccharides differ from their cellulosic counterparts in both the nature of their monomers and their lower degree of polymerization.

Another key component of plant cell wall is lignin, which is often closely associated with cellulose-hemicellulose complexes and can account for 5 to 8% of organic residues (Kögel-Knabner, 2002). Lignin is a polyaromatic macromolecule that provides rigidity and protection to plant cell walls. It is composed of several precursors, known as monolignols, including coumaryl, coniferyl, and sinapyl alcohols (Kögel-Knabner, 2002). The relative abundance of these precursors offers valuable insights into both the plant source (angiosperms or gymnosperms) and the degree of lignin degradation, which can be used to infer the overall degradation state of organic matter (Thevenot et al., 2010).

Other compounds, present in smaller proportions within organic matter, include lipids, tannins, and structural biopolymers such as cutin and suberin. These compounds primarily serve protective functions in plants (Kögel-Knabner, 2002).

2.3.2. Dynamics of organic matter degradation

Historically, soil organic matter was primarily identified based on its darker coloration relative to the surrounding soil matrix. As research progressed, spectroscopic methods requiring the separation of the mineral and organic phases of soils were developed (Lehmann and Kleber, 2015). In 1786, an alkaline extraction protocol (pH 13) was established to isolate the organic fraction from soil. The substances extracted through this method were collectively termed "humic substances", which were widely accepted as representative of the organic matter content in soils. However, concerns arose regarding the existence of these humic substances outside the context of this extraction process, and inconsistencies within the scientific models prompted the development of a new approach to describe the degradation of soil organic matter (Lehmann and Kleber, 2015).

This new approach, known as the "Soil Continuum Model" (SCM), proposes that organic matter exists as a continuum of organic fragments, continually decomposed by microorganisms (Figure 1.7). As decomposition progresses, the proportion of polar and ionizable functional groups increases, enhancing the solubility of organic matter in soil solution. The interaction with soil mineral surfaces and incorporation into soil aggregates help protect the organic matter from further degradation (Kleber et al., 2021). These adsorption processes on mineral surfaces and the formation of aggregates are reversible.

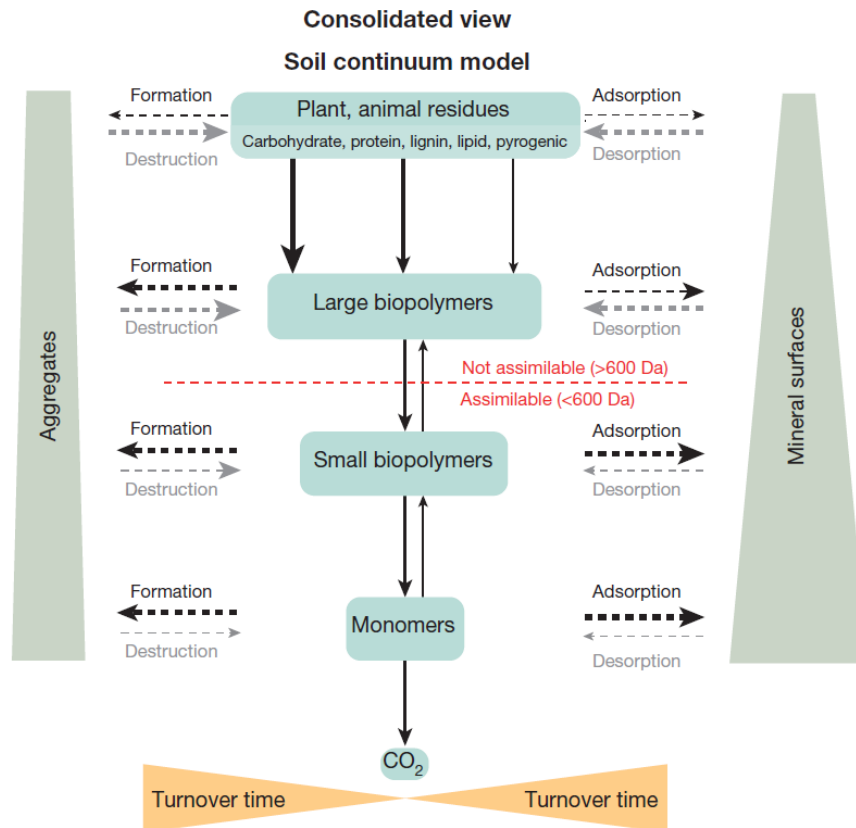


Figure I.7 - Reconciliation of current conceptual models for the fate of organic debris into a consolidated view of a SCM of organic matter cycles and ecosystem controls in soil (Lehmann and Kleber, 2015).

The SCM offers a significant advantage in providing a scientifically grounded explanation for the varying turnover rates of organic compounds in soils. It accounts for the presence of decomposer organisms and their respective enzymes, the energy resources required by these organisms, and the properties and abundance of mineral surfaces that can shield organic matter from degradation (Lehmann and Kleber, 2015).

Approximately 90% of soil organic matter is composed of high-molecular-weight compounds containing highly polymerized aromatic and aliphatic monomers. These molecules feature a diverse array of functional groups, including carboxyl, hydroxyl, ketone, ester, amine, nitroso, and thiol functions. Each of these chemical groups has a specific pH range in which they exist in an ionic form, enabling interaction with trace elements. The remaining 10%

of SOM consists of various organic compounds, such as carbohydrates, proteins, organic acids, amino acids, lipids, siderophores, and phenolics (Ondrasek et al., 2019).

2.3.3. Classification of organic matter

There is a wide range of exogenous organic matters used as soil amendments to enhance soil quality (e.g., cattle manure, green waste compost and crop residues). For instance, cattle manure is primarily composed of organic matter such as hay, straw, and animal excrement, and is rich in essential nutrients like nitrogen, potassium, and phosphorus (Reddy et al., 2000), which promote plant growth and improve soil fertility. Cattle manure also contributes to enhancing soil structure, retaining moisture, and fostering beneficial microbial activity (Li, 2021). Green waste compost consists of materials such as garden waste, dead leaves, grass clippings, branches, and plant debris. A cover crop is a plant or group of plants cultivated between main cropping cycles to prevent soil erosion, improve soil fertility, and provide additional agronomic benefits. Crop residues, in general, refer to plant fragments left in the field after the harvest and threshing of crops or after pasture grazing. Farmers frequently use these residues as a natural fertilizer to boost crop health, increase yields, and reduce reliance on chemical fertilizers (Kumar and Goh, 1999; Siavoshi et al., 2011).

Although these exogenous organic matters are used for similar purposes, they differ significantly in their chemical and biochemical composition. Consequently, classifying these exogenous organic matters is challenging due to their heterogeneous nature and variability in nutrient content, decomposition rates, and potential environmental impacts. A practical and effective classification system is based on parameters that directly influence their agronomic performance. As an illustration, Lashermes et al. (2010) proposed a classification system to predict the potential nitrogen availability of these materials. The classification is based on the organic nitrogen content of exogenous organic matter and the proportion of soluble, cellulose-, and lignin-like fractions.

2.3.4. Organic matter application affecting trace element mobility

In addition to enhancing soil quality at different levels, organic matter also influences the mobility of trace elements (Adriano, 2001). Indeed, organic compounds interact with trace elements through various mechanisms. For instance, several functional groups included in organic matter, such as carboxyl, carbonyl, and phenol groups (Kumar et al., 2013), can form complexes with trace elements (Huang et al., 2016). In addition, microorganisms and inorganic components present in composted materials can also play a role in trace element adsorption: e.g., Pb can be adsorbed by microorganisms generated during the composting process (Vargas-García et al., 2012), whereas Cd may be adsorbed nearly irreversibly onto the inorganic fraction (Hettiarachchi et al., 2003). Organic matter can also adsorb trace elements directly onto its surface or indirectly via mineral particles by altering soil physicochemical properties such as pH and redox potential.

Precipitation reactions may also occur when trace elements form stable complexes with organic acids (e.g., Cu) or phosphorus compounds (e.g., Pb) derived from added organic matter (Garcia-Mina, 2006; Katoh et al., 2013). These reactions are generally favored by an increase in pH. Redox reactions are also particularly important for trace elements that exhibit multiple oxidation states (e.g., As, Cr). These processes can occur through: (1) the involvement of active functional groups in redox reactions (e.g., quinones; Yuan et al., 2011); and (2) the oxidation of added organic matter (Hashimoto et al., 2011).

The application of exogenous organic matter (e.g., compost, manure) may typically reduce the bioavailability of trace elements to plants, potentially limiting their accumulation (Huang et al., 2016). However, the impact of these exogenous organic matters varies depending on the nature of the trace element. For example, cation-forming elements (e.g., Cd, Cu, Pb, Zn) are more likely to be immobilized by organic matter, in contrast to anions (e.g., As and Mo) that are more mobile and available after the addition of organic matter (Udovic and McBride, 2012). The type, composition, and stability of organic matter also influence the bioavailability of trace elements in the soil (Huang et al., 2016). Organic matter can hold trace elements in two main forms: (1) available, adsorbed onto organic molecules; or (2) unavailable, bound within

the chemical structure of the organic matter (He et al., 1992; Soumaré et al., 2002). Additionally, as organic matter decomposes or as soil conditions (e.g., pH) change over time, organic matter stability decreases, potentially releasing previously immobilized trace elements (Arif et al., 2016). Despite the chemical similarities between cattle manure, compost, and cover crop residues (Khater, 2015), these organic materials do not exert the same effects on the retention of trace elements in soils. For instance, Li et al. (2021) demonstrated opposite trends between compost application that led to a reduction in the trace element bioavailability, and manure application that increased this bioavailability. This difference can be attributed to the higher degree of decomposition in compost compared to manure, which results in a greater abundance of functional groups. These functional groups enhance the soil CEC, thereby improving the retention of trace elements.

Consequently, various antagonistic effects can be observed depending on the nature of trace elements, the different soil types, the bioavailability of trace elements in these soils, the plant species under consideration, and the diversity of added organic matter, among other factors. Therefore, it is crucial to take all these variables into account when studying the transfer of trace elements from soil to plant considering uncontaminated and contaminated agroecosystems.

2.4. Rare earth elements and stable isotopes as tracers for the soil-plant transfer

The low concentrations of trace elements in the environment pose a significant challenge for studying them within the soil-plant system compartments. To address these anticipated challenges, advanced geochemical tracing tools can be used to investigate soil-plant transfer processes and the effects of organic matter. In the following sections, the use of rare earth elements (REE) and stable isotopes of trace elements (specifically Cu, Zn, Fe, and Pb) as geochemical tracers will be discussed.

2.4.1. Rare earth elements

REE include 15 trace elements from the lanthanide family (Figure I.8), namely lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm; the only element that does not occur naturally making it an artificial element), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). Sometimes, scandium (Sc) and yttrium (Y) are considered in this group (Figure I.8; Connelly et al., 2005). In the periodic table, REE are classified in order of increasing mass from left to right and can be divided into light REE (LREE, from La to Eu) and heavy REE (HREE, from Gd to Lu). Sometimes used in the literature, medium REE (MREE, from Pr or Nd to Dy or Ho) can be considered as an intermediate class.

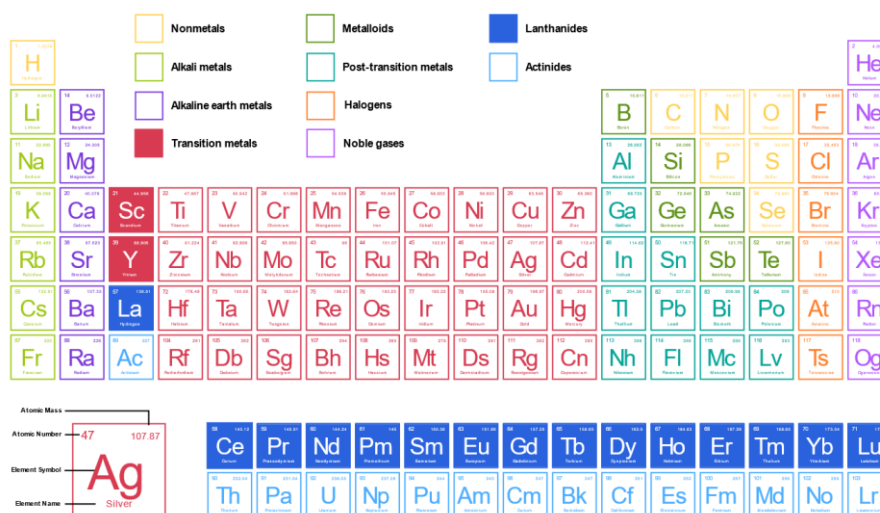


Figure I.8 – Distribution of rare earth elements in the periodic table.

Despite their name, REE are not “rare” or less abundant in the upper continental crust (UCC) than some other trace elements. For example, Ce, the most widespread REE (63 mg kg^{-1} ; Figure I.9), has a similar content to Zn (67 mg kg^{-1} ; Rudnick and Gao, 2014). Even the least abundant REE such as Tm and Lu, ranging from 0.3 to 0.5 mg kg^{-1} (Rudnick and Gao, 2014; Tyler, 2004), remain more concentrated than Cd and Se in the UCC (0.09 mg kg^{-1} ; Ramos et al., 2016; Rudnick and Gao, 2014). In general, LREE exhibit greater natural abundance compared to HREE (Ramos et al., 2016).

Like other elements on Earth, the natural distribution of REE is subject to the Oddo-Harkins rule, which means that REE with even atomic numbers (Ce, Nd, Sm, Gd, Dy, Er and Yb) are more abundant than their neighbors with odd atomic numbers (La, Pr, Eu, Tb, Ho, Tm and Lu). This “zigzag” distribution phenomenon (Figure I.9) is mainly explained by the greater stability of atomic nuclei with even numbers of protons and neutrons compared to those with odd numbers (Nikanorov, 2009; Ramos et al., 2016).

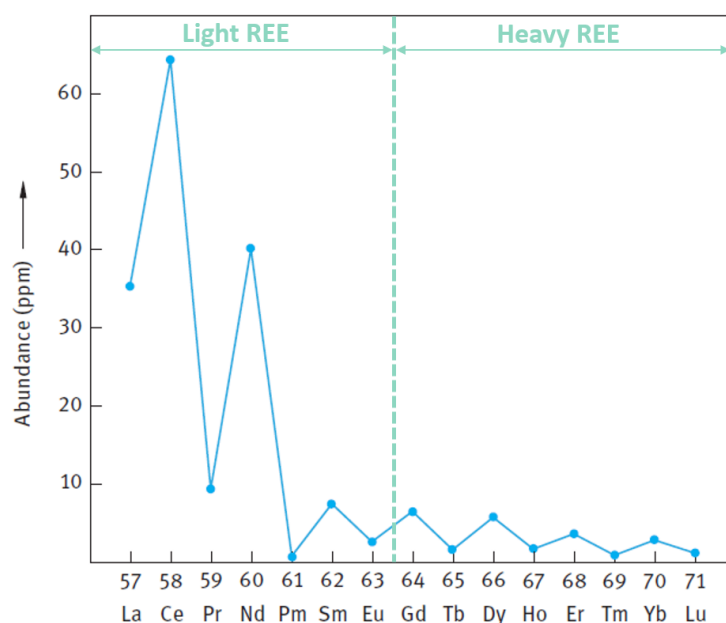


Figure I.9 - Abundance of rare earth elements (mg kg^{-1}) in the upper continental crust and visualization of the “zigzag” effect due to the Oddo-Harkins rule (adapted from Golloch, 2017).

REE are widely dispersed in over 270 minerals (Jordens et al., 2013; Ramos et al., 2016), from primary minerals formed during rock creation before any chemical alteration, to secondary minerals formed near the surface because of precipitation and alteration reactions (Aide and Aide, 2012; Balaram, 2019). Like certain metals, REE have an affinity for oxygen, and are thus found mainly in silicates (~43% of all REE minerals), carbonates (23%), oxides (14%), and phosphates (14%; Chakhmouradian and Wall, 2012). LREE tend to concentrate more in carbonates and phosphates, while HREE are found mainly in oxides and some phosphates (Dushyantha et al., 2020).

The distribution of REE in minerals is influenced by structural constraints, as well as by the relative availability of specific REE in the crystallization

environment. Consequently, different minerals, as well as samples of the same mineral from different rock types, can show significant variations in their REE distribution patterns (Chakhmouradian and Wall, 2012). In addition, some common minerals may show substitution of REE, such as fluorite (CaF_2) where Ce replaces Ca, or zircon (ZrSiO_4) where Y and HREE replace Zr (Aide and Aide, 2012).

Rare earth elements in soil

REE abundance in soil is primarily controlled by the parent material, although other factors such as soil texture, weathering history, pedogenic processes, and organic matter content can also play a role to a lesser extent (Kovaříková et al., 2019; Tyler, 2004). Then, REE concentrations in soils exhibit significant variability based on the origin of the parent material. For example, soils derived from igneous rocks, sandstones, and shales generally have higher REE contents (ranging from 174 to 219 mg kg^{-1}) compared to those derived from loess and limestone (ranging from 137 to 174 mg kg^{-1} ; Hu et al., 2006). REE contents in soils often represent the weighted mean of the REE contents of the constituent minerals and the relative abundances of REE-bearing minerals (Aide and Aide, 2012). As a result, the average REE concentrations found in topsoil in Belgium are comparable to those found in the upper continental crust (Table I-2).

Table I-2 – Average total rare earth element (REE) contents in the upper continental crust (UCC) and in the Belgian top soil (mg kg^{-1} ; Rudnick and Gao, 2014; Salminen et al., 2005).

REE	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
UCC	31	63	7.1	27	4.7	1	4	0.7	3.9	0.83	2.3	0.3	2	0.31
Belgian top soil	32	65	7.5	28	5.3	1	5	0.8	4.7	0.94	2.7	0.4	3	0.41

However, the natural REE cycle is being disrupted by anthropogenic activities over the past three decades (Brioschi et al., 2009). Indeed, the intensified extraction and utilization of REE have contributed to this disruption. Specifically, the mining and processing of REE ores, emissions from coal and oil/gas power plants, leaching of potentially toxic substances from landfills containing discarded technologies, and the application of REE-enriched fertilizers are adding significant amounts of REE to environment and then to soils (Hu et al., 2006; Thomas et al., 2014). For instance, snowfall atmospheric

deposition can contain up to 66 ng L^{-1} of total REE (Aubert et al., 2002) and hospital effluents may contain substantial quantities of Gd derived from magnetic resonance imaging procedures (Brioschi et al., 2013; Fedele et al., 2008). Additionally, the use of mineral P-fertilizers at a rate of $300 \text{ kg ha}^{-1} \text{ year}^{-1}$ can introduce up to 170 g ha^{-1} of additional REE into soils (data for China; Todorovsky et al., 1997).

The distribution and mobilities of REE in soils mainly depends on the pH value of the rhizosphere and the redox potential of the soil (Cao et al., 2001; Kovaříková et al., 2019) and can follow different possible pathways identified by Aide and Aide (2012); (1) plant uptake, (2) erosion, (3) leaching of REE-inorganic complexes by percolating water, (4) organic complexation, which can result in either mobilization or immobilization of REE, (5) leaching (eluviation-illuviation) of clay with co-adsorbed REE, (6) precipitation reactions that remove REE from percolating water, and (7) adsorption of REE by inorganic colloids such as phyllosilicates and oxyhydroxides (Figure I.10). All of these processes contribute to the fractionation of REE within the soil-plant system, making them potential tracers for pedogenetic processes (Laveuf and Cornu, 2009).

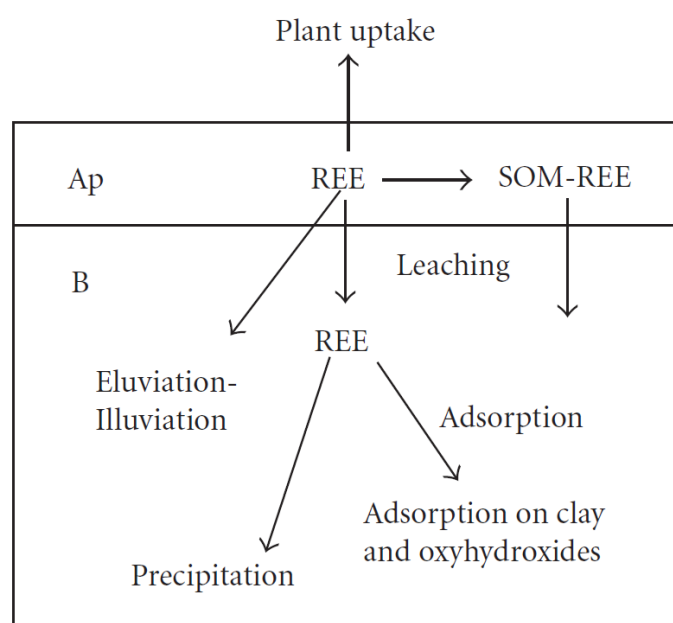


Figure I.10 - Conceptual diagram of potential REE migration and sequestration pathways in soil. Soil horizon Ap (disturbed horizon) and B (accumulation horizon; Aide and Aide, 2012).

Rare earth elements in plant

REE are found in all plants (with contents at least an order of magnitude lower than in soils; Brioschi et al., 2013) and commonly taken up through root absorption, although absorption through the leaf surface after spraying has been demonstrated (Sun et al., 1994). REE are absorbed and translocated in the same way as other trace elements (Kovářiková et al., 2019), i.e., filtered by the Casparian strip in roots and weakly transported to shoots, resulting in higher concentrations in roots than in shoots (10 to 100 times higher in roots; Brioschi et al., 2013).

REE contents in plants are variable. Tyler and Olsson (2005) reported that total REE contents in leaves can differ by up to one order of magnitude between species (up to five orders of magnitude for La in leaves of different species; Koyama et al., 1987). The abundance of REE in plants is influenced not only by intrinsic species-specific factors (Wyttenbach et al., 1998), but also by the soil REE content and speciation, soil pH and redox conditions, as well as the soil content of Fe-oxyhydroxides, and organic matter (Brioschi et al., 2013, 2009).

The impact of REE on plant health remains a topic of ongoing debate (Kabata-Pendias, 2011), but evidence suggests that REE are neither essential nor inherently toxic to plants (Tyler, 2004; Wyttenbach et al., 1998). Indeed, various studies have reported both positive and negative effects of REE application on plant growth (Diatloff et al., 2008; Tao et al., 2021). Nevertheless, Fedele et al. (2008) claim that the REE contents in European soils do not present a risk to human or environmental health at a continental scale.

Rare earth elements as geochemical tracers

Over the past few decades, REE have gained prominence across various Earth science disciplines, particularly in geochemistry where they are frequently employed as tracers for geological, pedogenetic, environmental, and biological processes, due to their unique and similar chemical and physical properties (Laveuf and Cornu, 2009; McLennan, 1989). Indeed, no other group of elements in the periodic table exhibits such similarity as the REE (Tyler, 2004) since they share comparable electronic configurations, including a large ionic radius, a trivalent oxidation state, and an electronegativity lower than that of transition metals (Henderson, 1984; Laveuf and Cornu, 2009).

The similar chemical and physical properties of REE contribute to their widespread occurrence as a group and their comparable behavior in the environment (Henderson, 1984; Hu et al., 2006; Laveuf and Cornu, 2009). Nevertheless, as the 4f orbitals are progressively filled from La to Lu, subtle differences appear. Specifically, there is a gradual decrease of the effective ionic radius (ranging from 103.1 pm for La^{3+} to 86.1 pm for Lu^{3+} , Figure I.11) and an increase in electronegativity (Laveuf and Cornu, 2009), leading to dissimilarities among the elements based on their atomic number and mass (Tyler, 2004). For instance, the smaller ions (HREE) display lower solubility compared to LREE and are more likely to form stable complexes with electronegative ligands (Cantrell and Byrne, 1987; Martinez et al., 2018; Monei et al., 2022; Tyler, 2004). As a result, LREE are preferentially transported from roots to shoots, resulting in a higher LREE/HREE ratio in the shoots (Tyler, 2004).

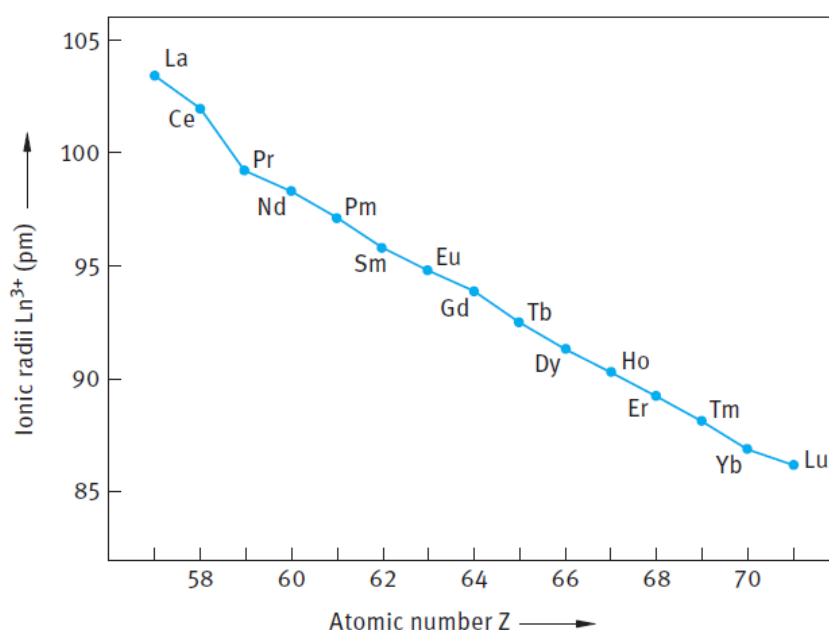


Figure I.11 – Reduction in ionic radius of rare earth elements with increasing atomic number (Gollock, 2017).

Due to these dissimilarities, specific individual elements or groups of elements can become either enriched or depleted relative to others when transferred from one compartment to another (e.g., soil, plant, or solution). This process is known as fractionation (Laveuf and Cornu, 2009).

In addition, under natural environmental conditions, Ce and Eu can present an extra oxidation state (Ce^{4+} and Eu^{2+} , respectively) in response to oxidizing and reducing conditions. These additional oxidation states can induce positive or negative peaks in REE distribution patterns following fractionation processes, referred to as positive or negative Ce and Eu anomalies. For instance, the reduction of Eu (Eu^{3+} to Eu^{2+}) under decreasing redox potentials, such as in the rhizosphere, enhances Eu mobility, resulting in a positive Eu anomaly in plant tissues (Brioschi et al., 2013; Krzciuk and Gałuszka, 2020). However, abnormal concentrations of specific REE can also produce anomalies. For example, anthropogenic Gd often results in a characteristic positive Gd anomaly in the REE distribution patterns of surface waters (Brioschi et al., 2013; Knappe et al., 2005).

Consequently, scientists analyze the REE distribution as a whole group and graphically represent them in order of increasing atomic number (from La to Lu, REE patterns; Figure I.12). However, due to the Oddo-Harkins rule, REE display markedly contrasted concentrations (Henderson, 1984). To get rid of this phenomenon and facilitate the interpretation of REE distributions, concentrations are commonly normalized to a reference standard (Henderson, 1984; McLennan, 1989). This reference is selected based on the system under investigation and usually consists of reference materials, such as Post-Archean Australian Shale (PAAS; McLennan, 1989), North American Shale Composite (NASC; Gromet et al., 1984), or Upper Continental Crust (UCC; Taylor and McLennan, 1985).

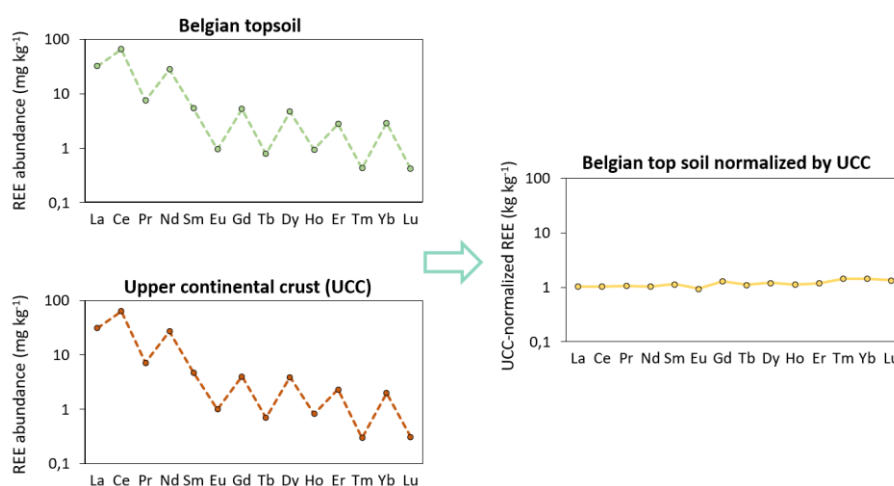


Figure I.12 - Example of rare earth element distribution patterns in Belgian topsoil normalized by the upper continental crust (UCC).

The use of normalized REE patterns enables the direct evaluation of relative enrichments or depletions of LREE or HREE, as well as Ce and Eu anomalies. In all instances, fractionations are determined using normalized concentrations (Laveuf and Cornu, 2009). The magnitude of Ce and Eu anomalies is quantified by comparing the normalized values of Ce and Eu to their expected values (Ce* and Eu*), which are determined by averaging the concentrations of the elements immediately preceding and following Ce and Eu in the periodic table. Anomalies are characterized as negative or positive based on whether the Ce/Ce* and Eu/Eu* ratios are below or above 1, respectively, illustrated by negative or positive peaks in the normalized patterns (Brioschi et al., 2013).

2.4.2. Cu, Zn, Fe, and Pb stable isotopes

Isotopes are atoms with nuclei that contain the same number of protons but differ in the number of neutrons. They are conventionally represented by the notation ${}^A_ZX$, where A represents the mass number (i.e., sum of protons and neutrons in the nucleus) and Z denotes the atomic number (i.e., number of protons) of the element X. Because of its redundancy, the atomic number is generally omitted when writing the different isotopes of the same element, leading to the notation ${}^AX$. These isotopes are generated through nuclear processes (nucleosynthesis), which have occurred in stars throughout the Universe history (Allègre, 2008), and can be categorized into stable and radioactive (unstable and decay over time) isotopes. Most elements in the periodic table possess two or more naturally occurring isotopes, whether stable or radioactive. However, 21 elements, including fluorine (F), sodium (Na), and arsenic (As), are monoisotopic, having only one stable isotope (Hoefs, 2021; Sharp, 2017).

Since the chemical and physical properties of atoms are primarily determined by their electronic configurations, isotopes of the same chemical element exhibit similar properties. However, the variation in mass resulting from different neutron numbers leads to subtle differences in their properties, known as “isotopic effects” (Sharp, 2017). This results in isotopic fractionation, which is the partitioning of isotopes between two substances or phases of the same substance, leading to different isotope ratios (Hoefs, 2021; White, 2023).

The primary processes responsible for isotope fractionation are: (1) mass-dependent effects, which include isotope exchange reactions (i.e., equilibrium isotope distribution) and kinetic processes (i.e., differences in reaction rates among isotopic molecules); and (2) mass-independent effects (Hoefs, 2021; White, 2023). The first mass-dependent effect concerns the distribution of isotopes at thermodynamic equilibrium, which is precisely dictated by the relative mass differences between the isotopes of an element. Indeed, due to the presence of multiple isotopes for elements, chemical compounds, including molecules and crystals, exhibit a variety of isotopic forms. For example, the water molecule (H_2O) exists in several isotopic variants, such as H_2^{18}O , H_2^{17}O , H_2^{16}O , D_2^{18}O , and D_2^{17}O , among others, each in different proportions (with H_2^{16}O constituting approximately 97%, H_2^{18}O around 2.2%, and H_2^{17}O about 0.5%). Consequently, when the H_2O molecule participates in a chemical process, all of its isotopic forms are involved. Therefore, it is essential to consider not only the equilibrium equations for H_2O , but also those for all its isotopic variants (Allègre, 2008; Hoefs, 2021). Moreover, mass-dependent relationships also apply to many kinetic processes. Indeed, during transfer phenomena, isotopes of different masses will move at different speeds, with lighter isotopes traveling faster. This variation in velocity can lead to isotopic fractionation. Indeed, lighter and thus faster molecules will react more rapidly, primarily because faster molecules experience more frequent collisions, and heavier molecules are generally more stable and dissociate less frequently during collisions (lower chemical reactivity). As a result, there is an observable variation in isotopic composition between the reactants and the products of a chemical reaction (Allègre, 2008; Hoefs, 2021). Additionally, specific physicochemical properties, such as density, melting point, and vapor pressure, along with parameters during reaction processes, such as temperature, can significantly influence fractionation processes (Allègre, 2008; Hoefs, 2021). Finally, certain natural processes exhibit fractionation patterns that are not mass-dependent. The mechanisms underlying these mass-independent fractionations remain unclear and will not be mentioned in this document (Hoefs, 2021).

Such fractionation is typically very small, often on the order of a few tenths or hundredths of one percent. These small differences, detectable through the high precision of modern measurement techniques, are the focus of this discipline and are utilized as tracers for geological and environmental processes (Allègre, 2008; Sharp, 2017).

The delta value (δ)

In isotope geochemistry, it is standard practice to express the isotopic composition² of a chemical element as a ratio (Allègre, 2008). Since variations in isotope abundance are dependent on relative mass differences, each sample with a homogeneous isotopic composition is characterized by a unique isotopic ratio value. Typically, the ratio (R) is measured between the two most abundant isotopes, with the heavier isotope compared to the lighter one (Nielsen, 1979). McKinney et al. (1950) introduced the delta (δ) notation to express the relative difference of isotopic ratios of an element in a single sample compared to a standard reference:

$$\delta = \left(\frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \right) \times 1000$$

Delta values are expressed in per mil (‰). A positive δ value indicates that the ratio of heavy to light isotopes in the sample is greater than that in the standard, while a negative δ value signifies the opposite. For instance, a sample with a $\delta^{66}\text{Zn}$ value of +2.3‰ exhibits a $^{66}\text{Zn}/^{64}\text{Zn}$ ratio that is 2.3 per mil higher than that of the standard.

To compare isotope data across different laboratories, an internationally accepted set of standards is essential. An ideal standard, used globally as the "zero-point" on a δ value scale, should exhibit homogeneity in composition, be available in sufficient quantities, be manageable for chemical preparation and isotopic measurement, and possess an isotope ratio close to the midpoint of the natural range of variation (Hoefs, 2021). For metal isotopes, standards are typically provided by two main institutions: the Institute for Reference Materials and Measurements (IRMM) in Belgium and the National Institute of Standards and Technology (NIST) in the United States. Both IRMM and NIST primarily offer standard materials in the form of purified metals or salts that are readily soluble (Hoefs, 2021; White, 2023).

² Terminology: Sharp (2017) claimed that 'isotope' should be used with a modifier and 'isotopic' should be used alone. Thus, write "the oxygen isotope composition of..." where 'oxygen' modifies 'isotope,' and "the isotopic composition of..." where 'isotopic' stands alone.

Moreover, it is standard practice to report the difference or change in isotopic composition between two samples (Sharp, 2017). This difference is denoted by the "big delta" symbol (Δ) and can be expressed as:

$$\Delta_{A-B} = \delta_A - \delta_B$$

- Δ_{A-B} is the difference in isotopic values between sample A and sample B (‰).
- δ_A is the delta value of sample A.
- δ_B is the delta value of sample B.

Stable isotope geochemistry has traditionally focused on variations in the isotopic ratios of elements such as C, H, O, N, and S that are integral to living organisms. However, there has been a significant rise in the use of non-traditional stable metal isotopes, including Cu, Fe, Mo, Se, Sr and Zn. For instance, these trace elements absorbed from the soil by plants undergo various transport processes, which can induce isotope fractionation, with the extent of fractionation potentially varying in response to the plant physiological status, developmental stage, nutritional condition, and the environmental conditions under which the plant grows (Wiggenhauser et al., 2022). Furthermore, it has been demonstrated that the adsorption, complexation, or chelation of elements such as Zn on/with organic molecules (directly involved in the transport processes or not) within the soil-plant system can influence the speciation, mobility, and bioavailability of these elements, ultimately leading to isotopic fractionation (Jouvin et al., 2009; Wiggenhauser et al., 2022).

Therefore, this document will specifically focus on the fractionation of Cu, Zn, Fe, and Pb isotopes within the soil-plant system, where isotope fractionation usually exhibits mass-dependent behavior (Wiggenhauser et al., 2022). The selection of Cu, Zn, Fe, and Pb isotopes for this study is grounded in their technical suitability for purification and their relevance to understanding biogeochemical and environmental processes. The isotopes of Cu, Zn, and Fe were prioritized due to their essential roles as micronutrients for plants, enabling detailed investigation into nutrient acquisition and transport mechanisms. Specifically, Cu isotopes have proven valuable in studying the transfer processes between soil and plant tissues, shedding light on nutrient uptake pathways. Iron isotopes, pivotal for exploring plant strategies to acquire this often insoluble yet vital element, enhance our understanding of its bioavailability in soils. Zinc isotopes, along with Pb, serve as tracers for identifying atmospheric and natural sources, with Pb, a non-essential

element, acting as a counterpoint to the biologically active Cu, Zn, and Fe. Collectively, these isotopes provide a robust framework for assessing nutrient cycling and environmental contamination dynamics.

Copper stable isotopes

Copper is a transition metal element occurring naturally in oxidation states (+I) and (+II) and has two stable isotopes: ^{63}Cu (69.1% in abundance) and ^{65}Cu (30.9%; Hoefs, 2021; Maréchal et al., 1999).

Copper is an essential micronutrient for plant growth and development. Consequently, Cu isotopes can be used to investigate isotopic fractionation occurring between soil and plant, as well as among different plant parts, thus enhancing our understanding of Cu uptake mechanisms in plants (Figure I.13).

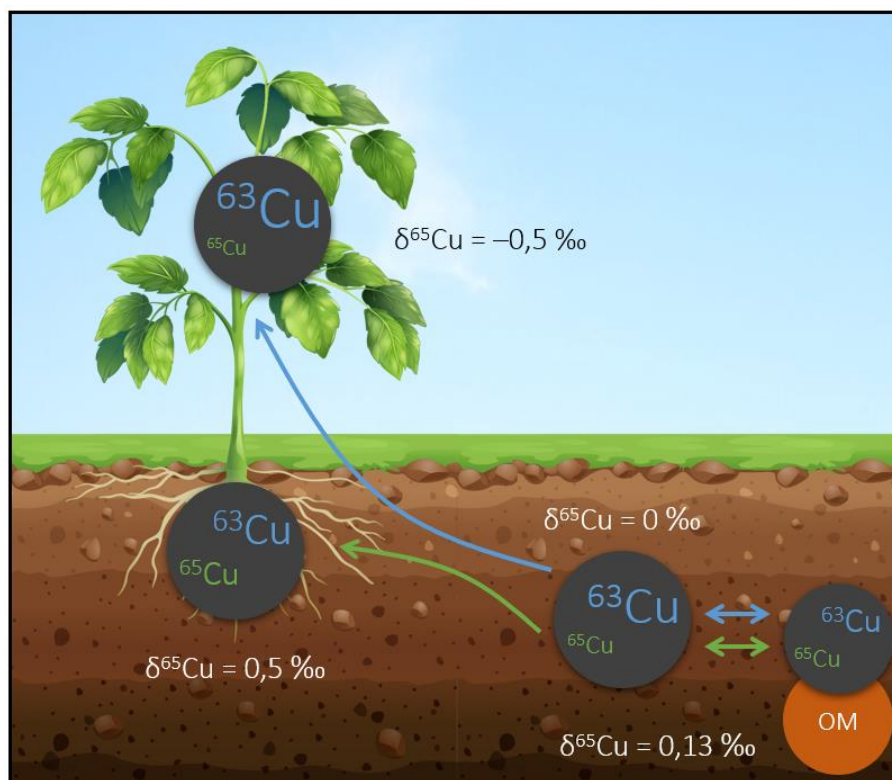


Figure I.13 - Schematic representation of Cu isotope fractionation within the soil-plant system (fictional data).

Numerous studies have demonstrated isotopic fractionation during Cu uptake in various plant species (Hoefs, 2021; Wiggnerhauser et al., 2022). Some authors posited that plants exhibit a preference for absorbing lighter Cu

isotopes from the soil (Ryan et al., 2013; Weinstein et al., 2011). According to the data collection by Zheng et al. (2024) from several studies, $\delta^{65}\text{Cu}$ values in plant-soil systems ranged from -2.59‰ to $+1.73\text{‰}$, while $\Delta^{65}\text{Cu}$ values between plants and soil ($\Delta^{65}\text{Cu}_{\text{plant-soil}}$) varied from -1.00‰ to -0.11‰ , reflecting different Cu uptake strategies. Additionally, Wiggerhauser et al. (2022) reported that Cu isotope fractionation between soil and plants, as well as between roots and shoots ($\Delta^{65}\text{Cu}_{\text{shoot-root}}$), could be positive, negative, or neutral.

Furthermore, it has been shown that Cu isotopes can also bind to organic matter and thus undergo fractionation. Indeed, aqueous Cu-organic complexes formed during the decomposition of organic matter can facilitate the mobilization of heavier Cu isotopes within the soil (Křibek et al., 2020; Mihaljevič et al., 2018; Weinstein et al., 2011; Zheng et al., 2024).

Zinc stable isotopes

Zinc is a transition metal element that naturally occurs in a stable oxidation state (+II) and has five stable isotopes: ^{64}Zn (48.6% in abundance), ^{66}Zn (27.9%), ^{67}Zn (4.1%), ^{68}Zn (18.8%), and ^{70}Zn (0.6%; Record, 2011).

Zinc is an essential element for most living organisms, playing a critical role in various biochemical processes. Like Cu, multiple studies have highlighted the fractionation of Zn isotopes during its uptake and transport to roots, translocation from roots to shoots, and subsequent remobilization (Caldelas and Weiss, 2017; Moynier et al., 2009; Smolders et al., 2013; Viers et al., 2007). Indeed, Bigalke et al. (2010) highlighted that plants preferentially uptake light Zn isotopes. Moreover, Moynier et al. (2009) observed an enrichment in light Zn isotopes in the leaves compared to other plant parts, Weiss et al. (2004) measured a depletion of heavy Zn isotopes from roots to shoots, with values ranging from -0.13 to -0.26‰ , and Houben et al. (2014) claimed that heavier Zn isotopes were preferentially retained in the roots compare to shoots ($\Delta^{66}\text{Zn}_{\text{root-shoot}} = +0.24$ to $+0.40\text{‰}$). However, Viers et al. (2007) reported the opposite trend, showing that plant roots and shoots were enriched in heavy Zn isotopes ($\delta^{66}\text{Zn}$ of $+0.42$ to $+0.76\text{‰}$) relative to the litter layer (0.12 to 0.25‰) and the most superficial soils.

The mechanisms underlying Zn isotope fractionation remain poorly understood, but they are likely influenced by surface adsorption, solution speciation, and membrane-regulated uptake processes (Hoefs, 2021). For instance, the sorption of Zn onto Fe/Mn-oxyhydroxides results in an

enrichment of heavy Zn isotopes within the solid phase (Bryan et al., 2015; Juillot et al., 2008). Additionally, the sorption of Zn onto organic matter can lead to variable Zn isotope fractionation, depending on the specific type of organic matter involved (Jouvin et al., 2009; Opfergelt et al., 2017).

Anthropogenic activities have led to significant Zn contamination in various environmental systems (Hoefs, 2021). Indeed, significant inputs of Zn into soils can occur, for example, through atmospheric deposition resulting from industrial emissions or the accumulation of pyrometallurgical waste (Houben et al., 2014). Several authors have demonstrated that Zn isotopes can be utilized to identify atmospheric sources, including those originating from mining and smelting operations (Sivry et al., 2008; Weiss et al., 2007). For example, Bigalke et al. (2010) detected lighter Zn isotopes in soils heavily polluted by emissions from a nearby smelter. Consequently, the potential of Zn isotopes as tracers for Zn contamination has been widely supported by several studies (Cloquet et al., 2008; Mattielli et al., 2009; Sonke et al., 2002).

Iron stable isotopes

Iron is a transition metal element that naturally occurs in both (+II) and (+III) oxidation states, enabling it to participate in a broad spectrum of redox reactions. It is the third most abundant element on Earth and possesses four stable isotopes: ^{54}Fe (5.8% in abundance), ^{56}Fe (91.8%), ^{57}Fe (2.1%), and ^{58}Fe (0.3%; Hoefs, 2021).

Iron is indispensable for all living organisms. However, Fe is a limiting nutrient due to its predominant form in soils, Fe(III), which is nearly insoluble. To overcome this limitation, higher plants have evolved distinct strategies to enhance Fe availability, some of which lead to the fractionation of Fe isotopes, while others do not. As summarized by Hoefs (2021) and Wiggerhauser et al. (2022), based on the work of Guelke and von Blanckenburg (2007), the Fe isotope signatures in plants reflect these different Fe acquisition strategies. Strategy I plants (e.g., tomato, bean) induce chemical reactions in the rhizosphere that reduce Fe(III) to Fe(II) prior to uptake, incorporating lighter isotopes into their roots, with further depletion occurring during transport to leaves and seeds. In contrast, strategy II plants (e.g., oat, maize) release phytosiderophores³ that mobilize Fe(III) and transport Fe(III)-complexes

³ Phytosiderophores are low-molecular-weight organic compounds secreted by the roots of certain plants, primarily grasses such as maize, barley, and wheat. These

directly into their roots via a specialized membrane transport system, which does not cause isotopic fractionation relative to the soil Fe abundance. Guelke and von Blanckenburg (2007) reported that the $\Delta^{56}\text{Fe}_{\text{plant-soil}}$ value in strategy I was 1.8‰ lighter compared to that in strategy II. The presence or absence of a Fe reduction step is likely a key factor contributing to the distinct Fe isotope fractionation observed in strategy I and II plants during Fe acquisition. However, several studies suggest that the distinct $\Delta^{56}\text{Fe}_{\text{plant-source}}$ values for strategy I and II plants are not universally applicable (Kiczka et al., 2010; Wiggerhauser et al., 2022). Indeed, additional processes beyond root surface reduction and chelation by phytosiderophores may influence Fe fractionation during plant acquisition. For instance, Fe precipitation as Fe(III) oxides in the root apoplast can induce significant isotope fractionation between pore water and root plaque⁴ ($\Delta^{56}\text{Fe}_{\text{root plaque-pore water}}$ ranging from +1.41 to +2.24‰; Chen et al., 2021; Garnier et al., 2017). It is important to note that the utilization of strategy I mechanisms under Fe-sufficient conditions can impact the fractionation of other elements, such as Cu (Ryan et al., 2013; Wiggerhauser et al., 2022).

Iron isotope fractionation between roots and shoots ($\Delta^{56}\text{Fe}_{\text{shoot-root}}$) exhibits considerable variability, ranging from -0.60 to +2.02‰ (Wiggerhauser et al., 2022), and indicating no clear preference for the transport of either light or heavy Fe isotopes from root to shoot. Additionally, Fe isotopes display significant fractionation among different aerial parts (Chen et al., 2021; Guelke and von Blanckenburg, 2007), which appears to be influenced by the plant's strategy for Fe acquisition. Moreover, since Fe remobilization involves the reduction of Fe(III) to Fe(II) for transport, Fe isotopes may undergo fractionation during this process as Fe is redistributed from older to newer plant tissues. Consequently, this remobilization could modify the Fe isotope composition of leaves throughout the growing season (Kiczka et al., 2010; Wiggerhauser et al., 2022).

Lead stable isotopes

Lead is a post-transition metal element that has four stable isotopes: ^{208}Pb (52.4% in abundance), ^{207}Pb (22.1%), ^{206}Pb (24.1%), and ^{204}Pb (1.4%; Komárek

compounds play a crucial role in iron acquisition by chelating iron from the soil, where it is typically poorly soluble and thus difficult for plants to absorb.

⁴ Root plaque refers to a layer of iron oxide and other minerals that form on the surface of plant roots.

et al., 2008). ^{204}Pb is the only non-radiogenic isotope since it is not derived from the radioactive decay of any other element. Consequently, its abundance has remained constant since the Earth's formation. In contrast, the isotopes ^{208}Pb , ^{207}Pb ; and ^{206}Pb are radiogenic, originating from the decay of their respective parent isotopes ^{232}Th , ^{235}U , and ^{238}U . In environmental sciences, Pb isotopic compositions are commonly expressed as the ratios $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$. These ratios are normalized with the non-radiogenic ^{204}Pb isotope, whose abundance, though low, is stable over time. However, ratios such as $^{206}\text{Pb}/^{207}\text{Pb}$, $^{208}\text{Pb}/^{206}\text{Pb}$ are also used, with the first one being particularly favored due to its precise analytical determination and the relatively high abundances of these two isotopes (Komárek et al., 2008; Record, 2011).

Lead in the environment primarily originates from two principal sources: (1) natural erosion of local or distant rocks, transported by wind, which exhibit a broad range of isotopic signatures due to the diverse isotopic compositions of various geological sources; and (2) anthropogenic contamination resulting from industrial activities, which typically constitutes the majority of environmental Pb. The primary Pb anthropogenic sources include leaded gasoline, coal combustion, metallurgical activities, and waste incineration. Each of these sources has a distinct Pb isotopic composition (Table I-3; Komárek et al., 2008; Record, 2011).

Table I-3 - Examples of Pb isotopic compositions ($^{206}\text{Pb}/^{207}\text{Pb}$) from different anthropogenic sources in Europe (Komárek et al., 2008).

Anthropogenic sources	$^{206}\text{Pb}/^{207}\text{Pb}$ range	Location	References
Leaded gasoline	1.069 - 1.094	France	Monna et al. (1997)
Coal combustion	1.170 - 1.180	Belgium	Walraven et al. (1997)
Filter from Pb smelter	1.127 - 1.131	France	Cloquet et al. (2006)
Incinerator ash	1.154 - 1.156	Switzerland	Chiaradia and Cupelin (2000)

In contrast to the isotopes of Cu, Zn, and Fe, the isotopic composition of Pb is minimally influenced by physico-chemical fractionation processes. Consequently, Pb released into the atmosphere through activities, such as incineration and combustion, maintains the isotopic signature of its original ore. This characteristic makes Pb isotopes a highly effective tool for tracing the sources and pathways of Pb pollution. Although Pb is not subject to fractionation processes, it is important to recognize that distinct geochemical reservoirs are interconnected, then, the final isotopic composition of Pb arises from the amalgamation of various sources. (Komárek et al., 2008; Record, 2011).

Lead is one of the most prevalent toxic elements found in soil, where it serves no known biological function (Kushwaha et al., 2018). As the Pb isotopic composition in uncontaminated soils primarily results from the weathering of bedrock, it tends to be more radiogenic (typically $^{206}\text{Pb}/^{204}\text{Pb}$ between 18.5 and 19.5; Cheema et al., 2020). However, anthropogenic Pb contamination in soils, primarily through dry and wet deposition, poses a substantial environmental threat, particularly in industrial areas. Elevated levels of Pb in soils can severely disrupt plant growth and metabolism. Additionally, Pb can accumulate in various plant tissues, thereby entering the food chain and adversely affecting multiple organs in the human body (Cheema et al., 2020; Kushwaha et al., 2018).

Due to its high affinity for organic and colloidal materials, Pb in soil is generally considered to be predominantly insoluble, resulting in limited availability for plant uptake. However, Pb from anthropogenic sources tends to accumulate mainly in the surface layer of soil, potentially increasing its bioavailability (Kushwaha et al., 2018). It has been demonstrated through sequential extraction that anthropogenic Pb is typically concentrated in the exchangeable/carbonate-bound and reducible (Fe-oxyhydroxide) fractions, indicating that natural Pb is primarily associated with the residual fraction (Emmanuel and Erel, 2002; Teutsch et al., 2001). The Pb isotopic signature in soil is therefore influenced by both natural and anthropogenic sources. In Europe, the $^{206}\text{Pb}/^{207}\text{Pb}$ ratios vary between 1.116 and 1.727 in agricultural soils, with a median value of 1.202 (Figure I.14; Reimann et al., 2012).

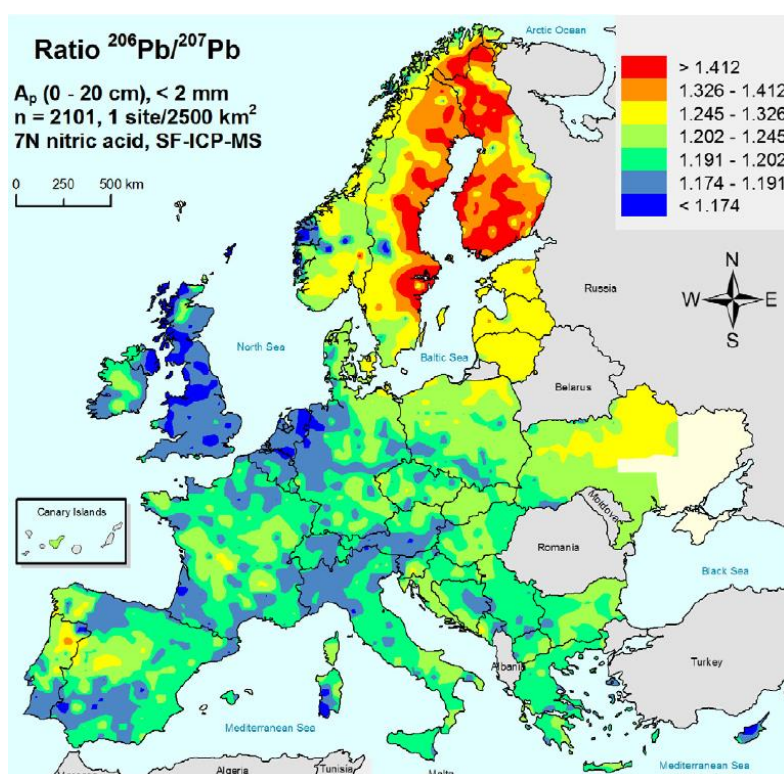


Figure I.14 – Map of the $^{206}\text{Pb}/^{207}\text{Pb}$ ratio in European agricultural soils (Reimann et al., 2012).

To address the knowledge gap regarding the transfer of trace elements from soil to plants, it is crucial to consider the role of exogenous organic matter in modulating these transfer processes. While previous studies have emphasized the influence of organic matter on the mobility of specific elements, particularly in contaminated environments, the underlying mechanisms remain inadequately understood, especially within contamination-free agroecosystems. Furthermore, the application of geochemical tracers, such as rare earth elements and stable metal isotopes, combined with more detailed characterizations of organic matter, presents a promising approach for gaining valuable insights into element dynamics, as well as their interaction with organic matter inputs in both contaminated and uncontaminated agroecosystems.

3. Research objectives and thesis outline

The main research objective was therefore to assess the influence of exogenous organic matter application on the transfer of trace elements in the soil-water-plant continuum in uncontaminated and contaminated agroecosystems.

For this purpose, the transfer of trace elements in the soil-plant system has been studied through both experiences conducted under controlled conditions (greenhouses) and under real conditions (in situ; fields) considering four contrasted study sites in Wallonia, Belgium, including different environmental contexts and trace element contents. Three exogenous organic matters (cattle manure, green waste compost, and cover crop restitution) were considered in these experiments. To better understand the geochemical processes involved, we relied on two powerful, innovative geochemical tracing tools (rare earth elements and stable isotopes of Cu, Zn, Fe, and Pb) and organic matter characterization. The main objective can be divided into four sub-objectives (sub-research questions) which correspond to the four data chapters presented in this document (Figure I.15):

- I. To what extent does studying the transfer of rare earth elements within the soil-plant system reflect the environmental conditions that govern the transfer of trace elements? We assessed rare earth elements in soil-plant system to identify the biogeochemical processes governing their transfer in agroecosystems through tracing: (1) the transfer from soil to plant and within the various plant parts; and (2) the environmental conditions (such as redox conditions through Ce and Eu).
- II. Which of the plant-available trace element compartments is most relevant for accurately representing the transfer of trace elements between soil and plants, particularly in soils with varying trace element levels deriving from diverse environmental contexts? To better characterize the soil-plant transfer of trace element, we assessed the relevance of several plant-available trace element compartments (soil solution, soil water-extracts, and three-step sequential extraction) based on concentrations and geochemical tracers (rare earth elements).

- III. How does the application of three types of exogenous organic matter and their related chemical composition influence the transfer of trace elements from soil to plant under controlled greenhouse experiment and in the field? In addition to studying trace element concentrations within the soil-plant system following exogenous organic matter application, we characterized organic inputs using nuclear magnetic resonance spectroscopy (NMR), pyrolysis–gas chromatography–mass spectrometry (Py-GC-MS), and Rock-Eval pyrolysis.
- IV. What is the behavior of four elements (Cu, Zn, Fe, and Pb) within the soil-plant continuum after application of exogenous organic matter using isotope analyses? We conducted precise chemical monitoring within the different compartments of the soil-water-plant continuum after exogenous organic matter application utilizing non-conventional stable isotope signatures of Cu, Zn Fe, and Pb.

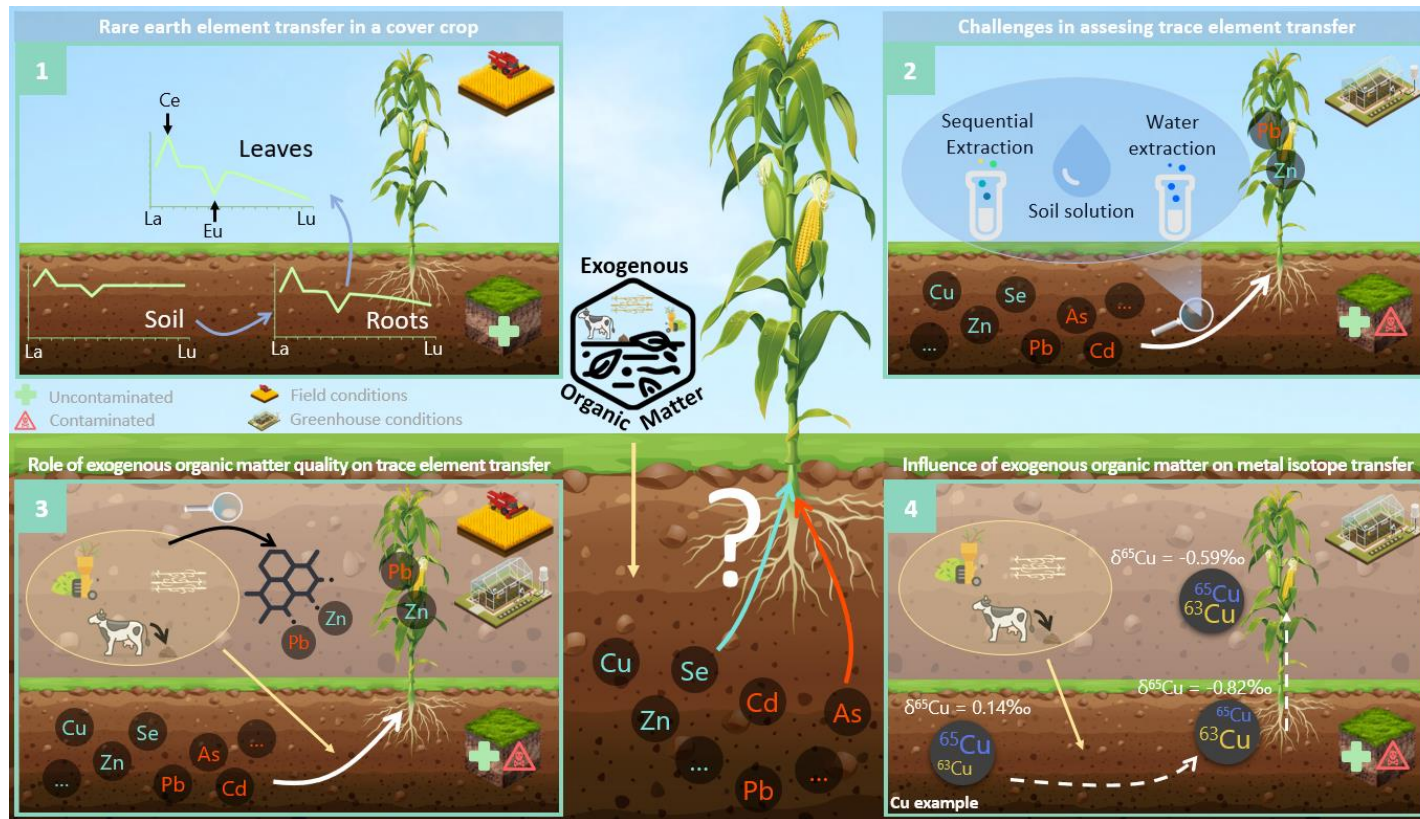


Figure I.15 - Conceptual diagram of the four research sub-objectives.

II. Materials and methods

The experiments conducted as part of this thesis are divided into two distinct categories: (1) a greenhouse experiment under controlled conditions; and (2) two field experiments conducted in situ under real conditions. In this section several aspects of the experimental approach will be detailed, from the description of the study areas to the implementation of the experiments. The sample collection process, the subsequent sample treatment, and the multiple physico-chemical analyses carried out will also be explained in detail.

1. Study areas

To meet the thesis's objectives, we studied the transfer of trace elements in both uncontaminated and contaminated agroecosystems in Wallonia, Belgium. Indeed, Wallonia has a range of agroecosystems with contrasting environmental contexts (Goidts and van Wesemael, 2007) and contamination levels and origins (Liénard and Colinet, 2016). Therefore, four contrasted study sites, including different environmental contexts and trace element concentrations, were selected (Figure II.1A): Vieusart (province of Walloon Brabant) as the uncontaminated site, Sainte-Walburge and Bressoux (city of Liège, province of Liège) as two anthropogenically contaminated sites including an increasing gradient of trace element concentrations, and Aubange (Belgian Lorraine, province of Luxembourg) as a naturally-enriched site (i.e., lithogenic enrichment of trace elements).

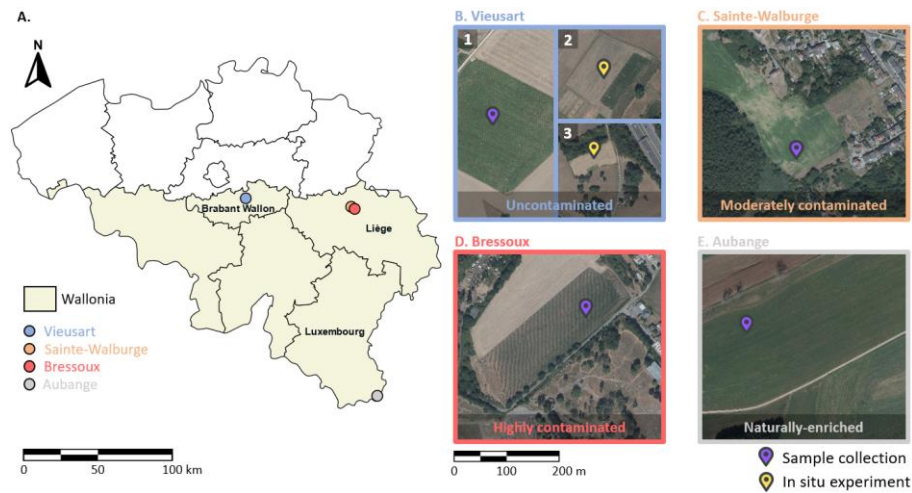


Figure II.1 – Location of the four study areas. The points of interest represent the agricultural plots for samples collection in the greenhouse experiment (purple) and for the in-situ experiments (yellow).

Vieusart is located in the sandy-loam region, where 47.5% of professional farms are dedicated to arable farming, predominantly cereal and fodder crops. Sainte-Walburge and Bressoux are situated in the grassland region, where only 9.1% of professional farms focus on arable farming (dairy farming being the predominant activity). Lastly, Aubange is located in the Jurassic region, where 47.5% of professional farms are dedicated to arable farming, with cereals remaining the primary marketable crop (Service public de Wallonie, 2023).

As part of the experiment in greenhouses, soil material was collected on January 2021, on one agricultural plot from each selected site (Figure II.1B-E, purple symbols). These soil materials have been characterized for several physical and chemical parameters (Table II-1), with protocols described in section 5. The last crops grown before sample collection (i.e. in 2020) were spelt (*Triticum spelta*) in Vieusart, potatoes (*Solanum tuberosum*) in Sainte-Walburge and maize (*Zea mays*) in Bressoux and Aubange (Service public de Wallonie, 2020). In addition, in the site of Vieusart, two supplementary uncontaminated agricultural plots (Figure II.1B, yellow symbols) were selected for two distinct in-situ experiments.

Table II-1 - Averages and standard deviations (in brackets, n=2) of soil physical and chemical parameters.

Physico-chemical parameter	Vieusart	Sainte-Walburge	Bressoux	Aubange
pH _{H₂O}	6.5 (0.0)	7.8 (0.0)	7.0 (0.0)	7.3 (0.0)
pH _{KCl}	5.8 (0.0)	6.8 (0.0)	6.1 (0.0)	6.2 (0.0)
Total C (%)	1.25 (0.05)	11.1 (0.10)	15.8 (0.40)	2.43 (0.49)
Total N (%)	0.13 (0.01)	0.35 (0.01)	0.52 (0.01)	0.23 (0.01)
CEC (cmol _c kg ⁻¹)	11.1 (0.4)	15.2 (0.7)	26.9 (3.8)	20.8 (1.2)
Clay (%)	19 (0)	22 (1)	18 (0)	24 (0)
Silt (%)	47 (1)	50 (1)	34 (0)	25 (0)
Sand (%)	34 (1)	29 (1)	48 (0)	51 (0)

1.1. Vieusart: uncontaminated site

The site of Vieusart is a typical loamy agricultural soil from the northern Wallonia, classified as a Luvisol according to the World Reference Base for Soil Resources (WRB; Mantel et al., 2023; Service public de Wallonie, 2005) and located on a sandy formation more or less clayey (Sint-Huibrechts-Hern formation) surmounted by a thick aeolian loess deposit (Brabant silt plateau; Herbosch and Blockmans, 2005). It is characterized by a temperate oceanic climate with an average annual air temperature of 10.5 °C and average annual precipitation of 790 mm (IRM, 2020a). Since it is representative of uncontaminated agricultural soils mainly found in Wallonia, we used this area as the uncontaminated soil reference.

Three agricultural plots located at the experimental farm of the UCLouvain (FERM platform, Corroy-le-Grand, Belgium) were selected for three different experiments: (1) the first plot (50°40'47" N, 4°38'8" E) to collect soil material for the greenhouse experiment (Figure II.1B, plot 1); (2) the second plot (50°40'11" N, 4°38'11" E) for a field experiment to evaluate the use of rare earth elements as a soil-plant geochemical tracers (Figure II.1B, plot 2); and

(3) the third plot (50°40'15" N, 4°37'54" E) for a field experiment to evaluate the influence of soil organic matter on trace element transfer over two consecutive years (Figure II.1B, plot 3).

1.2. Sainte-Walburge and Bressoux: anthropogenically contaminated sites

Situated close to the city of Liège, the site of Sainte-Walburge (50°39'52" N, 5°35'20" E) is a loamy agricultural soil classified as a Luvisol/Cambisol (Mantel et al., 2023; Service public de Wallonie, 2005) and located on a clayey chalk formation (Gulpen Formation) surmounted by a red clay with flints (Barchy and Marion, 2000). Not far from the first site, the site of Bressoux (50°38'15" N, 5°36'39" E), whose soil type is not mapped but classified as a Luvisol (Mantel et al., 2023; Service public de Wallonie, 2005), is located on alluvial deposits (Ancient Alluvium) containing sandy silt, sand, and clay (Barchy and Marion, 2000). Both sites are characterized by a temperate oceanic climate with an average annual air temperature of 11.2 °C and average annual precipitation of 850 mm (IRM, 2020b). These sites are considered as two anthropogenically contaminated sites with an increasing gradient of trace element concentration from Sainte-Walburge to Bressoux, resulting from metal, textile, and coal industries since the 18th century and a marked presence of industrial artifacts, such as coal, clinker, slag, and construction debris in soils.

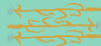
1.3. Aubange: naturally-enriched site

Finally, the site of Aubange (49°34'34" N, 5°46'5" E) is a loamy-stony agricultural soil classified as a Cambisol (Mantel et al., 2023; Service public de Wallonie, 2005) and located on the Aubange Formation composed of a complex of sandstone, ferruginous and non-ferruginous calcareous sandstone, siltstone, and mudstone (Belanger et al., 2002). It is characterized by a temperate oceanic climate with an average annual air temperature of 9.4 °C and average annual precipitation of 1090 mm (IRM, 2020c). This site was selected because of its lithogenic enrichment in trace elements, such as As, Cr, Mn, Ni and Zn.

2. Description and collection of exogenous organic matters

To carry out the experiments, three distinct exogenous organic matters were considered, i.e., cattle manure, green waste compost, and cover crop restitution (considered as exogenous even though it is usually already present on the plot). These organic materials were freshly collected a few days before application and have been characterized once for several chemical parameters, as part of the experiment in greenhouses (Table II-2).

Table II-2 - Averages and standard deviations (in brackets, n=2) of exogenous organic matter chemical parameters (greenhouse experiment).

Chemical Parameter	Cattle manure 	Green waste compost 	Cover crop restitution 
Total C (%)	37.7 (0.49)	27.3 (0.14)	39.4 (0.21)
Total N (%)	2.98 (0.05)	1.88 (0.04)	2.58 (0.06)
CEC ($\text{cmol}_c \text{ kg}^{-1}$)	37.3 (7.7)	54.6 (1.3)	No data
$\text{pH}_{\text{H}_2\text{O}}^5$ (-)	8.9	8.4	5.6

2.1. Cattle manure

Cattle manure is a natural organic fertilizer derived from the excrement of cow and bulls. The cattle manure was freshly collected annually from the UCLouvain experimental farm prior to the start of each experiment.

⁵ 1:10 mass ratio

2.2. Green waste compost

The green waste compost (size <15 mm) came from the composting platform of Basse-Wavre (Brabant Wallon). The composting process takes around 8 to 10 months. Initially, green waste, including materials such as garden waste, dead leaves, grass clippings, branches, and plant debris, is shredded to ensure a uniform consistency. This material then undergoes natural decomposition facilitated by the activity of microorganisms. After the composting period (7 to 8 months), the compost is sieved and left to rest for 1 to 2 months to finally end up in a nutrient-rich organic amendment for the soil, improving soil physico-chemistry and growth yield (in BW, 2017; Mugnai et al., 2012). Since many years, the compost from Basse-Wavre has always complied with the requirements laid down in the certificate of use issued by the Walloon Region. It therefore has all the qualities required for use in agriculture (in BW, 2017).

2.3. Cover crop restitution

A cover crop is a plant or group of plants grown between regular cropping cycles to prevent soil erosion, enhance soil fertility, and provide additional agronomic benefits. In general, crop residues are plant fragments that remain in the field following the harvest and threshing of crops or the grazing of pastures.

Depending on the experiment, several mixtures of three plant species were used as cover crop restitution. The composition of the crop residues for the greenhouse experiment was an equimassic mixture of common oat (*Avena sativa*), field mustard (*Sinapis arvensis*), and lacy phacelia (*Phacelia tanacetifolia*) and collected in the plot 1 (Figure II.1B). For the two consecutive years of the in-situ experiment conducted in plot 3 (Figure II.1B), the composition of the crop residues (restituted directly to the field) was: (1) sorghum (*Sorghum bicolor* × *Sorghum sudanense*), Egyptian clover (*Trifolium alexandrinum*), and common sunflower (*Helianthus annuus*) for the first year; and (2) Egyptian clover (*Trifolium alexandrinum*), lacy phacelia (*Phacelia tanacetifolia*), and lopsided oat (*Avena strigosa*) for the second year.

3. Greenhouse experiment with uncontaminated and contaminated soils

Influence of exogenous organic matter inputs on trace element dynamics in uncontaminated and gradually contaminated soils was studied in a greenhouse (UCLouvain experimental greenhouses, Louvain-la-Neuve, Belgium) cultivating maize (*Zea mays*) from 12th April to 9th July 2021 for 88 days (Figure II.2).

3.1. Experimental setup

At each site, approximately 200 L of soil material were collected randomly in a circle of 7 m in diameter in the top 20 cm depth using a spade (Figure II.1B-E, purple symbols). The soil material was then dried (25 °C in a drying room for seven days) and sieved at 1.2 cm. Approximately 15 kg of the sieved soil were mixed with 20 g of NPK 9-7-14 (equivalent to 240 kg_N ha⁻¹) and exogenous organic matters (if applied: 245 g of cattle manure corresponding to 35 t ha⁻¹, 245 g of green waste compost corresponding to 35 t ha⁻¹, or 35 g of cover crop restitution corresponding to 5 t ha⁻¹), and then potted (10 L pots of 30 cm in diameter and 30 cm in height) before sowing one maize seed in each pot. A plant-free control was added to the experiment. For representativeness purpose, three replicates per modalities were considered, totaling 60 pots (4 soils × 5 modalities × 3 replicates; Figure II.2A-B). During the experiment, each pot was watered with 1 to 3 L per week of tap water according to the weather conditions. In each pot, a rhizon (10-cm long hydrophilic polyether sulphone membrane with a 0.15-μm porosity; 19.21.21F, Rhizosphere, Wageningen, The Netherlands) connected to a 60-mL polypropylene syringe (BD Plastipak luer lock) was installed vertically in the top 10 cm of the soil to collect soil solutions (Figure II.2A; Argo et al., 1997).

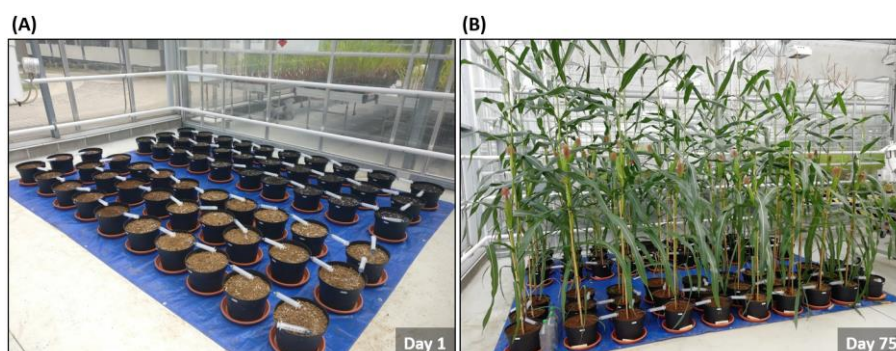


Figure II.2 – Pictures of the experimental setup in the UCLouvain greenhouse on day 1 (A) and day 75 (B).

3.2. Sample collection

Soil solutions were collected three times during the experiment (5th May, 26th May, and 22nd June 2021). They were immediately acidified to achieve a 2% HNO₃ concentration prior to trace element analysis, with the exception for the solutions collected on 26th May, which were used for dissolved organic carbon analysis (Figure II.3).

We collected plant samples once after 88 days (9th July 2021) separating roots, stems, and leaves of maize, as well as a sample of soil (few grams) from each pot after the experiment (mixed or not with exogenous organic matter) for further soil organic matter (SOM) characterization. Monitoring parameters (ambient temperature, humidity and irradiance) were measured by sensors in the greenhouse during the entire experiment and revealed little variability (Table II-3).

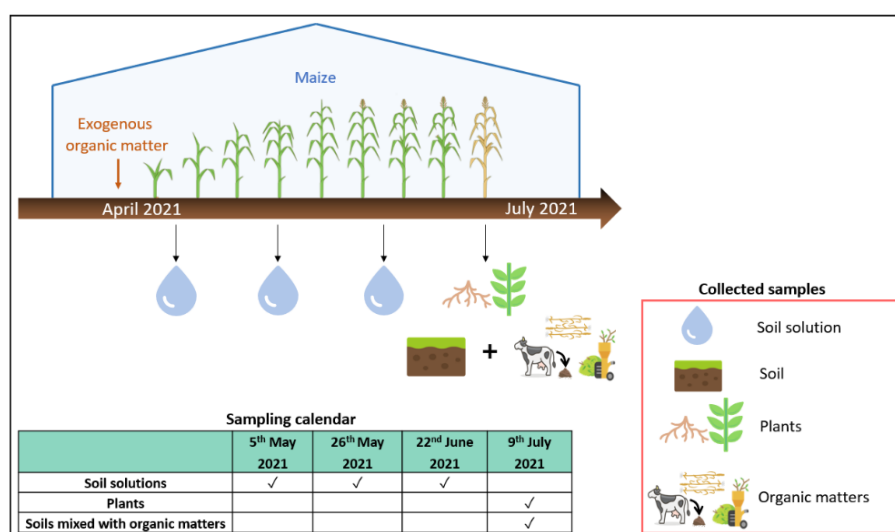


Figure II.3 - Sample collection timeline for the greenhouse experiment.

Table II-3 - Statistics on parameters monitored in the experimental greenhouse (12th April - 9th July 2021).

Parameter	Mean	Standard deviation	Min-Max
Ambient temperature (°C)	22.9	4.2	12.6 – 37.2
Air humidity (%)	61	13	23 – 89
Irradiance (W/m ²)	212	271	0 – 1000 ^a

^a Sensor limited to a maximum threshold of 1000 W/m²

4. Field experiments with uncontaminated soil

4.1. Experiment 1: rare earth elements as trace element tracers

The first in-situ experiment aimed to validate the use of rare earth elements as tracers for trace element transfer from soil to plant in a winter cover crop.

4.1.1. Experimental setup

The experiment was carried out from September 2020 to March 2021 on the plot 2 (340 m × 70 m; 135 m a.s.l.) of the site of Vieusart (Figure II.1B). The land was covered with a cover crop composed of Persian clover (*Trifolium resupinatum*) and sorghum (*Sorghum bicolor* × *Sorghum sudanense*) sown at the end of August 2020. There were also regrowths of faba bean (*Vicia faba*) and spelt (*Triticum spelta*) from the previous crop. For representativeness purposes, soil, plant, and soil solution samples were collected within three distinct sub-areas (ca. 50 m away; Figure II.4).

4.1.1. Sample collection

In each sub-area, corresponding to a circle of 7 m in diameter, a composite soil sample including eight sub-samples was considered at two depths (0–30 cm and 30–50 cm) using an auger (16th October 2020). We performed a soil characterization for both 0–30 and 30–50 cm depth: average soil pH_{KCl} were 6.2 and 6.1, respectively, and soil carbon content, 1.2 and 0.5%, respectively.



Figure II.4 - Location of the study area and sampling strategy in the sub-areas (Vieusart, plot n°2).

Soil solution samples were collected in each sub-area using five rhizons (19.21.21F, Rhizosphere, Wageningen, The Netherlands) installed vertically in the top 10 cm of the soil at the circle periphery. The five collected samples were merged into a single composite soil solution sample per sub-area to obtain sufficient volume for chemical analysis and were immediately acidified (2% HNO_3). Soil solutions were collected five times, approximately each month (21st October 2020, 16th November 2020, 15th December 2020, 14th January 2021, and 4th February 2021). Plant samples considered three different species grown together: bean (*Vicia faba*), Persian clover (*Trifolium resupinatum*), and spelt (*Triticum spelta*). Several specimens were collected in each sub-area (within 5 m around the circle center point), considering both roots and shoots, and stored in plastic bags. Plant sampling was performed three times following the plant growth stages: early (16th October 2020), middle (15th December 2020), and late (4th February 2021). Finally, earthworms (including multiple ecological categories) were sampled on 4th February 2021 by 10-20 specimens per sub-area in the first 10-cm soil depth. To complete the data set, a single sample of unfiltered fresh deposited snow was directly collected on plant leaves on 14th January 2021 (Figure II.5).

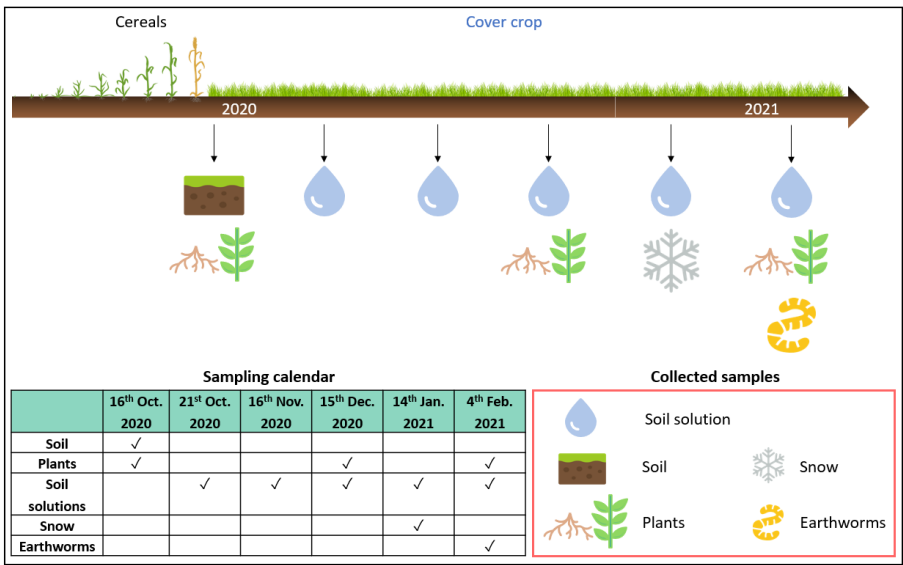


Figure II.5 - Sample collection timeline for the in-situ experiment.

4.2. Experiment 2: trace element dynamics assessment

The second in-situ experiment aimed to study the influence of exogenous organic matter applications on the transfer of trace elements from soil to plant under real conditions over two consecutive years and two different crops: spring barley (*Hordeum vulgare*, year 1) and maize (*Zea mays*, year 2).

4.2.1. Experimental setup

The experiment was carried out from 24th March to 29th July 2022 (year 1) and from 8th May to 20th September 2023 (year 2) on the plot 3 (74 m × 46 m; 127 m a.s.l.) of the site of Vieusart (Figure II.1B).

The plot was divided into four distinct land strips (74 m long and 3 m wide) corresponding to exogenous organic matter application modalities (Figure II.6). The first land strip was not amended with organic matter, constituting the control (Figure II-7B). Strips 2, 3, and 4 were respectively amended with green waste compost (48 t ha⁻¹; Figure II-7A), cattle manure (45 t ha⁻¹), and

the restitution of cover crop (8 t ha^{-1}), from the plot and composed of sorghum (*Sorghum bicolor* $\times$ *Sorghum sudanense*), Egyptian clover (*Trifolium alexandrinum*), and sunflowers (*Helianthus annuus*) for year 1 and Egyptian clover (*Trifolium alexandrinum*), lacy phacelia (*Phacelia tanacetifolia*), and lopsided oat (*Avena strigosa*) for year 2.

Each strip was subdivided into three sampling sub-areas ($3 \text{ m} \times 1 \text{ m}$; Figure II.8A-B), distributed to cover all the heterogeneity of the strip. Soil, soil solution, and plant samples were collected in each sub-area (Figure II.8C).



Figure II.6 - Location of the study area and delimitation of the sub-areas (Vieusart, plot n°3).



Figure II-7 - Pictures of (A) the application of green waste compost and (B) four land strips after exogenous organic matter application: no application (1), green waste compost (2), cattle manure (3), and cover crop restitution (4).

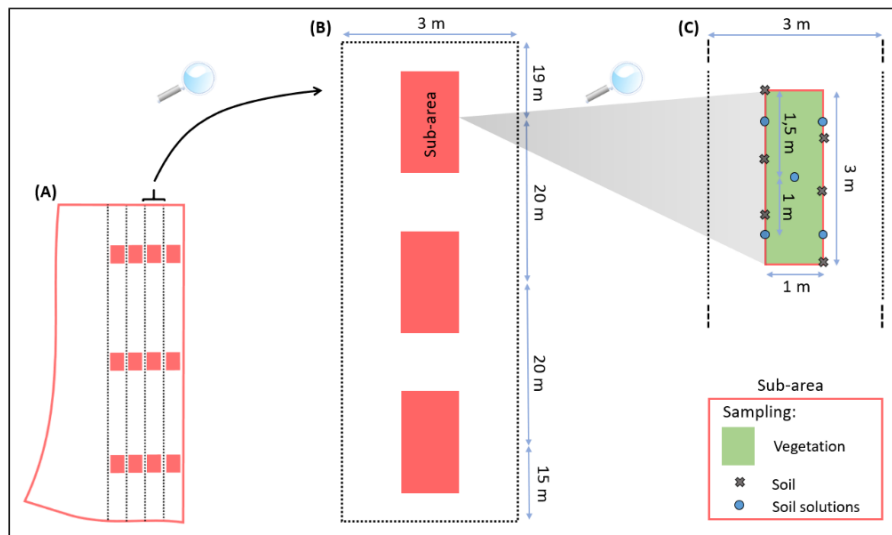


Figure II.8 - Schematic representation of the study area (A), one land strip (B), and sampling strategy in a sub-area (C).

4.2.2. Sample collection

Soil samples were collected once before the start of the experiment (23rd March 2022) at two different depths (0-30 and 30-50 cm), using an auger (Figure II.9). For each depth, six samples per sub-area were taken and then

merged into a composite sample representative of the sub-area (Figure II.8C). Exogenous organic matter applications were carried out each year, on 24th March 2022 and 8th May 2023 using agricultural machinery.

Soil solution samples were collected six times (23rd Mai 2022, 25th May 2022, 9th November 2022, 13th January 2023, 26th July 2023 and 13th September 2023) using 5 rhizons (19.21.21F, Rhizosphere, Wageningen, The Netherlands) per sub-area, installed vertically in the first 10-cm soil depth and separated from each other by 1 m (Figure II.8C). The five soil solution samples collected were merged into a composite sample to ensure sufficient volume for chemical analysis and directly acidified (2% HNO₃, except for the soil solutions collected on 25th May for dissolved organic carbon analysis).

Plant sampling (spring barley, *Hordeum vulgare*) were performed twice the first year, two months apart on 25th Mai 2022 and 25th July 2022, collecting about twenty specimens per sub-area, while plant samples (maize, *Zea mays*) were taken once the second year, at the end of the vegetation growth (20th September 2023) collecting one specimen per sub-area.

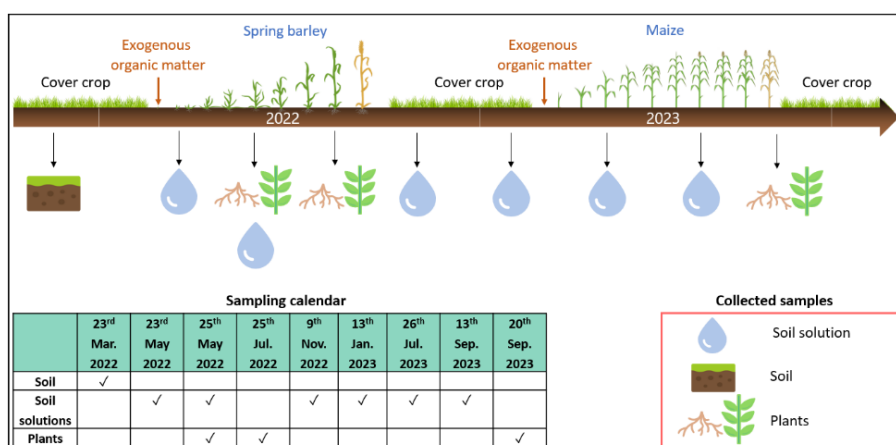


Figure II.9 - Sample collection timeline for the in-situ experiment over two consecutive years.

5. Sample analyses

5.1. Sample preparation

Collected soil and exogenous organic matter samples were dried (25 °C in a drying room for seven days), sieved (<2 mm), and ground using a soil grinder (Vibratory Disc Mill RS 200, Retsch, Haan, Germany). For plant material, shoot samples (i.e., stems and leaves) were gently cleaned with distilled water while root samples were cleaned with pressurized tap water to remove as much soil residues as possible. All plant samples were dried in a ventilated oven at 50 °C. Plant parts were then separated and weighed before grinding (Cyclotec 1093 Sample Mill, Foss A/S, Hillerød, Denmark). Collected solution samples (i.e., soil solutions and snow) were immediately acidified to reach 2% HNO₃ by adding suprapure 65% HNO₃ (trace element analysis), except for soil solutions intended for dissolved organic carbon analysis. Finally, earthworm samples were washed with distilled water and left on wet paper in Petri dishes for 12 days to evacuate their digestive tract content before being frozen in a freezer at -18 °C, dried in an oven at 40 °C, and ground in a mortar with liquid nitrogen.

The following sections detail the extensive analyses conducted on these samples (Figure II.10).

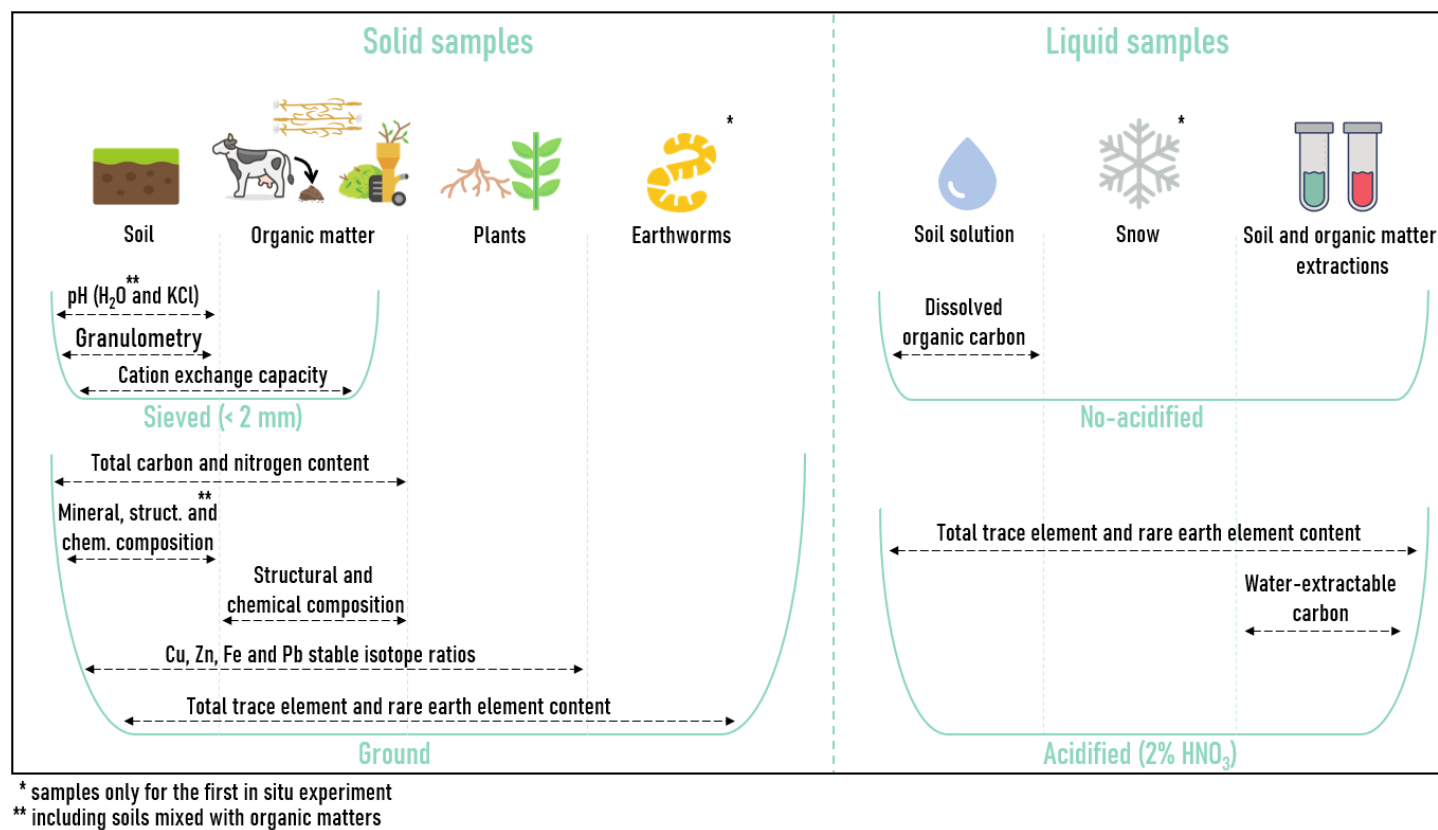


Figure II.10 - Schematic diagram of analyses carried out on solid and liquid samples collected during all experiments.

5.2. Mineral analyses

All mineral analyses introduced in this section were duplicated.

Soil pH

Soil pH embodies the pH of a solution (e.g., H_2O and KCl , noted $\text{pH}_{\text{H}_2\text{O}}$ and pH_{KCl} , respectively) in equilibrium with the soil. Measuring $\text{pH}_{\text{H}_2\text{O}}$ gives an account of the active acidity, i.e., the concentration of free protons (H^+ ions) in the solution. However, when measured in water, pH does not take account of protons bound to the exchange complex. The addition of K^+ ions (via KCl) releases H^+ ions bound to the exchange complex and represents exchangeable acidity. The difference between $\text{pH}_{\text{H}_2\text{O}}$ and pH_{KCl} is called potential acidity and generally varies from 0.5 to 1.5 pH units (Baize, 2000a; Pansu and Gautheyrou, 2006).

For this purpose, 5 g of sieved (<2 mm) soil sample were mixed with 25 mL of Milli-Q water⁶ or KCl 1 M (1:5 mass ratio) then homogenized by agitation for 1 h at regular 20-min intervals. $\text{pH}_{\text{H}_2\text{O}}$ and pH_{KCl} analyses were performed in the supernatant using a pH probe (SenTix® 81, WTW, Germany) and a pH-meter (InoLab® pH 720, WTW, Germany) previously calibrated with pH 4 and pH 7 standard solutions.

Soil particle size

To determine the particle-size distribution (clay, silt, and sand particles) of a soil samples, we measured the granulometry using the sedimentation method (Pansu and Gautheyrou, 2006). We followed the "Robinson pipette" method described by Baize (2000). Approximately 10 g of sieved soil sample were mixed with 200 mL of 6% hydrogen peroxide (H_2O_2) to oxidize the organic matter, and heated to 50°C on a hot plate until the sample was completely dry. Then, 50 mL of a solution containing sodium hexametaphosphate (36 g L^{-1}) and sodium carbonate (8 g L^{-1}) were added to disperse clay particles. The samples were then topped up to 200 mL with demineralized

⁶ Milli-Q® water is ultra-pure water produced through a multi-stage purification process. Free from impurities, ions and contaminants and widely utilized in laboratory for its high quality (resistivity of $18.2 \text{ M}\Omega \text{ cm}$ at 25°C).

water and ultrasonicated for 2 min using a sonicator (Branson sonifier 250, VWR International, USA) to facilitate soil particle dispersion. Sand-size particles were collected by sieving through a 250 μm sieve (coarse sands, 200-2000 μm) and a 50 μm sieve (fine sands, 50-200 μm). The remaining fractions were then suspended in a 1 L water-filled column and collected in three steps, each involving the pipetting of 20 mL at specific times and depths, following Stokes' law of sedimentation: (1) At time 0, halfway up the column (coarse silts, 20-50 μm ; fine silts, 2-20 μm ; and clays, <2 μm), (2) After 4 min and 48 s, 30 cm from the top of the column (fine silts and clays), and (3) After 24 h, 10 cm from the bottom of the column (clays). All of these fractions were finally placed in a drying oven at 105 °C and weighed. The coarse and fine sand fractions were weighed directly after sieving and evaporation. Coarse and fine silt fractions were calculated by the difference in mass between each sample recovered and evaporated after the required sedimentation time. Noted that for clay fractions, we subtracted the mass of sodium hexametaphosphate presents in the 20 mL pipetted.

Cation exchange capacity

To determine the capacity of the soil and exogenous organic matter to retain cations (i.e., the number of negative charges present on the exchange complexes), we used the ammonium acetate method at pH 7 (Metson, 1956) followed by spectrophotometric determination of ammonium ions.

Approximately 5 g of sieved soil or exogenous organic matter sample mixed with 20 g of pre-cleaned sand were introduced in a column containing absorbent cotton and a fine layer of sand (1 cm) to filter and stabilize the flow of solutions, followed by another layer of sand placed on top for the same purpose (Figure II.11). For each sample, 150 mL (6×25 mL) of 1 M ammonium acetate (pH 7) were added to the top of the column. Ammonium ions (NH_4^+), added in excess, exchange with cations (Na^+ , Mg^{2+} , K^+ , and Ca^{2+}) on the soil exchange complex. Then, excess ammonium acetate not sorbed onto the exchange complex was washed with 125 mL (5×25 mL) of 99% ethanol. Finally, sorbed NH_4^+ were desorbed by the addition of an excess solution of 10% KCl (pH 3). The containing NH_4^+ solutions collected were diluted $\times 50$ with Milli-Q water in a 250 mL volumetric flask. The determination of cation exchange capacity is achieved through the quantification of NH_4^+ using a Spectroquant® ammonium kit and a spectrophotometer (Genesys 10S UV-Vis®, Thermo Scientific, USA) at a wavelength of 690 nm, establishing a direct

relationship with the absorbance measurement of the solution introduced into each cuvette via the Beer-Lambert law.

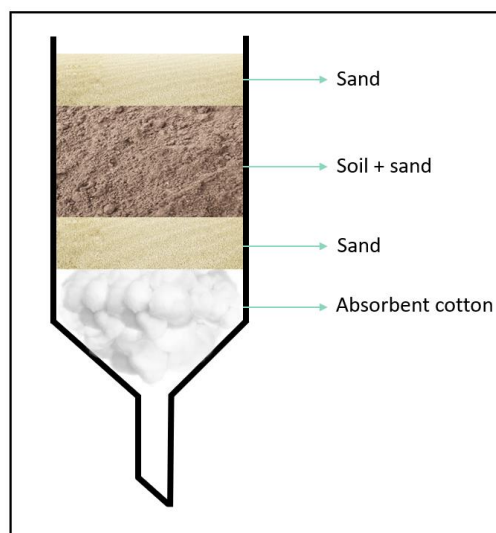


Figure II.11 – Schematic diagram of the experimental setup for cation exchange capacity analysis.

Mineralogical composition

We characterize crystallized minerals in soil samples using X-ray diffraction (XRD) method which exploits the ability of crystals in the soil to diffract X-rays at specific angles, generating characteristic diffraction patterns and providing information on soil structure and mineralogical composition (Baize, 2000a; Pansu and Gautheyrou, 2006). In practice, a micro-spoon of ground soil sample was deposited homogeneously on a glass slide and inserted into the diffractometer (XRD, Bruker D8 advance diffractometer, Bruker, Karlsruhe, Germany), with the following experimental parameters: Cu K α , 40 kV, 30 mA, primary Soller slit 2°, divergence slit 1 mm, secondary Soller slit 2°, anti-scatter slit 1 mm, and a detector slit of 0.2 mm. Data acquisition was conducted over a 2 θ range from 2° to 90° at a scan rate of 1°/min, with a detection limit of 5% (Mauclet et al., 2023). An internal database was used to identify the crystalline phases.

5.3. Organic analyses

Total carbon and nitrogen content

To determine both carbon and nitrogen content, between 10 and 30 mg of ground soil or exogenous organic matter sample were inserted in tin foil and then analyzed by gas chromatography (Elementar vario EL cube, Langenselbold, Germany). In the analyzer, samples were oxidized in a catalytic combustion chamber into CO₂, H₂O and NO_x. NO_x, reduced to N₂, and CO₂ were detected, while other gases were retained. Detection is based on the difference in thermal conductivity between a reference flow of He and a mixed flow of He analytes. The concentration of total carbon and total nitrogen is proportional to this difference in thermal conductivity (Elementar.com, 2024). Due to the absence of soil inorganic carbon (determined by Rock-Eval analysis), we consider the total carbon content as the organic carbon content. These analyses were performed in duplicate.

Extractable carbon and nitrogen in water extraction

Soil extractable carbon and nitrogen were assessed using a water extraction by adding 20 mL of Milli-Q water to 2 g of sieved soil samples in a 50 mL centrifuge tube, then shaking for 2 h using a mechanical shaker (Universal Shaker SM 30 B, Edmund Bühler GmbH, Bodelshausen, Germany). The supernatants were isolated by centrifugation at 4000 rpm for 25 min (Centrifuge Jouan GR4.12, France) then filtered with 20-μm Whatman paper filters and 0.2-μm nylon Acrodisc filter (PSF and nylon, Pall). Carbon and nitrogen water-extractable present in the filtrate were then analyzed by total organic carbon analyzer including a total nitrogen module (TOC-L, Shimadzu, Kyoto, Japan). The sample is injected into the high-temperature furnace for catalytic oxidation, producing both CO₂ and NO. Carbon dioxide is then detected by non-dispersive infrared (NDIR) for total organic carbon measurement while NO is converted to NO₂ and detected by chemiluminescence for total nitrogen measurement (Shimadzu.com, 2011). Dissolved organic carbon concentrations in soil solutions were also determined by TOC-L instrument.

Structural and chemical composition of organic matter

The quantitative and qualitative analysis of ground soil organic matter and exogenous organic matter samples has been explored using three analytical

methods: nuclear magnetic resonance spectroscopy (NMR), pyrolysis – gas chromatography – mass spectrometry (Py-GC-MS), and Rock-Eval pyrolysis (Derenne and Quénéa, 2015; Kögel-Knabner, 2000). These three analyses, carried out solely on soil and organic matter samples before and after the greenhouse experiment, were performed at the Sorbonne Université (Paris, France).

1) Nuclear magnetic resonance spectroscopy

NMR spectroscopy is a spectroscopic technique widely used in geochemistry and various other disciplines that utilizes the magnetic properties of certain atomic nuclei, such as carbon, providing information on the structure and chemical environment of the molecules (Dais and Spyros, 2012; Simpson et al., 2012; Yao et al., 2021). In recent years, NMR techniques have been used to obtain structural information about organic matters (Dai et al., 2001; Inbar et al., 1989; Kögel-Knabner, 1997; Mathers et al., 2000; Simpson et al., 2008) and to understand precisely specific interactions between trace elements and organic matter (Simpson, 2006). And it is with this aim of understanding more precisely the structure of organic matters and then the sorption phenomena of trace elements with exogenous and soil organic matter that the solid-state ^{13}C -NMR spectroscopy technique was exploited in this document.

In practice, solid-state ^{13}C -NMR spectroscopy was carried out at the Institute of Materials of the Paris Center (IMPC) on soil samples mixed or not with organic matter collected at the end of the greenhouse experiment (after-experiment soil samples), using a Bruker Avance 500 NMR spectrometer (Bruker Analytik GmbH, Rheinstetten, Germany). The sites considered were Vieusart, Sainte-Walburge, and Bressoux for the modalities of no application, cattle manure, green waste compost, and cover crop restitution (totaling 12 samples, i.e., 3 sites $\times$ 4 modalities $\times$ 1 replicate). The Aubange site was not included in the ^{13}C -NMR analyses due to its high total iron content in the soil (20.4%), which could damage the analyzer.

We pre-treated samples to decarbonate and eliminate minerals before ^{13}C -NMR analysis. A solution of 1 mL of 6 M HCl and 10 mL of 10% HF were added to 1 g of after-experiment ground soil sample in a 15 mL tube. After stirring for 2-3 h, the sample was centrifuged at 3000 rpm for 10 min. The supernatant was then removed before being subjected to further acid hydrolysis, followed by centrifugation. Finally, the sample pellet was rinsed 3 times with Milli-Q water, then placed in an oven (45 °C) for evaporation until completely dry.

Spectrometer operated at a ^{13}C resonance frequency of 125 MHz, equipped with a 4 mm zirconium rotor. Cross-polarization magic angle spinning (CP-MAS) was employed with a spinning speed of 14 kHz. The contact time was set to 1 ms and the scan delay was 1 s. Depending on the material, between 1624 and 4712 scans were accumulated. The chemical shift was referenced to tetramethylsilane (TMS) and further calibrated using adamantane as an external reference. No spinning sidebands were observed in the samples.

Spectra were deconvoluted using DMFit 2015 software (Massiot et al., 2002). Indeed, ^{13}C -NMR analysis hinges on detecting carbon atoms within organic compounds, each with unique chemical shift values representing different carbon types. Signal intensity at a specific shift reflects the abundance of that carbon type. Then spectra are segmented into regions based on similar shifts, aiding in comparing carbon atom chemistry. Integrating signal intensities within these regions enables quantifying specific carbon types (Baldock and Preston, 1995; Mathers et al., 2000). Based on Kögel-Knabner (1997) and Mathers et al. (2000) works, it was decided to define four main chemical shift regions corresponding to alkyl (0-45 ppm), O-alkyl (45-110 ppm), aromatic (110-160 ppm), and carbonyl (160-220 ppm) C atoms (Figure II.12). The proportions of each component were determined by integrating and summing the areas of the peaks (Between 15 and 25 peaks per spectrum) within each region.

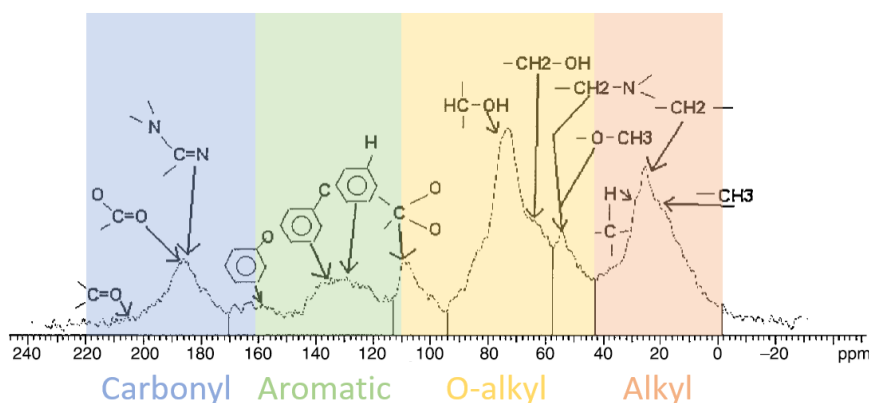


Figure II.12 - Chemical shift assignments for a ^{13}C -NMR spectrum (modified from Mathers et al., 2000).

2) Pyrolysis – gas chromatography – mass spectrometry

To analyze the structure and chemical composition of organic compounds, we used Py-GC-MS analytical technique. It combines pyrolysis “Py”, which

thermally decomposes a sample into volatile compounds in the absence of oxygen, with gas chromatography “GC” that separates these compounds according to their physico-chemical properties (volatility and interactions with the stationary phase), and mass spectrometry “MS” that identifies and quantifies individual compounds (Mazzetto et al., 2019; Mehrabanian, 2013; Meier and Faix, 1992).

Among the products commonly identified during pyrolysis of a soil organic matter (SOM) sample, lignin stands out as an essential compound for studying the state of degradation of SOM (Mazzetto et al., 2019; Mehrabanian, 2013). Indeed, due to its abundance in plants and its transfer to the soil via aboveground and/or belowground parts, lignin provides crucial information for the estimation of the SOM pool size and its stabilization (Thevenot et al., 2010). Consequently, we used Py-GC-MS method for characterizing and quantifying lignin in soils, by analyzing the proportions of its monomers (Figure II.13) released after pyrolysis, namely vanillyl (V), syringyl (S), and cinnamyl (C), which can be used as biochemical indicators of the origin and decomposition state of lignin and SOM.

Before-experiment soil, exogenous organic matter, and after-experiment soil samples were then analyzed by Py-GC-MS at the *Milieux environnementaux, transferts et interactions dans les hydrosystèmes et les sols* (METIS). The sites considered were Vieusart, Sainte-Walburge, Bressoux, and Aubange for the modalities of no application, cattle manure, green waste compost, and cover crop restitution, totaling 23 samples (i.e., 4 soils + 3 exogenous organic matters + 4 sites × 4 modalities × 1 replicate). Approximately 5 to 10 mg of samples (depending on initial carbon content) were subjected, in the presence of tetramethylammonium hydroxide (TMAH), to Curie point pyrolysis at a Curie temperature of 650 °C for 10 s using a pyrolysis unit (Pilodist), coupled to a gas chromatograph (GC, Trace Ultra Thermo Electron) and a mass spectrometer (MS, DSQ 1 Thermo). After an initial 10 min at 50 °C, the GC oven temperature was ramped from 50 to 310 °C at a rate of 2 °C/min. Semi-quantitative data were obtained from the TMAH-Py-GC-MS analysis using Agilent ChemStation software. This involved manually subtracting the background signal from the total ion current for each peak of interest and integrating the peak areas. The relative abundance of each compound was determined by dividing the area of each peak by the sum of the areas of all identified pyrolysis product peaks. Compound identification for each peak was

performed using mass spectrometry with reference to the NIST compound library and published literature (Barré et al., 2018; Vidal et al., 2016).

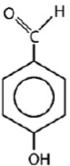
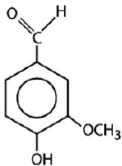
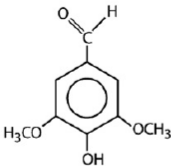
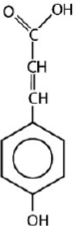
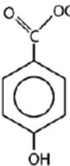
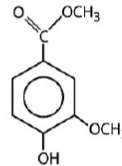
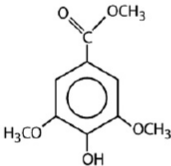
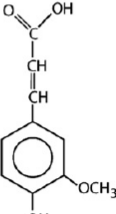
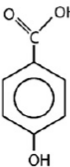
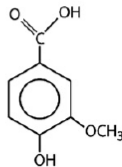
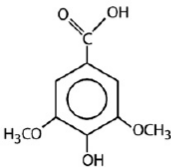
	<i>p</i> -Hydroxyl phenols	Vanillyl phenols	Syringyl phenols	Cinnamyl phenols
Aldehydes	 <i>p</i> -Hydroxybenzaldehyde	 Vanillin	 Syringaldehyde	 <i>p</i> -Coumaric acid
Ketones	 <i>p</i> -Hydroxyacetophenone	 Acetovanillone	 Acetosyringone	 Ferulic acid
Acids	 <i>p</i> -Hydroxybenzoic acid	 Vanillic acid	 Syringic acid	

Figure II.13 - Monomers of lignin released during the pyrolysis (Thevenot et al., 2010).

We calculated several indices derived from the analysis of S, C and V monomers by Py-GC-MS (Loh et al., 2008; Thevenot et al., 2010):

- **total lignin (SCV)** is the sum of syringyl (S; syringaldehyde, acetosyringone, and syringic acid), cinnamyl (C; *p*-coumaric and ferulic acids) and vanillyl (V; vanillin, acetovanillone, and vanillic acid) phenols (Loh et al., 2008). This index is generally regarded as a quantitative measure of soil lignin. As decomposition progresses, total lignin typically decreases.
- **the acid-to-aldehyde (Ad-to-Al)** ratios of V and S units serve as indicators of lignin degradation in soil. As decomposition progresses, the Ad-to-Al ratios of these units increase.

3) Rock-Eval pyrolysis

Initially developed to evaluate the oil and gas properties of sedimentary rocks (Baudin et al., 2007), we used Rock-Eval pyrolysis to characterize soil and exogenous organic matters based on their thermal stability (Derenne and Quénéa, 2015; Disnar et al., 2003; Sebag et al., 2016). After a pyrolysis step (heating in an oxygen-free environment to decompose the organic matter), the sample is oxidized (heating in the presence of oxygen) to quantify the oxidizable organic matter remaining in the sample (Figure II.14).

In practice, Rock-Eval analysis was performed on before-experiment soil, exogenous organic matter, and after-experiment soil samples at the *Institut des Sciences de la Terre de Paris* (ISTeP). The sites considered were Vieusart, Sainte-Walburge, Bressoux, and Aubange for the modalities of no application, cattle manure, green waste compost, and cover crop restitution (totaling 55 samples, i.e., 4 soils + 3 exogenous organic matters + 4 sites × 4 modalities × 3 replicates).

The analysis initiates by heating 10 to 60 mg of sample (depending on initial C content) to 200-300 °C under a nitrogen atmosphere to release the most volatile compounds, corresponding to free hydrocarbons (S1). Subsequently, the temperature is increased at a rate of 25-30 °C/min up to 650 °C, causing the cracking of organic matter and releasing additional hydrocarbons (S2). The quantities of S1 and S2 are measured using a flame ionization detector (FID). At the same time, an infrared detector (IR) quantifies the CO and CO₂ (S3) released during pyrolysis. Following the pyrolysis step, the remaining residue undergoes high-temperature oxidation (750-850 °C) in the presence of air to convert any residual organic carbon into CO and CO₂ (S4 and S5), which are again quantified by infrared spectroscopy (Baudin et al., 2007; Behar et al., 2001; Disnar et al., 2003).

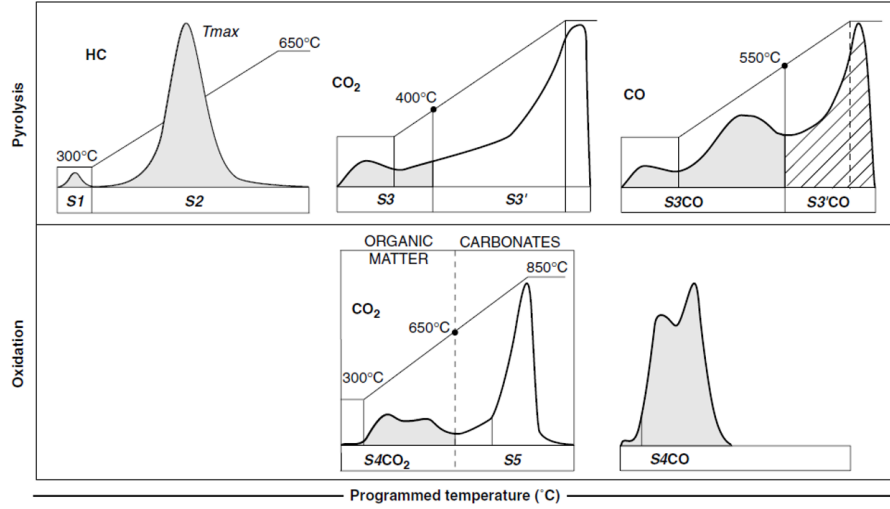


Figure II.14 – Schematic visualization of the Rock-Eval analysis (Disnar et al., 2003).

On the basis of the numerous parameters obtained during Rock-Eval analysis, we calculate new parameters useful for characterizing the thermal stability of organic matter in samples (Behar et al., 2001; Derenne and Quénée, 2015).

- **Pyrolyzable carbon (PC)** index represents the total amount of carbon ($\text{mg}_C/\text{g}_{\text{sample}}$) released by the sample during the pyrolysis phase. It is directly influenced by the S1, S2, S3, S3CO, and S3'CO peaks, the latter corresponding to CO contributions from both the mineral and organic fractions of the sample. This parameter is independent of total organic carbon.

$$\text{PC} = (S1 + S2) \times 0.083 + \left(\frac{S3 \times 12}{440} \right) + \left(\frac{S3\text{CO} + \frac{1}{2} S3'\text{CO}}{280} \times 12 \right)$$

- **Residual carbon (RC)** index represents the total amount of carbon ($\text{mg}_C/\text{g}_{\text{sample}}$) released by the sample during the oxidation phase. It is directly influenced by the S4CO and S4CO₂ peaks. This parameter is also independent of TOC.

$$\text{RC} = \left(\frac{S4\text{CO}_2 \times 12}{440} \right) + \left(\frac{S4\text{CO} \times 12}{280} \right)$$

- **Total organic carbon (TOC)** of a sample ($\text{mg}_C/\text{g}_{\text{sample}}$) can be obtained by combining the contributions from pyrolyzable carbon (PC) and residual carbon (RC) produced during pyrolysis and oxidation, respectively.

- **Hydrogen index (HI)**, analogous to the hydrogen/carbon ratio, provides an indication of the proportion of hydrogenated compounds present in the sample ($\text{mg}_{\text{hydrocarbons}}/\text{g}_{\text{TOC}}$).

$$\text{HI} = \frac{\text{S2} \times 100}{\text{TOC}}$$

- **Oxygen index (OI)**, analogous to the oxygen/carbon ratio, reflects the degree of oxidation of the organic matter within the sample ($\text{mg}_{\text{CO}_2}/\text{g}_{\text{TOC}}$).

$$\text{OI} = \frac{\text{S3} \times 100}{\text{TOC}}$$

5.4. Trace element and rare earth element analysis

We measured trace element (As, Ba, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, Sc, Se, Sn, Sr, Ti, V, and Zn) and REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) concentrations directly in liquid samples (soil solution and snow) and following a preparatory step for solid samples (soil, exogenous organic matter, plant and earthworm), considering either the total fraction (acidic digestion) or a specific fraction (water extraction and BCR sequential extraction⁷).

Acidic digestion

Approximately 100 mg of ground samples (soil, plant, exogenous organic matter and earthworm) were digested in a 7 mL Savillex (Teflon bottle) in an ISO 6 cleanroom using a mixture of suprapure acids (HNO_3 , HCl , and HF) and H_2O_2 in a four-step procedure. (1) A mixture of 0.5 mL of 65% nitric acid (HNO_3) and 0.5 mL of 40% hydrofluoric acid (HF) were added to each sample. The samples were degassed for half a day, heated to 90 °C for 2 days on a hot plate, and then evaporated at 40 °C. (2) Following the initial treatment, 1 mL of 30% hydrogen peroxide (H_2O_2) was progressively added to each sample. The samples were again degassed for half a day, and then evaporated at 40 °C. (3) Aqua regia mixture of 0.8 mL of HCl and 0.2 mL of 65% HNO_3 was added

⁷ The BCR sequential extraction procedure, developed by the European Community Bureau of Reference, is a standardized method designed to fractionate elements in soil or sediment samples into distinct chemical forms.

to each sample. The samples were heated to 90 °C for a day, and then evaporated at 40 °C. (4) Finally, 1 mL of 65% HNO₃ was added to each sample before heated to 90 °C for a day. Before each digestion step, the Savillex containers were placed in an ultrasonic bath for three cycles of three minutes each to mix and homogenize the solution.

Following the acidic digestion, the contents of the Savillex containers (sample in 1 mL of 65% HNO₃) were rinsed with 11 mL of high-purity Milli-Q water in a 15 mL polypropylene tube. Subsequently, various dilutions were performed using a 2% HNO₃ solution, with dilution factors of ca. ×120 for organic samples and ca. ×1200 for mineral samples.

Extractable elements in water and sequential extraction

Element distribution in soil solid phase was assessed using water and sequential extraction. A modified BCR three-step sequential extraction (Žemberyová et al., 2006) was performed on 1 g of sieved soil samples: (1) 40 mL of 0.11 mol L⁻¹ CH₃COOH (exchangeable fraction); (2) 40 mL of 0.5 mol L⁻¹ NH₂OH·HCl (reducible-iron/manganese oxides fraction); and (3) 2×10 mL of 8.8 mol L⁻¹ H₂O₂ before 50 mL of 1 mol L⁻¹ CH₃COONH₄ (oxidizable-organic matter and sulfides fraction). For each extraction step, soil samples were mixed with the extractant at 300 rpm for 16 h (mechanical shaker). The extracted solutions were then separated from the solid phase by: (1) centrifugation at 4000 rpm for 20 min; (2) filtration with 20-μm Whatman paper filters; and (3) filtration with 0.2-μm GHP Acrodisc. The precipitates were washed with 20 mL of Milli-Q water between every step. The residual fraction was obtained by the difference between the total soil concentration and the sum of the other three fractions. Besides the BCR extraction, we performed a water extraction (i.e., 1 g of sieved soil samples with 40 mL of Milli-Q water following the same mixing and separating steps as done for the BCR extraction). Trace element concentrations in extracted solutions were finally measured after acidification (2% HNO₃).

Element quantification

Trace elements and REE were quantified using inductively coupled plasma mass spectrometry (ICP–MS; iCAP Q ICP–MS, Thermo Fischer Scientific, Waltham, MA, USA) at the Earth and Life Institute analytical platform (MOCA, UCLouvain, Belgium). Due to its high sensitivity, low detection limits and low sample volume requirements, ICP-MS is a commonly used method for

determining trace levels of several elements in liquid samples with varying matrix composition (Bulska and Ruszczyńska, 2017).

The liquid samples are introduced into the instrument using a nebulizer, which transforms it into a fine aerosol. This aerosol is then transported with argon gas to the ICP torch, where it is atomized and ionized within an inductively coupled plasma (approximately 10000 K). These ions are then directed through a mass analyzer, which separates them based on their mass-to-charge ratio. This separation allows for the precise distinction of various elements and isotopes present in the sample. Finally, the separated ions are detected by a detector that measures their intensity. The intensity of the detected ions is directly proportional to the concentration of the elements in the sample, facilitating their accurate identification and quantification with high sensitivity and precision (Bulska and Ruszczyńska, 2017; Telgmann et al., 2017). From a practical perspective, common interferences were automatically corrected after analytical tests (e.g., Pourret et al., 2021). An internal standard (Ru, In, and Re) was used in each sample for drift instrumental correction.

The performance of the acidic digestion procedure was evaluated using certified organic (lichen IAEA-336) and mineral (basalt BHVO-2) reference materials. The average recovery, calculated as $(C_{\text{measured}} / C_{\text{certified}}) \times 100$, was $100 \pm 20\%$, except for the elements Ti, V, Cr, Ni, Se, Sn, Er, Tm, and Lu in IAEA-336 (134, 134, 132, 128, 130, 161, 79, 76, and 74%, respectively), and for Sb, As and Se in BHVO-2 (237 and 300, 374%, respectively). To assess the performance of the ICP-MS, a river water standard (SLRS-6) was included, resulting in an average recovery of approximately $100 \pm 20\%$, except for Sc (no data), Cd (163%), Sn (214%), and Se (190%). No contamination was detected during the digestion process, as indicated by average blank concentrations being less than 1% of the sample concentrations. Limits of detection were estimated to be $<0.01 \mu\text{g kg}^{-1}$, except for Ti, Zn, Se, and Mo, which were $<0.1 \mu\text{g kg}^{-1}$.

Trace elements and REE concentrations were measured in roots, stems, and leaves. With these concentrations and the measured biomass, we were able to calculate the concentrations in shoot (C_{shoot} , i.e., biomass-weighted average of stems and leaves) and in plant (C_{plant} , i.e., biomass-weighted average of roots, stems, and leaves) according to the following formulas:

$$C_{\text{shoot}} = \frac{(C_{\text{stems}} \times m_{\text{stems}}) + (C_{\text{leaves}} \times m_{\text{leaves}})}{m_{\text{stems}} + m_{\text{leaves}}}$$

$$C_{\text{plant}} = \frac{(C_{\text{roots}} \times m_{\text{roots}}) + (C_{\text{stems}} \times m_{\text{stems}}) + (C_{\text{leaves}} \times m_{\text{leaves}})}{m_{\text{roots}} + m_{\text{stems}} + m_{\text{leaves}}}$$

where C_{roots} , C_{stems} , and C_{leaves} were trace element and REE content in roots, stems, and leaves, respectively, and m_{roots} , m_{stems} , and m_{leaves} were the biomass collected of roots, stems, and leaves, respectively.

REE profiles were normalized using specific reference materials: (1) the upper continental crust (UCC; Rudnick and Gao, 2014) for soil samples (Cidu et al., 2013), and (2) local soil for BCR extraction, soil water-extract, roots, stems, leaves, shoots, plant, and soil solution samples (Brioschi et al., 2013). REE indices commonly referenced in the literature were calculated from the measured (Agnan et al., 2014; Miao et al., 2008; Wyttenbach et al., 1998): (1) anomalies for Ce, Eu, Tb, and Yb, calculated by dividing the normalized value by the expected value (determined by averaging the values of the elements immediately preceding and following in the periodic table, denoted as Ce*, Eu*, Tb*, and Yb*, respectively), and (2) the LREE/HREE ratio using the corresponding normalized concentration ratios:

$$\frac{\text{LREE}}{\text{HREE}} = \frac{(\text{La} + \text{Ce} + \text{Pr} + \text{Nd} + \text{Sm} + \text{Eu})/6}{(\text{Gd} + \text{Tb} + \text{Dy} + \text{Ho} + \text{Er} + \text{Tm} + \text{Yb} + \text{Lu})/8}$$

To evaluate the transfer intensities of trace elements from one compartment to another in the soil-plant system, transfer factors (TF) were calculated as follows (Adriano, 2001; Antoniadis et al., 2017; Marchiol et al., 2004):

$$TF_{A \rightarrow B} = \frac{C_B}{C_A}$$

with C_A and C_B , the trace element concentrations in compartment A and B, respectively, which can be soil, root, stem, leaf, shoot, plant, or plant-available trace element proxies (soil solution, soil water-extract, and BCR exchangeable fraction).

Total Al, Ca, Fe, K, P, S, and Si contents of soil and organic matter samples used for the greenhouse experiment were measured using a portable X-ray fluorescence (pXRF) instrument (Thermo Scientific Niton XL3t GOLDD+; Appendix A, Table VI-2).

5.5. Cu, Zn, Fe, and Pb stable isotope analysis

Stable isotope analysis of Cu, Zn, Fe, and Pb was carried out on before-experiment soil, exogenous organic matter, and plant samples from the greenhouse experiment. Three sites (Vieusart, Bressoux, and Aubange) were considered for three modalities (no application, cattle manure, and green waste compost) to obtain the most contrasted isotopic signatures (totaling 23 samples (i.e., 3 soils + 2 exogenous organic matter + 3 sites $\times$ 3 modalities $\times$ 2 plant parts $\times$ 1 replicate). Copper, Zn, Fe, and Pb isotope analysis involved a four-steps procedure: (1) calcination; (2) acid digestion; (3) column chromatography purification; and (4) isotope measurement. These four steps were performed at the *G-Time Laboratory* at the *Université Libre de Bruxelles* (Brussels, Belgium) and are described in the following sections.

Calcination

Between 0.5 and 2 g of ground sample (according to the resin and analyzer requirements: between 10000 and 300000 ng for Cu-Zn, and Fe and >250 ng for Pb) were calcinated in a crucible to decarbonate the sample using an oven (Carbolite ELF 11/14B Economy Chamber Furnace, Carbolite®, England) for at least 14 h straight. The temperature was first set to 150 °C and gradually increased to 800 °C during the first 5 h.

Acid digestion

Following the calcination step, the residues were digested with a mixture of suprapure acids (HNO_3 , HCl , and HF) and H_2O_2 via two microwave cycles (Microwave Digestion System – Multiwave Go, Anton Paar®, Austria) and hot plate evaporation steps.

First, the samples were inserted with 12 mL of 14 M HNO_3 in microwave reactors for a first heat cycle (190 °C, 40 min). After degassing, 2 mL of 14 M HNO_3 and 1 mL of 40% HF were added to each reactor and inserted in the microwave for a second cycle with the same parameters. Then, reactor contents were transferred in a Savillex for approximately three evaporation steps on a hot plate (90 °C): 14 M HNO_3 + 30% H_2O_2 , 40% HF if needed and 8 M HCl . The samples were finally recovered in 1 mL of 8 M HCl before column chromatography purification.

Column chromatography purification

The purification/separation process for Cu, Zn, Fe, and Pb isotopes was adapted from Vanderstraeten et al. (2020), building on the methodology of Maréchal et al. (1999). The procedure was performed using column chromatography with ion exchange resins (Bio-Rad, AG® 1-X8 Anion Exchange Resin, analytical grade, 100–200 and 200–400 mesh, chloride form; Figure II.15) on various columns: (1) Triskem (AC-142-TK column); (2) Bio-Rad (Mini Bio-Spin® column); and (3) custom-made column using a 60-mL polypropylene syringe. Column chromatography with resins is a widely employed technique for achieving high-purity isotopes. The process involved passing a metal-containing solution through a column packed with resin, where the resin acted as a stationary phase. By carefully adjusting the elution conditions, such as the type and concentration of eluent, isotopes of Cu, Zn, Fe, and Pb can be selectively eluted, yielding purified fractions (Table II-4, Table II-5, Table II-6, Table II-7).

Copper, Zn, Fe, and Pb were isolated from the sample matrix using 1 mL of AG1-X8 resin with 200–400 mesh size (AC-142-TK column; Figure II.15A). Zinc was further purified in a second step using the same resin following cleaning procedures (Figure II.15B). Then, Cu was purified on a separate column using 0.5 mL of fresh AG1-X8 resin (200–400 mesh) in a Mini Bio-Spin column (Figure II.15C). Finally, Pb was purified using a third column (custom-made column; Figure II.15D) packed with 0.2 mL of AG1-X8 resin with 100–200 mesh size. Each purified collected sample was evaporated on a hot plate at 90 °C, then re-dissolved in 1 mL of 14 M HNO₃ and 100 µL of H₂O₂. The solution was subsequently evaporated again prior to analysis.

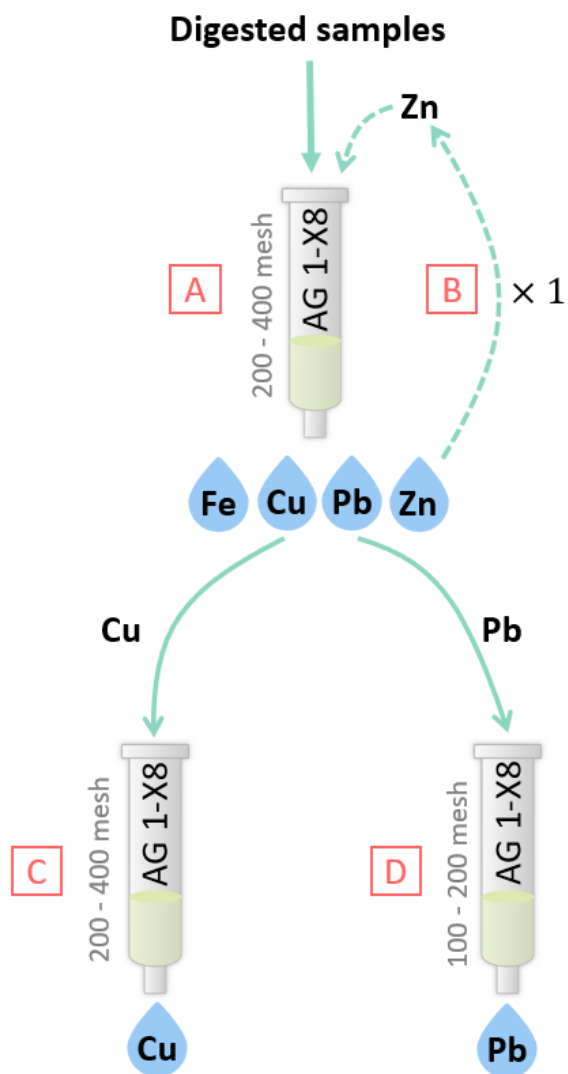


Figure II.15 – Overview diagram of the purification steps on resin column chromatography. First Cu, Zn, Fe, and Pb purification (A) and second Zn (B), Cu (C), and Pb (D) purification.

Table II-4 – First elution protocol for Cu, Zn, Fe, and Pb purification (Figure II.15A).

Step	Eluent	Volume (mL)
Cleaning	H ₂ O	5
Cleaning	6 M HCl	5
Cleaning	H ₂ O	5
Cleaning	1 M HNO ₃	5
Cleaning	H ₂ O	5
Cleaning	1 M HNO ₃	5
Cleaning	H ₂ O	5
Conditioning	8 M HCl	5
Loading + Pb collecting	8 M HCl	1 + 1
Rinsing + Pb collecting	8 M HCl	4
Cu collecting	8 M HCl	25
Fe collecting	0.5 M HCl	15
Zn collecting	1 M HNO ₃	20

Table II-5 – Second elution protocol for Zn purification (Figure II.15B).

Step	Eluent	Volume (mL)
Cleaning	H ₂ O	5
Cleaning	6 M HCl	5
Cleaning	H ₂ O	5
Cleaning	1 M HNO ₃	5
Cleaning	H ₂ O	5
Cleaning	1 M HNO ₃	5
Cleaning	H ₂ O	5
Conditioning	6 M HCl	5
Loading	6 M HCl	1 + 1
Discarding	6 M HCl	20
Discarding	0.5 M HCl	10
Zn collecting	1 M HNO ₃	20

Table II-6 - Second elution protocol for Cu purification (Figure II.15C).

Step	Eluent	Volume (mL)
Cleaning	H ₂ O	2
Cleaning	8 M HCl	2
Cleaning	H ₂ O	2
Cleaning	1 M HNO ₃	2
Cleaning	H ₂ O	2
Cleaning	1 M HNO ₃	2
Cleaning	H ₂ O	2
Conditioning	8 M HCl	2 × 2 mL
Loading	8 M HCl + 30% H ₂ O ₂ (20 µL)	1
Rinsing	8 M HCl	2 × 1 mL
Cu collecting	8 M HCl	5 × 2 mL

Table II-7 - Second elution protocol for Pb purification (Figure II.15D).

Step	Eluent	Volume (mL)
Cleaning	H ₂ O	1
Cleaning	0.5 M HBr	1
Cleaning	6 M HCl	1 + 1
Cleaning	H ₂ O	1
Conditioning	0.5 M HBr	1
Loading	0.5 M HBr	1 + 1
Rinsing	0.5 M HBr	1 + 1 + 1
Pb collecting	6 M HCl	2 + 1 + 1

Isotope measurement

Copper, Zn, Fe, and Pb isotope ratios were measured by multiple collector – inductively coupled plasma – mass spectrometry (MC-ICP-MS) using a Nu Plasma II High-Resolution (Nu Instruments, North America). The Nu Plasma II is a cutting-edge scientific device employing advanced magnetic sector technology to achieve unparalleled precision in isotope detection. This instrument combines the high ionization efficiency of “ICP” technology for

nearly all elements with the precision of thermal ionization mass spectrometry equipped with a sensor array (“MC-MS”), enabling simultaneous measurement of isotopes across a wide range of elements (Becker, 2005; E-Store, 2024; Vanhaecke et al., 2009). The isotopic signatures of three certified standard reference materials (basalt BHVO-2, soil SRM-2709a, and apple leaves NIST-1515) were analyzed to evaluate the performance of the protocol.

The isotopic ratios obtained by MC-ICP-MS analysis have been normalized using internationally recognized standard solutions (NIST 976 for Cu, JMC Lyon for Zn and IRMM-014 for Fe). This normalization has two aims: firstly, to ensure consistent and comparable data between the different studies and, secondly, to correct potential measurement biases introduced during mass spectrometry. Consequently, isotope ratios are often expressed using the delta (δ) equation, which facilitates interpretation and communication of results (Hoefs, 2021; Sharp, 2017):

$$\begin{aligned}\delta^{65}\text{Cu} (\text{‰}) &= \left[\frac{(^{65}\text{Cu}/^{63}\text{Cu})_{\text{Sample}}}{(^{65}\text{Cu}/^{63}\text{Cu})_{\text{NIST SRM 976}}} - 1 \right] \times 1000 \\ \delta^{66}\text{Zn} (\text{‰}) &= \left[\frac{(^{66}\text{Zn}/^{64}\text{Zn})_{\text{Sample}}}{(^{66}\text{Zn}/^{64}\text{Zn})_{\text{JMC Lyon}}} - 1 \right] \times 1000 \\ \delta^{56}\text{Fe} (\text{‰}) &= \left[\frac{(^{56}\text{Fe}/^{54}\text{Fe})_{\text{Sample}}}{(^{56}\text{Fe}/^{54}\text{Fe})_{\text{IRMM-014}}} - 1 \right] \times 1000\end{aligned}$$

The difference between two δ values between two samples was characterized by the notation Δ :

$$\Delta^X = \delta_{\text{Sample 1}}^X - \delta_{\text{Sample 2}}^X$$

where X can be Cu, Zn, or Fe.

6. Data processing and statistical analyses

The collected data were subjected to processing (such as data preparation, normalization, visualization, etc.) and statistical analyses.

Raw data were initially cleaned and organized to remove any inconsistencies or errors. This included checking for missing values, outliers, correcting dilutions and ensuring the data was in a suitable format for analysis. All results have been presented in the form of graphs, charts and tables to facilitate interpretation and understanding of trends and data patterns. All graphs, charts, and tables were performed using the *ggplot2* package from R programming language (Wickham, 2016) or the spreadsheet software Excel. For graphical editing, most of the visuals were refined with Inkscape, an open-source vector graphics editor.

Statistical analyses were performed using the software R version 4.0.4 (R Core Team, 2021). The analysis mainly included non-parametric and parametric tests and principal component analysis (PCA). For testing statistically significant differences, the non-parametric Kruskal-Wallis, Wilcoxon or parametric Student's *t*-test tests were applied with a significance level of $\alpha = 0.05$. Subsequently, pairwise comparisons were carried out using the post-hoc Dunn test, also with $\alpha = 0.05$, utilizing the *dunn.test* package (Dinno, 2017). PCA was conducted on element concentrations that were log-ratio transformed using the centered log-ratio transformation (*clr* function from the *rgr* package) to assess correlations between elements (Garrett, 2013).

III. Data chapters

1. Rare earth element transfer in a cover crop⁸

1.1. Abstract

Transfer of trace elements, such as toxic metals, from soil to plant is a cornerstone for risk assessment. Rare earth elements (REE) are frequently used as environmental tracers to understand biogeochemical processes in the soil–plant system. In this study, we combined trace element and REE measurements in the soil–plant continuum to evaluate the element transfer between different compartments. We specifically aimed at: (1) assessing the geochemical relevance and representativeness of intermediate compartments (soil solution and soil water-extract as an approximation of the bioavailable soil fraction) by comparing the REE normalized patterns; and (2) characterizing the environmental conditions that control the trace element transfer by quantifying the REE indices. For that purpose, we compared geochemical signatures in a cover crop (bean, Persian clover, and spelt) in Belgium, including soil, root, shoot, soil solution, soil water-extract, earthworm, and snow samples. Evaluation of the element mobility was performed using both soil extractability and transfer factors. The main result showed dissimilar REE patterns between soil/plant samples and soil solution/soil water-extract samples, indicating that the intermediate compartments (i.e., soil solutions or soil water-extracts) do not chemically represent the bioavailable fraction of elements without obvious propensity to biological accumulation (unlike Cd, Cu, or Zn). Compared to light REE, heavy REE were more extractable and thus transferred to plants unlike what is observed in the literature. According to their different extractabilities, Ce and Eu allowed to highlight distinct transfer from soil to plant due to possible adsorption or organic matter complexation that should be further confirmed by studying contrasted soils.

⁸ Slightly adapted from Arbalestrie et al. (2022) *Biogeochemistry*, 161: 373–38 (doi: 10.1007/s10533-022-00989-7).

1.2. Introduction

Trace elements, whose concentration is below 0.1% in the continental crust, include metals (Cd, Cu, Mn, Ti, V, Zn...) and metalloids (As, Sb...) that may induce potentially harmful effects on human and ecosystem health. The environmental cycling of trace elements depends on both element sources and compartment conditions (Kabata-Pendias, 2011; Rauch and Pacyna, 2009). In agricultural soils, they are originated from (He et al., 2005): (1) natural sources, mainly resulting from parent material alteration according to the mineral composition; and (2) anthropogenic sources, such as organic amendments, fertilizers, and pesticides. Transfer of trace elements from soil to plant, and their recycling by vegetation, involve multiple processes that depend on pedological, biological, or climatic factors, all of them resulting in changes of element speciation. For instance, the main soil-associated factors affecting the trace element availability in soils are soil pH, redox potential, constituent content (both clays and organic matter control the cation exchange capacity), and “aging” of added elements promoting the element scavenging over time (Antoniadis et al., 2017). Moreover, the chemical speciation (cationic vs anionic) and biological role (essential vs non-essential) of the element also control their transfer from soil to plant (Kabata-Pendias, 2011). Yet, environmental and human health concerns depend on the mobility and phytoavailability of these trace elements in the soil–plant system. Soil solution and soil extraction are frequently used as proxies for evaluating this available fraction (Antoniadis et al., 2017; Chojnacka et al., 2005; Kabata-Pendias, 2004), in parallel with element concentrations directly accumulated in plants or concentration ratios between compartments called transfer factors. The choice of the protocol used to collect such solutions, however, highly constrains the interpretation of transfer processes (Di Bonito et al., 2018). Also, concentrations in these compartments alone cannot directly confirm the representativeness of the available fraction. Predicting the actual transfer of trace elements and the related risk assessment still remains complex, encouraging the use of geochemical tracers to identify processes (e.g., adsorption or leaching) that influence the chemical dynamics of elements at the soil–plant interface.

Rare earth elements (REE), also called lanthanides, include 14 natural trace elements divided into light REE (LREE, from La to Eu) and heavy REE (HREE, from Gd to Lu). Sometimes, medium REE (MREE, from Pr or Nd to Dy or Ho)

can be considered as an intermediate class. They are characterized by a similar electronic configuration, including a large ionic radius, a trivalent oxidation state, and a lower electronegativity than those of the transition elements (Henderson, 1984; Laveuf and Cornu, 2009). However, REE behave differently according to their atomic number: for example, LREE are estimated to be more soluble and less complexed than HREE (Cantrell and Byrne, 1987), promoting LREE mobility and availability (Martinez et al., 2018; Monei et al., 2022). Then, root uptake largely depends on element speciation, as well as plant physiology (Tyler, 2004): e.g., LREE seem to be preferentially translocated from roots to shoots, inducing a higher LREE/HREE ratio in shoots. Thus, the comparison of REE concentrations between compartments (soil, plant, solution, etc.) helps to describe the geochemical processes involved at the interfaces. The use of normalized REE patterns allows direct evaluation of relative LREE or HREE enrichment or depletion. Moreover, among REE, Ce and Eu present an extra valence (Ce^{4+} and Eu^{2+} , respectively) that generates positive or negative anomalies after fractionation processes. For example, reduction of Eu (Eu^{3+} to Eu^{2+}) with decreasing redox potential (e.g., in the rhizosphere) improves the Eu mobility in soils, resulting to a positive Eu anomaly in plants while soil presents a negative Eu anomaly (Krzciuk and Gałuszka, 2020).

Thus, REE are helpful to trace biogeochemical processes (adsorption, leaching, redox and pH changes, etc.) in the soil–plant system (Laveuf and Cornu, 2009; Liang et al., 2005). In this study, we aimed at: (1) assessing the geochemical relevance and representativeness of the intermediate compartments (soil solution and soil extract as an approximation of the bioavailable soil fraction) by comparing the REE normalized patterns along the soil–plant continuum; and (2) characterizing the environmental conditions that control the trace element transfer by quantifying the REE indices. For this purpose, we conjointly analyzed trace elements and REE concentrations and compared geochemical signatures in the soil–plant continuum of a cover crop, including soil, root, shoot, soil solution, and soil water-extract samples, and evaluated the element mobility using both soil extractability and transfer factors. We hypothesize that, studying non-hyperaccumulator species in winter (i.e., wet period for soil solution sampling), we should better follow and understand trace elements and REE transfers.

1.3. Materials and methods

1.3.1. Study Area

The study was carried out from September 2020 to March 2021 in a cover crop of ca. 24000 m² (340 m × 70 m) located at the centre Alphonse de Marbaix, Corroy-le-Grand, Belgium (UCLouvain experimental farm, 135 m a.s.l.). The field was covered by Persian clover (*Trifolium resupinatum*) and sorghum (*Sorghum bicolor* × *Sorghum sudanense*) sown at the end of August 2020, as well as bean (*Vicia faba*) and spelt (*Triticum spelta*) regrowth from the previous crop. The study area is characterized by a temperate oceanic climate with a mean annual air temperature of 10.6 °C and a mean annual precipitation of 820 mm (www.meteo.be). It is located on an aeolian loess deposit formation and characterized by silty and well-drained soils, typical agricultural soils found in northern Wallonia. Average soil pH_{KCl} reached 6.2 and 6.1 at 0–30 and 30–50 cm depth, respectively, and soil carbon content, 1.2 and 0.5%, respectively.

1.3.2. Sampling procedure

For representative purposes, soil, plant, and soil solution samples were collected within three distinct sub-areas (ca. 50 m away). In each sub-area that corresponds to a circle of 7 m in diameter, a composite soil sample (i.e., eight sub-samples) was considered at two depths (0–30 cm and 30–50 cm) using an auger. Soil solution samples were collected in each sub-area using 5 rhizons (10-cm long hydrophilic polyether sulphone membrane with a 0.15-µm porosity; 19.21.01F, Rhizosphere, Wageningen, The Netherlands) installed vertically in the top 10 cm of the soil at the circle periphery. Sampling was performed using a 60-mL polypropylene syringe (BD Plastipak luer lock). The five collected samples were merged into a single composite soil solution sample per sub-area to obtain sufficient volume for chemical analysis. Five soil solutions were collected, approximately each month: 21 Oct. 2020, 16 Nov. 2020, 15 Dec. 2020, 14 Jan. 2021, and 4 Feb. 2021.

Plant samples considered three different species grown together: bean (*Vicia faba*), Persian clover (*Trifolium resupinatum*), and spelt (*Triticum spelta*).

Several specimens were collected in each sub-area (within 5 m around the circle center point), considering both roots and shoots, and stored in plastic bags. Plant sampling was performed three times following the plant growth stages: early (16 Oct. 2020), middle (15 Dec. 2020), and late (4 Feb. 2021). Finally, earthworms (including various ecological categories) were sampled on 4 Feb. 2021 by collecting on average 18 specimens per sub-area in the first 10-cm soil depth. To complete the data set, a single sample of unfiltered fresh deposited snow was directly collected on plant leaves on 14 Jan. 2021.

1.3.3. Sample preparation

Collected soil samples were dried (25 °C in a drying room for seven days), sieved (<2 mm), and ground using a soil grinder (Vibratory Disc Mill RS 200, Retsch, Haan, Germany). For plant material, samples were gently cleaned with distilled water to remove as much soil residue as possible and dried in a ventilated oven at room temperature. Shoots were separated from roots before grinding (Cyclotec 1093 Sample Mill, Foss A/S, Hillerød, Denmark). Earthworm samples were washed with distilled water and left on wet paper in Petri dishes for 12 days to evacuate their digestive tract content before being frozen in a freezer at -18 °C, dried in an oven at 40 °C, and ground in a mortar with liquid nitrogen.

Approximately 100 mg of ground soil, plant, and earthworm samples were digested in a Savillex (Teflon bottle) in an ISO 6 cleanroom (Earth and Life Institute, UCLouvain, Belgium) using a mixture of suprapure acids (HNO₃, HCl, and HF) and H₂O₂ in a four-step procedure (Agnan et al., 2013). Heating plate temperature was fixed of 90 °C for heating steps (at least for 24 h) and 40 °C for evaporation steps. Finally, samples were preserved in 2% HNO₃ solutions before analysis. All cleaning and analytical procedures used high purity Milli-Q water (18.2 MΩ cm).

A water extraction was performed on 2 g of soil samples for each sub-area and depth by adding 20 mL of Milli-Q water. The samples were stirred for 2 h and then centrifuged at 4000 rpm for 25 min. Then, samples were filtered, first with 20-μm Whatman paper filters, and then with 0.2-μm GHP Acrodisc (PSF and nylon, Pall). All liquid samples (soil solutions, soil water-extracts, and snow) were acidified to reach 2% HNO₃ before analysis.

1.3.4. Chemical analyses

A set of 11 trace elements (Ba, Cd, Co, Cr, Cu, Mn, Pb, Sr, Ti, V, and Zn) and 14 REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) was quantified using an ICP–MS (iCAP Q ICP–MS, Thermo Fischer Scientific, Waltham, MA, USA) at the Earth and Life Institute analytical platform (MOCA, UCLouvain, Belgium). Common interferences were automatically corrected after analytical tests (e.g., Pourret et al., 2021). An internal standard (Ru, In, and Re) was used in each sample for drift instrumental correction. In order to evaluate the performance of the procedure for organic and mineral matrices, two certified materials well characterized for REE concentrations (lichen IAEA-336 and basalt BHVO-2, respectively) were added for each series. The average recovery ($C_{\text{measured}} / C_{\text{certified}} \times 100$) calculated for each analyte was approximately: (1) $90 \pm 5\%$ for the lichen IAEA-336, except for Ti ($110 \pm 5\%$), for Cd, Cr, Gd, Mn, Pr, V, and Zn ($100 \pm 5\%$), for Er, Ho, Pb, and Tm ($80 \pm 5\%$), and for Lu ($70 \pm 5\%$); and (2) $90 \pm 5\%$ for the basalt BHVO-2, except for Cr, and V ($110 \pm 5\%$), for Ba, Co, Cu, La, Ti, and Zn ($100 \pm 5\%$), and for Ho ($80 \pm 5\%$). The blank samples were on average $0.005\text{--}252 \text{ ng L}^{-1}$ according to the element (Er to Ti, respectively), which represented $<1\%$ of the sample concentration analyzed (except for Cd and Ti with 2%). Limits of detection were estimated to $<1 \text{ ng kg}^{-1}$, except for Cr, Cu, Mn, Pb, Sr, and V ($<0.01 \text{ } \mu\text{g kg}^{-1}$), for Ba and Zn ($<0.1 \text{ } \mu\text{g kg}^{-1}$), and for Ti ($<1 \text{ } \mu\text{g kg}^{-1}$).

1.3.5. Data processing and statistical analyses

To evaluate the transfer of elements between compartments, two indices were considered (Adriano, 2001; Antoniadis et al., 2017; Marchiol et al., 2004): the transfer factor from soil to plant ($\text{TF}_{\text{soil-plant}}$) and the transfer factor from root to shoot ($\text{TF}_{\text{root-shoot}}$), calculated as follows:

$$\text{TF}_{\text{soil-plant}} = \frac{C_{\text{shoot}}}{C_{\text{soil}}}$$
$$\text{TF}_{\text{root-shoot}} = \frac{C_{\text{shoot}}}{C_{\text{root}}}$$

with C_{shoot} , C_{root} , and C_{soil} , the element concentrations in shoot, root, and soil, respectively.

Rare earth elements were presented as normalized profiles as done in the literature using: (1) UCC (upper continental crust; Rudnick and Gao, 2014) reference material for soil samples (Cidu et al., 2013); (2) soil (0–30 cm depth) for soil water-extract (except for soil water-extract samples from 30–50 cm depth normalized by 30–50 cm soil depth), plant, soil solution, and earthworm samples (Brioschi et al., 2013) for a better comparison; and (3) snow samples for soil solution samples to evaluate the potential atmospheric input. To facilitate comparisons, all graphs were performed using the same log scale. Several REE indices frequently used in the literature were calculated based on measured concentrations (Agnan et al., 2014; Miao et al., 2008; Wyttenbach et al., 1998): Ce, Eu, Tb, and Yb anomalies calculated by dividing the normalized value by the expected value (obtained by averaging the values of the elements immediately prior and after), and LREE/HREE ratio using the following normalized concentration ratio:

$$\frac{\text{LREE}}{\text{HREE}} = \frac{(\text{La} + \text{Ce} + \text{Pr} + \text{Nd} + \text{Sm} + \text{Eu})/6}{(\text{Gd} + \text{Tb} + \text{Dy} + \text{Ho} + \text{Er} + \text{Tm} + \text{Yb} + \text{Lu})/8}$$

We only considered REE anomalies if >1.2 or <0.8 and we evaluated the average relative standard deviations to 8, 5, 4, and 3% for Ce, Eu, Tb, and Yb anomalies, respectively. Statistical tests were performed using R 4.0.4 (R Core Team, 2021). Statistically significant differences were tested using the non-parametric Kruskal-Wallis test ($\alpha = 0.05$) and the post-hoc Dunn test ($\alpha = 0.05$) with the *dunn.test* package (Dinno, 2017). Principal component analyses (PCA) were performed to identify the relationships between elements using FactoMineR and factoextra packages (Lê et al., 2008) on element concentrations after centered log-ratio transformation (*clr* function) using *rgr* package (Garrett, 2013). Scatter plots were performed using the *ggplot2* package (Wickham, 2016).

1.4. Results

1.4.1. Trace elements

Trace element concentrations

Trace element concentrations (Table III-1) showed higher values in soil samples compared to other compartments, ranging from Cd (on average, 0.33 and 0.18 mg kg⁻¹ at 0–30 and 30–50 cm soil depth, respectively) to Ti (2030 and 2606 mg kg⁻¹, respectively). In plant samples, trace elements were, on average, 3-times more concentrated in roots compared to shoots and still ranged from Cd (0.41 and 0.08 mg kg⁻¹ in roots and shoots, respectively) to Ti (301 and 114 mg kg⁻¹, respectively). Soil water-extract samples showed increasing concentrations from Cd (0.08 and 0.04 µg kg⁻¹ at 0–30 and 30–50 cm depth, respectively) to Ba (136 and 62.3 µg kg⁻¹, respectively). They represented 0.01–1.9‰ of the soil element concentrations. Concentrations in soil solutions ranged from Cd (0.02 µg L⁻¹) to Zn (160 µg L⁻¹) with noticeable heterogeneity between sampling dates (average relative standard deviation of 47%). The soil solution/soil ratios had the same element order as observed for soil extractability. In general, soil solutions were more concentrated than snow sample, except for Cd, Cr, Mn, Pb, and Ti. Finally, earthworm samples showed lower concentrations than shoots, except for Cd, Co, and Zn.

Table III-1 - Summary table (means and standard deviations) of trace element and sum of rare earth element (Σ REE) concentrations for each compartment sampled at the centre de Marbaix.

Matrix		n	Ba	Cd	Co	Cr	Cu	Mn	Pb	Sr	Ti	V	Zn	Σ REE
			<i>mg kg⁻¹</i>											
Soil	0–30 cm	3	230 (10.3)	0.33 (0.03)	9.01 (0.64)	58.0 (3.65)	13.7 (1.33)	315 (21.3)	21.4 (1.20)	37.7 (2.15)	2030 (399)	64.3 (5.28)	45.8 (0.94)	111 (14.2)
	30–50 cm	3	226 (9.29)	0.18 (0.03)	9.31 (1.57)	62.8 (2.83)	12.2 (1.49)	263 (87.5)	15.1 (1.18)	32.0 (6.07)	2610 (419)	64.5 (7.41)	36.0 (2.71)	106 (10.4)
Plant	shoot	27	20.4 (12.0)	0.08 (0.09)	0.51 (0.39)	6.70 (4.80)	8.25 (2.38)	44.5 (21.2)	1.36 (1.16)	18.0 (7.47)	114 (108)	3.74 (4.02)	40.1 (12.8)	7.93 (6.84)
	root	27	61.2 (25.2)	0.41 (0.18)	1.83 (0.75)	26.1 (27.5)	15.8 (5.64)	101 (39.5)	4.99 (3.40)	27.4 (7.26)	301 (227)	15.6 (6.26)	56.5 (36.6)	28.9 (12.4)
Earthworm		3	2.61 (0.56)	6.47 (0.78)	3.50 (0.79)	0.68 (0.08)	7.16 (0.17)	19.7 (11.0)	0.47 (0.20)	8.46 (3.06)	13.7 (1.04)	0.71 (0.01)	335 (9.15)	1.07 (0.19)
			<i>μg kg⁻¹</i>											
Soil water-extract	0–30 cm	3	136 (109)	0.08 (0.03)	0.28 (0.17)	1.82 (1.04)	8.31 (1.11)	13.0 (10.3)	1.21 (1.52)	11.8 (1.34)	20.8 (12.0)	9.44 (2.08)	87.2 (79.7)	4.95 (3.86)
	30–50 cm	3	62.3 (67.2)	0.04 (0.02)	0.46 (0.21)	3.49 (1.34)	4.11 (1.12)	16.8 (14.2)	1.21 (0.97)	9.62 (1.97)	59.8 (18.2)	5.49 (3.35)	26.9 (32.7)	13.2 (10.3)
			<i>μg L⁻¹</i>											
Soil solution		15	22.6 (7.05)	0.02 (0.00)	0.16 (0.04)	0.47 (0.12)	5.00 (2.04)	2.46 (2.13)	0.08 (0.13)	79.4 (9.48)	0.82 (0.85)	2.90 (0.55)	160 (85.5)	0.40 (0.32)
Snow		1	1.69	0.03	0.10	0.66	2.75	9.73	1.24	1.48	1.84	0.43	33.7	0.86

Trace element transfer factors

Transfer factors ($TF_{\text{soil-plant}}$ and $TF_{\text{root-shoot}}$) were calculated for each trace element and each sampling date in *Trifolium resupinatum*, *Vicia faba*, and *Triticum spelta* (Figure III.1). The transfer from soil to *Trifolium resupinatum* showed significant differences between elements, including Ti, V, Pb, Co, and Cr with the minimum values ($TF_{\text{soil-plant}} < 0.05$) and Zn, Sr, and Cu with the maximum values ($TF_{\text{soil-plant}} > 0.5$) for the first sampling date (Figure III.1A). Statistically significant differences were observed with increasing $TF_{\text{soil-plant}}$ over time (>2 times for half of the elements, and up to >20 times for Ti), except for Cd and Sr where no evolution was evidenced. Zinc showed a singular pattern with higher $TF_{\text{soil-plant}}$ during the early season. The transfer from root to shoot showed more consistent pattern, both between trace elements and sampling dates (Figure III.1B). Cadmium, however, appeared as the lowest translocated element. $TF_{\text{root-shoot}}$ were generally higher than $TF_{\text{soil-plant}}$, except for Cd, Cu, and Zn. The two other plant species showed similar patterns for both factors, with higher heterogeneity for *Triticum spelta* (Figure III.1C–F).

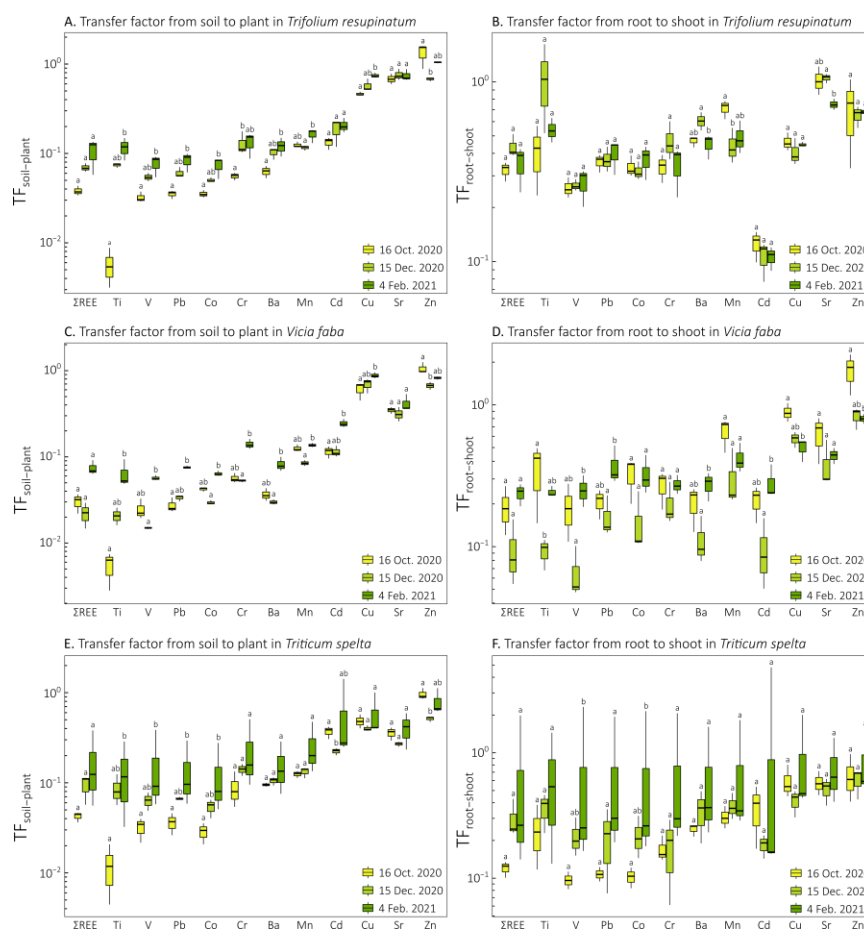


Figure III.1 - Transfer factors from soil to plant (TF_{soil-plant}; A, C, and E) and from root to shoot (TF_{root-shoot}; B, D, and F) of trace elements and sum of rare earth elements (ΣREE) in Persian clover (*Trifolium resupinatum*; A and B), bean (*Vicia faba*; C and D), and spelt (*Triticum spelta*; E and F) collected at three sampling dates at the centre de Marbaix. Letters indicate statistically significant differences between sampling dates.

Trace element relationships

The first component of the PCA (54% of data variance; Figure III.2A) was influenced by Sr, Zn, Cu, and Ba (positive scores) and Ti, Pb, Mn, and Cr (negative scores). This dimension opposed soil solutions and, to a lesser extent, soil water extracts (0–30 cm depth) with positive scores and soil samples with negative scores. Also, plant samples have essentially negative scores. The second component (22% of data variance) grouped V and Ba (positive scores) in opposition to Cd and, to a lesser extent, Co

(negative scores). Earthworm samples mostly drove this dimension with negative scores, mainly influenced by Cd concentrations.

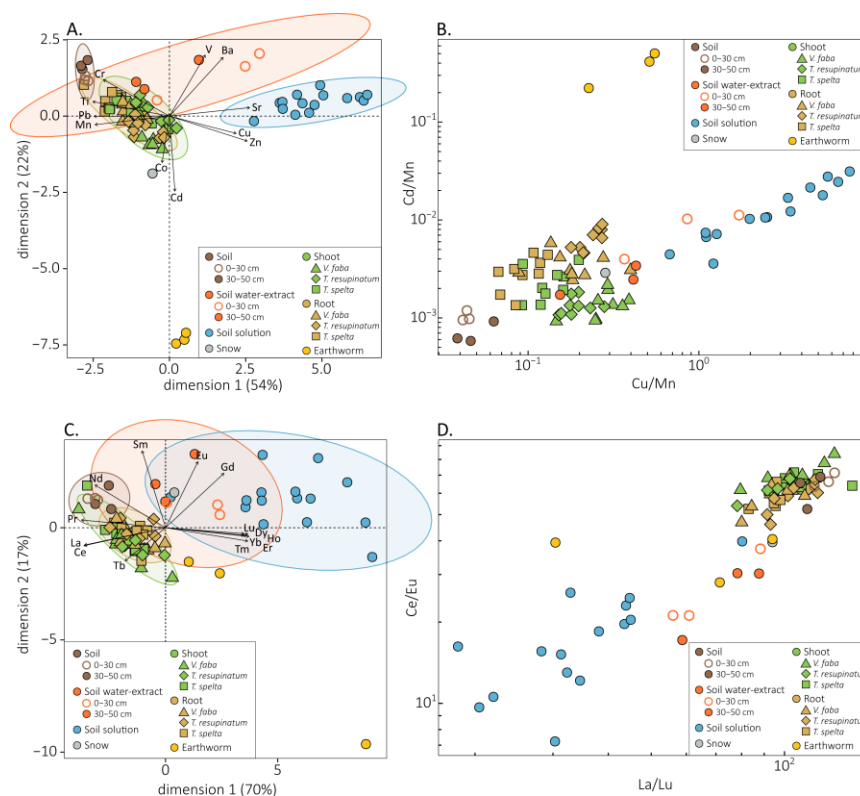


Figure III.2 - Principal component analysis of log-ratio transformed trace element (A) and rare earth element (C) concentrations and element ratios Cd/Mn vs Cu/Mn (B) and Ce/Eu vs La/Lu (D) in samples collected at the centre de Marbaix.

Based on the PCA, we considered contrasting elements (Cd, Cu, and Mn) to plot relationships between trace elements for all compartments: Cd/Mn vs Cu/Mn (Figure III.2B). Two main end-members emerged: soils (with low Cd/Mn and Cu/Mn ratios) and soil solutions (with higher ratios and higher heterogeneity). Soil water extract samples showed an intermediate signature with lower ratios in the 30–50 cm depth. Despite that plant samples fell in-between the two end-members, they presented a fractionation with higher relative Cd/Mn ratios for roots and higher relative Cu/Mn ratios for shoots. Distribution of plant samples discriminated plant species, particularly for root samples with *Triticum spelta* closer to the soil end-member and *Trifolium resupinatum* closer to the soil solution end-member. Finally, earthworm samples had higher Cd/Mn ratios than all other compartments (from 40 to 500 times for soil

solutions and soils, respectively) and the snow sample was located between the two previously mentioned end-members.

1.4.2. Rare earth elements

Rare earth element concentrations and transfer factors

Total REE (Σ REE) showed decreasing concentrations in the following order (Table III-1): soil (111 mg kg^{-1} at 0–30 cm soil depth) > root > shoot > earthworm (1.07 mg kg^{-1}). Soil water-extract samples represented 0.04 and 0.12% of soil Σ REE concentrations at 0–30 and 30–50 cm depths, respectively (soil Σ REE concentrations about 2.7-times higher at 30–50 cm depth). Heavy REE were 42 and 36% more extractable than LREE at 0–30 and 30–50 cm depths, respectively. Moreover, REE extractability was in the same range as Ti, Co, Cr, Mn, and Pb. Soil solutions had Σ REE concentrations of $0.40 \mu\text{g L}^{-1}$, corresponding to half of the snow sample Σ REE concentrations. The soil solution/soil REE concentration ratios showed similar trends as observed for soil water-extract/soil, with increasing ratios of 90% from LREE to HREE. However, it is noteworthy that Ce was relatively less extractable (16 and 38% at 0–30 and 30–50 cm depth, respectively) and Eu relatively more extractable (30 and 18%, respectively) compared to their neighboring elements in the periodic table.

The REE transfer from soil to *Trifolium resupinatum* showed similar pattern as observed for trace elements with increasing $\text{TF}_{\text{soil-plant}}$ over time, despite no statistically significant difference (Figure III.1A). The $\text{TF}_{\text{soil-plant}}$ measured for REE (from 0.04 to 0.14 according to the element and sampling date) were close to those of Ti, V, Pb, Co, Cr, or Ba. However, distinct behaviors appeared with increasing $\text{TF}_{\text{soil-plant}}$ of 20% from LREE to HREE. The REE $\text{TF}_{\text{root-shoot}}$ in *Trifolium resupinatum* showed consistent pattern between sampling dates as for the trace elements (Figure III.1B). Similar trends were observed for *Vicia faba* and *Triticum spelta* (Figure III.1C–F).

REE normalized patterns of soil and soil water-extract samples

UCC-normalized REE patterns were studied at both 0–30 and 30–50 cm depths (Figure III.3A). Results showed similar patterns for the three sub-areas. We thus averaged sub-areas in the following results. The

comparison between the two soil depths also showed similar patterns, despite statistically significant higher ($p < 0.05$) LREE/HREE ratios in the topsoil (on average, 1.24) than in the subsoil (1.18). Both REE patterns, however, showed a negative Eu anomaly (on average, 0.80 and 0.82 at 0–30 and 30–50 cm depth, respectively).

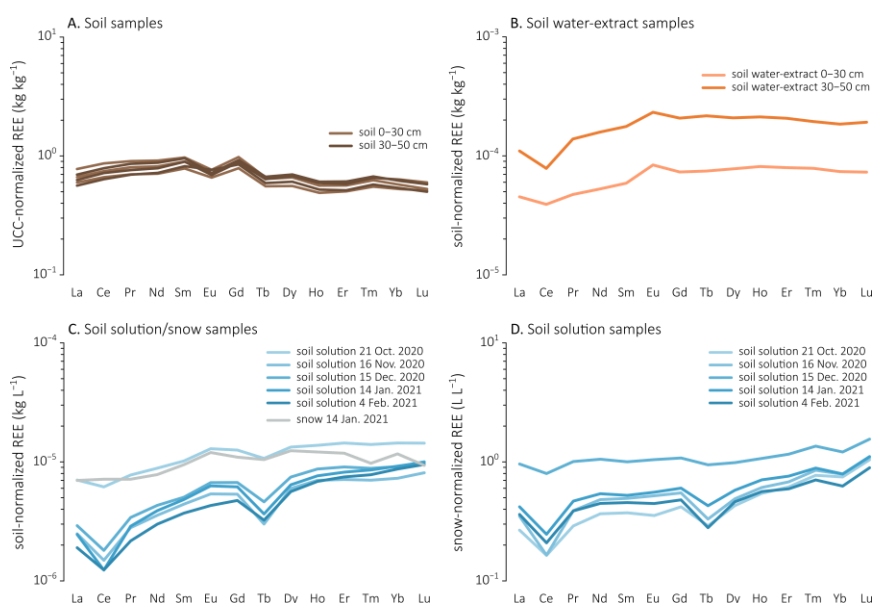


Figure III.3 - Normalized profiles of rare earth elements (REE) from samples collected at the centre de Marbaix: UCC-normalized soil profiles (A), soil-normalized soil water-extract profiles (B), soil-normalized soil solution and snow profiles (C), and snow-normalized soil solution profiles (D).

The soil water-extract samples, normalized by the corresponding soil horizon (0–30 and 30–50 cm depth), showed distinct REE behaviors than soil samples (Figure III.3B): relative MREE enrichment, LREE/HREE ratios < 1 , negative Ce anomaly, and positive Eu anomaly. Although soil water-extract REE patterns were similar between both soil depths, the negative Ce anomaly was more pronounced at 30–50 cm depth (on average, 0.63) compared to 0–30 cm depth (0.85).

REE normalized patterns of soil solution and snow samples

All soil solution samples showed similar soil-normalized REE patterns (Figure III.3C), including negative Ce anomaly (on average, 0.61), negative Tb anomaly (0.64), and low LREE/HREE ratios (0.51). These characteristics were not fully observed in soils (Figure III.3A) nor soil water-extracts (Figure III.3B). Only the soil solutions collected on 15 Dec. 2020 was

slightly different from the other samples, with 2.7-times higher Σ REE concentrations and 1.5-times less pronounced negative Ce anomaly.

The only snow sample collected on 14 Jan. 2021 showed distinct REE pattern to soil solutions: no obvious negative Ce and Tb anomalies and no relative HREE enrichment (Figure III.3C). We thus normalized soil solution samples to the snow concentrations to highlight differences between these two compartments (Figure III.3D). Therefore, snow-normalized REE profiles still showed negative Ce (on average, 0.59) and Tb (0.72) anomalies and presented a low negative Yb anomaly (0.81). Beside these anomalies, the REE profiles were relatively flat with the exception of the last HREE (Tm to Lu): LREE/HREE of 0.68.

REE normalized patterns of plant and earthworm samples

Soil-normalized REE patterns of plant samples showed similar trends between considered species and parts of plant without noticeable anomaly (Figure III.4A-C). Despite relatively flat profiles, all REE patterns showed a relative MREE depletion, modifying the LREE/HREE ratio (on average, 0.86 for shoots and 0.83 for roots). However, REE concentrations highlighted systematic higher values in roots compared to shoots (on average, 6.0 times for *Vicia faba*, 2.7 times for *Trifolium resupinatum*, and 3.4 times for *Triticum spelta*). Also, REE concentrations increased over time in shoots (except for *Vicia faba*) and roots (except for *Triticum spelta*). The increasing ratios, from the first sampling date to the last one, were between 2.5 and 4.1 for shoots according to the species. The respective ratios for roots were either lower (from 1.8 to 2.4) or showed no evolution over time (*Triticum spelta*).

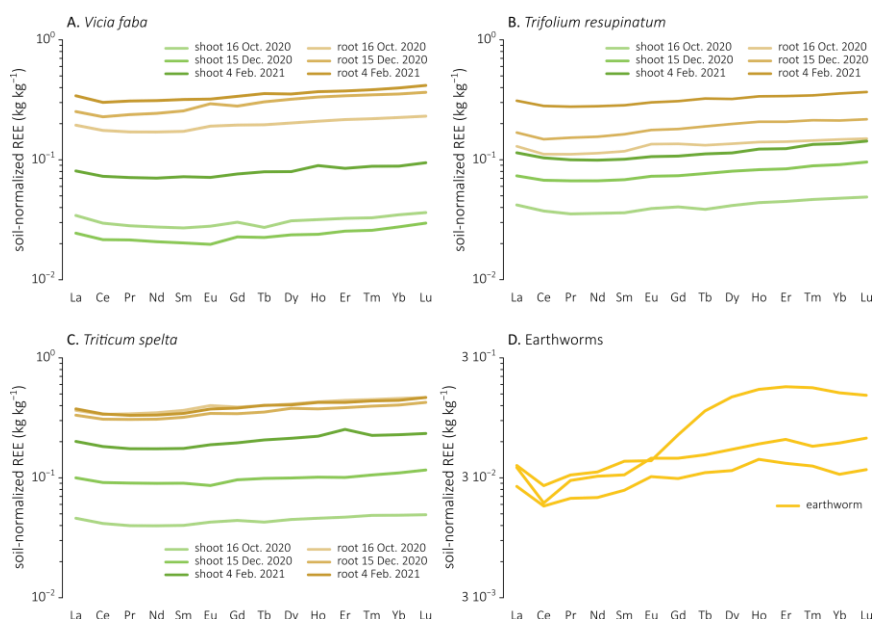


Figure III.4 - Soil-normalized profiles of rare earth elements (REE) from plant (shoot and root) and earthworm samples collected at the centre de Marbaix: bean (*Vicia faba*; A), Persian clover (*Trifolium resupinatum*; B), spelt (*Triticum spelta*; C), and earthworms (D).

Earthworms collected in each sub-area indicated different soil-normalized REE patterns than the other compartments considered (Figure III.4D): low LREE/HREE ratios (0.49) and negative Ce anomaly (0.69) as observed in soil solution samples, but no pronounced negative Tb anomaly. One composite sample (i.e., a sub-area) showed singular REE pattern with higher relative HREE concentrations and more pronounced negative Eu anomaly (0.76).

Rare earth element relationships

As for trace elements, a PCA was performed on REE concentrations (Figure III.2C). The first component (70% of data variance) was influenced by Dy, Er, Ho, Yb, Lu, and Tm (positive scores) and Pr, La, Ce, and Nd (negative scores). As observed on the first PCA (Figure III.2A), soil solutions and, to a lesser extent, 0–30 cm soil water-extracts (positive scores), were opposed to soil samples (negative scores). Also, the REE signatures of plants and soils were closer compared to the trace elements. The second component (17% of data variance) grouped Sm, Eu, Gd, and, to a lesser extent, Nd (positive scores).

Based on these results, we plotted the relationship between Ce/Eu (proxy of both Ce and Eu anomalies) and La/Lu (proxy of LREE/HREE fractionation) for all samples collected in this study (Figure III.2D). Once again, soil solutions (relatively low Ce/Eu and La/Lu) and soils (relatively high Ce/Eu and La/Lu) were the two main end-members. Plant signatures were close to soil ones (despite lower Ce/Eu and La/Lu), and their distribution was neither related to sampling dates nor plant species unlike for trace elements. Yet, shoots showed higher relative Ce/Eu ratio than roots, resulting in a discrepancy from the linear relationship between the two main end-members. Soil water-extract samples showed an intermediate signature despite lower relative Ce/Eu ratio. Finally, earthworm samples presented a high heterogeneity and the snow sample had a signature between soil and soil water-extract samples.

1.5. Discussion

1.5.1. Transfer of trace elements from soil to plant

Trace elements concentrations measured in soil and plant samples (Table III-1) were in the same order of magnitude as observed in the literature (Antoniadis et al., 2017; He et al., 2005; Kabata-Pendias, 2011). Their transfer from soil to plant was investigated using two transfer factors ($TF_{\text{soil-plant}}$ and $TF_{\text{root-shoot}}$; Figure III.1) that were in the same range as those found in Senesil et al. (1999). Although these transfers depended on sampling date, we distinguished, as expected, weakly transferred elements (including elements without or with low physiological role, such as Ti, V, Pb, and Co) from highly transferred ones (including plant nutrients, such as Zn and Cu, or Sr following the metabolic pathway of Ca). The physicochemical behavior of the considered element also influenced its transfer: for example, Cd had $TF_{\text{soil-plant}}$ 3-times greater than Pb due to its higher soil mobility and phytoavailability (Angelova et al., 2004). The uptake of essential elements followed the nutritional requirement, as observed for Zn with higher transfer from soil to roots and/or stem at the beginning of the growth (Nan et al., 2002; Wu et al., 2010), unlike continuous transfer over time for the other elements. The influence of plant species was observed in the trace element ratios where root samples of *Triticum spelta* were closer to the soil end-member than

Trifolium resupinatum (Figure III.1B). Differences between species (lower relative Cu and Cd accumulation in *Triticum spelta* compared to Mn) could be explained by low acquisition efficiency for some elements in monocotyledon compared to dicotyledon (Wiche et al., 2016b). Note that cover crop promotes the accumulation of trace elements and REE in plants.

The soil–plant transferability coincided with the soil extractability assessed using soil water-extract/soil concentration ratios (except for Mn and V; Table III-1). Similar patterns were evidenced for soil solution/soil concentration ratios, indicating geochemical commonalities between soil water-extracts and soil solutions: the more extractable an element is, the more it is present in the soil solution. The transfer from root to shoot, however, highlighted a lower heterogeneity among trace elements (mean $TF_{\text{root-shoot}}$ between 0.15 and 1.06 for *Trifolium resupinatum*) compared to $TF_{\text{soil-plant}}$ (except for Cd with $TF_{\text{root-shoot}} < 0.13$ due to high root accumulation; Green et al., 2006). Note that we cannot exclude any soil particle contamination in root samples (Han et al., 2005), which could explain high concentrations for lithogenic elements (e.g., Ti), but this does not prevent species differences observed in roots for both essential and non-essential elements (Figure III.1B).

The PCA and element relationships (Figure III.2A-B) indicate that the compartments considered behaved differently: (1) soils and soil solutions were the two end-members of this system in which both plants and soil water-extracts were located somewhere in between; (2) the different signatures of roots and shoots highlight distinct soil–root–shoot transfer processes (high Cu uptake by plant and transfer to shoot vs Cd accumulation in roots; Figure III.1), resulting in a discrepancy from the soil–soil solution linear relationship; and (3) soil solutions and soil water-extracts were highly heterogeneous according to the sampling date, sub-area, or soil depth.

1.5.2. Rare earth elements: implications for the soil–plant transfer understanding

Soil ΣREE concentrations measured in this study (111 mg kg^{-1} ; Table III-1) were in the same range as observed in European soils (about 126 mg kg^{-1} ; Fedele et al., 2008; Mihajlovic and Rinklebe, 2018). We also noticed low

spatial heterogeneity across the study area with similar soil Σ REE concentrations and REE patterns (Figure III.3A). However, all parts of plants showed an obvious concentration increase over time (up to 4 times; Figure III.4A-C), which reveals the element accumulation with time, as observed for trace elements (Figure III.1). The $TF_{\text{soil-plant}}$ of REE (on average, 0.07, close to data reported by Tyler, 2004) were comparable to values calculated for V, Pb, or Co, although REE did not correctly represent elements largely accumulated in roots (e.g., Cd) nor transferred to shoot (e.g., Cu or Zn). However, no species influence was observed for REE distribution unlike trace elements. Note that the mixing ratio of plant species in a cover crop do not significantly influence the REE accumulation (Wiche et al., 2016a). Due to higher soil–root transfer than root–shoot transfer, however, root REE concentrations were higher than shoot ones, as frequently reported in various crop species (Li et al., 1998; Lihong et al., 1999; Xu et al., 2002).

Despite similar trends between soil solutions and soil water-extracts, resulting to a linear relationship between soil extractability (i.e., soil water-extract/soil concentration ratio) and soil solution/soil concentration ratios (Figure III.5A), soil extractability does not appear as relevant compartments of element bioavailability and effective transfer from soil to plant (heterogeneous distribution of elements; Figure III.5B). Indeed, even if the most extractable elements were generally the most transferred from soil to plant, some exceptions occurred: relatively lower transfer for Ba, Cd, and V and higher transfer for Ti and Sr compared to their extractability. This was also evidenced by dissimilar REE patterns between soil/plant samples and soil solution/soil water-extract samples (Figure III.3 and Figure III.4), including distinct REE indices (Figure III.2C-D). This highlights that the plant REE composition is largely determined by the soil REE composition, while the intermediate compartments (i.e., soil solutions and soil water-extracts) do not represent the bioavailable chemical fraction. The large heterogeneity of these signatures with space (soil solutions and soil water-extracts) and time (soil solutions) may result from different soil chemistry or a sampling protocol bias (pF 3.46 using a 60 mL syringe with rhizons, likely including both capillary and gravitational water; Di Bonito et al., 2018), respectively. Indeed, the latter might be influenced by atmospheric deposition that would modify the chemical composition (e.g., the strong negative Tb anomaly in soil solution samples also present in the snow sample; Figure III.3C-D).

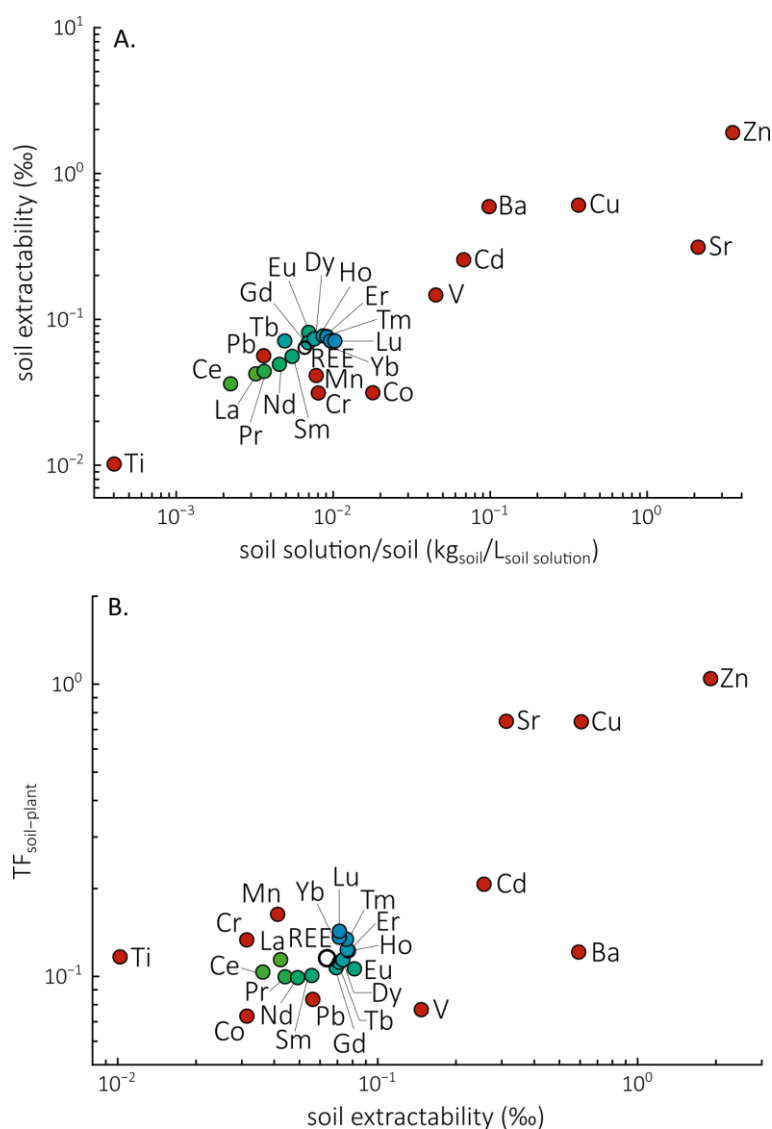


Figure III.5 - Relationship between soil extractability (soil water-extract/soil concentration ratio, 0–30 cm soil depth) and soil solution/soil concentration ratio (A) and between soil–plant transfer ($\text{TF}_{\text{soil-plant}}$) and soil extractability (B) of trace elements (red) and rare earth elements (REE, from green for LREE to blue for HREE), as well as the average REE (open circle), in a cover crop soil–plant system.

Distinct behaviors between LREE and HREE throughout the soil–plant system indicate higher HREE extractability (+42% for the topsoil), occurrence in soil solution (+90% after soil-normalization), and soil–plant transfer (+20% from the topsoil) compared to LREE. This contrasts with the higher HREE sorption on soil particles, especially on organic matters, reported in the literature (Martinez et al., 2018; Stille et al., 2006; Tyler,

2004). This discrepancy may result from distinct metal loading between LREE and HREE (Marsac et al., 2010) and we suggest that this slightly retained HREE serve as a bioavailable pool for plants, limiting HREE leaching (Figure III.5B). We hypothesize that: (1) REE fractionation is limited in the plant species studied (cover crop species); and/or (2) the relative non-enrichment of HREE in the soils studied limits this fractionation. As for LREE and HREE, Ce and Eu depicted diametrically opposed soil extractability ($Ce \ll Eu$), despite no $TF_{soil-plant}$ difference (Figure III.5). The difference of negative Ce anomaly between 0–30 and 30–50 cm soil water-extracts (Figure III.5B) may be explained by a higher Fe and Mn oxyhydroxides content in the deeper soil horizon that promote a Ce^{4+} adsorption (Brioschi et al., 2013). This is supported by the negative Ce anomaly in soil-normalized soil solution profiles (i.e., Ce relatively less soluble; Figure III.3), while plants can dissolved Fe and Mn oxyhydroxides in the rhizosphere and accumulated Ce^{4+} , preventing the negative Ce anomaly in soil-normalized plant profiles (Figure III.4; Cidu et al., 2013; Laveuf and Cornu, 2009; Pédrot et al., 2008).

All geochemical behaviors of REE between compartments in the soil–plant continuum studied and gaps identified were summarized in the Figure III.6, including comparison between UCC-normalized patterns.

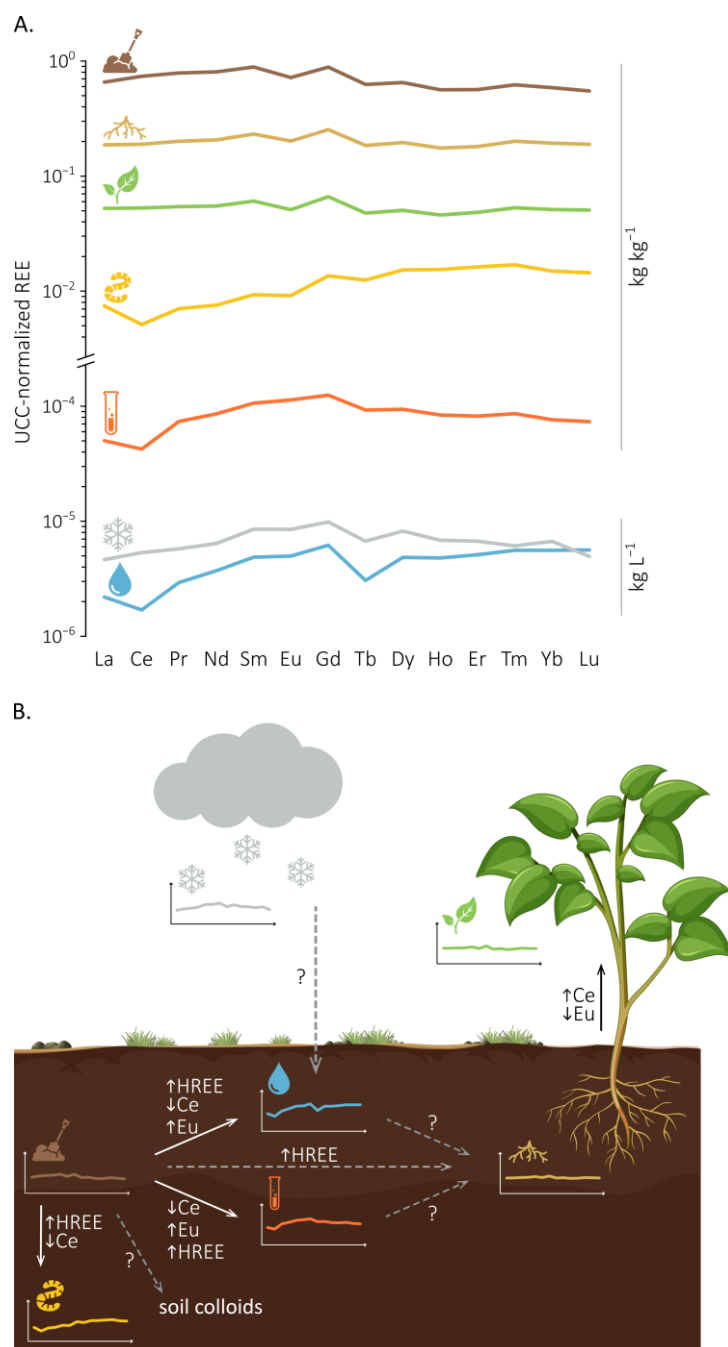


Figure III.6 - Synthesis of rare earth element (REE) transfer in a cover crop soil–plant system: UCC-normalized REE patterns of the different compartments considered (A) and hypothetical chemical relationships between compartments (B).

1.6. Conclusion

This paper aimed at evaluating the geochemical relevance and representativeness of soil solution and soil water-extract as intermediate compartments in the transfer of trace element from soil to plant. For that purpose, we compared REE normalized patterns along the soil–plant continuum. The main result showed dissimilar REE patterns between soil/plant samples and soil solution/soil water-extract samples, meaning that these intermediate compartments in the soil–plant system do not appear as relevant compartments for the element bioavailability. This confirms that is mentioned in the literature for trace elements, considering a set of elements without obvious propensity to biological accumulation (unlike Cd, Cu, or Zn). Moreover, REE distribution evidenced distinct extractability and transferability despite their similar chemical characteristics. We thus characterized the environmental conditions that may control trace element transfer by quantifying the REE indices. LREE/HREE ratios and Ce and Eu anomalies highlighted distinct processes between soil-to-soil solution and soil-to-plant thanks to possible adsorption on soil particles. This should be further confirmed by studying contrasted soils.

2. Challenges in assessing trace element transfer

2.1. Abstract

Trace elements can be either essential or toxic to living organisms depending on their concentration and chemical form. Their multiple physico-chemical properties and sources make their transfer from soil to plant complex to estimate. Yet, predicting their accumulation in plants intended for human consumption remains essential to limit health risks, particularly in highly concentrated soils. To address this challenge, scientists used geochemical compartments to better reflect the plant-available soil fraction. This study aimed to evaluate the relevance of three plant-available trace element compartments (soil solution, soil-water extract, and exchangeable fraction from a three-step sequential extraction) using both concentration measurements and geochemical tracers (rare earth elements, REE) in agroecosystems with varying environmental contexts and contamination levels. A greenhouse experiment was conducted using maize grown on four different agricultural soils over a 90-day period. The results indicated that transfer factors varied significantly depending on both the element and soil considered, with a decreasing value with higher contamination levels, suggesting a possible biological saturation mechanism during root uptake. The comparison of the three compartments revealed that: (1) the soil solution had higher transfer potential but exhibited considerable variability among the elements, potentially overestimating the transfer of highly mobile elements and being susceptible to contamination from irrigation water; (2) the soil-water extract was geochemically more representative of the soil-plant interface but had similar transfer characteristics to the soil solution; and (3) the exchangeable fraction showed nearly uniform transfer characteristics across the elements for a given soil. Finally, REE patterns supported these findings, indicating that soil-water extracts and the exchangeable fraction are the most reliable compartments for predicting soil-plant transfer.

2.2. Introduction

Trace elements are chemical elements whose concentration in the continental crust is less than 0.1%, including transition metals (Cd, Cr, Cu, Mn, Ni, Ti, V, Zn), post-transition metals (Pb, Sn), metalloids (As and Sb), non-metals (Se), and lanthanides (rare earth elements, REE). The diversity of their physico-chemical behavior (solubility, volatility, adsorption, complexation, etc.) and their multiple sources make it particularly complex to trace them and thus to understand their dynamics from one geochemical compartment to another. In agricultural soils, these elements have two types of sources (He et al., 2005): (1) parent material weathering with specific trace element contents depending on the rock nature (lithological source; Adriano, 2001; Kabata-Pendias, 2011); and (2) various anthropogenic inputs, such as organic amendments, fertilizers that are sources of Cd and Zn, and phytosanitary products with Cu as a fungicide (Komárek et al., 2013; Lambert et al., 2007).

Some trace elements are essential for many biochemical reactions in organisms, but all can become toxic above a certain concentration threshold (Alloway, 2012), with consequences for ecosystems and human health. However, their dynamics in the soil–plant system are not fully understood, in particular the factors favoring their retention or transfer in agroecosystems that are the basis of human nutrition. Indeed, increased retention of essential elements on the solid fraction of the soil limits bioavailability and is therefore a source of deficiencies for human populations. Conversely, mobilization of potentially harmful elements through the soil solution favors toxicity for living organisms. There is therefore a balance between these two antagonistic processes which differs according to the element considered (He et al., 2005). For instance, Se contributes to nutritional deficiencies resulting from low levels in some soils (Sharma et al., 2015; Winkel et al., 2015), a trend that tends to accelerate with current climate change according to projection results (Jones et al., 2017). Furthermore, most research is limited to understanding the transfer of trace elements in highly contaminated soils by anthropogenic sources (industrial wastelands, mining sites, etc.) through remediation studies (Houben et al., 2012), excluding uncontaminated, contaminated, or naturally-enriched cultivated soils where soil–plant transfer studies are all the more necessary in a human health and environmental context.

Both soil and plant characteristics, along with climate conditions, influence trace element availability and transfer in agroecosystems (Chojnacka et al., 2005). Antoniadis et al. (2017) distinguished soil variables (pH, redox potential, constituents, etc.) from plant variables (root exudates, selective uptake, translocation pathways, etc.) as the main soil–plant-associated factors affecting the trace element availability from soil to plant. The challenge of adequately measuring all these factors has led to the chemical transfer assessment initially through the transfer factor, comparing element contents between soil and plant, but without considering the fraction available to plants (Mirecki et al., 2015). Subsequently, the use of geochemical compartments, such as through soil solutions (Kabata-Pendias, 2004; Smethurst, 2000) or soil extracts (Chojnacka et al., 2005), allows to focus specifically on the bioavailable fraction (Kumpiene et al., 2017), providing a better representation of the soil–plant transfer. These compartments, however, reflect distinct behaviors making their geochemical significance complex (Rao et al., 2008; Száková et al., 2009). Thanks to their properties, REE could contribute to evaluate this geochemical relevance: despite their similar chemical characteristics (e.g., large ionic radius, trivalent oxidation states, lower electronegativity), some REE behave differently (Henderson, 1984; Laveuf and Cornu, 2009). Indeed, Ce and Eu have a second valence (Ce^{4+} and Eu^{2+} , respectively) that can induce positive or negative anomalies after fractionation processes. All of these properties make REE useful for tracing biogeochemical processes, such as adsorption, leaching, or redox and pH changes in the soil–plant system (Laveuf and Cornu, 2009; Liang et al., 2005).

The objective of this study was to assess the relevance of using three distinct plant-available trace element compartments (i.e., soil solution, soil water-extract, and three-step sequential extraction fractions) based on both concentrations and geochemical tracers (i.e., REE) in evaluating the transfer of trace elements from uncontaminated, anthropogenically contaminated, and naturally-enriched soils. For this purpose, we performed a greenhouse experiment using maize growing on four agricultural soils and considering soil, soil solution, and plant samples.

2.3. Materials and methods

2.3.1. Study area and soil sampling

The experiment was carried out on four contrasted agricultural soils of Wallonia, Belgium, including different trace element contents, originating from distinct environmental contexts: Vieusart (50°40'47" N, 4°38'8" E) as uncontaminated site from the Walloon Brabant (UCLouvain experimental farm); Sainte-Walburge (50°39'52" N, 5°35'20" E) and Bressoux (50°38'15" N, 5°36'39" E) as anthropogenically contaminated sites (gradient of trace element content resulting from metal, textile, and coal industries since the 18th century and a marked presence of industrial artifacts, such as coal, clinker, slag, and construction debris in soils), both located in Liège, province of Liège; and Aubange (49°34'34" N, 5°46'5" E) as naturally-enriched site (lithogenic metal-enrichment) from the Belgian Lorraine, province of Luxembourg. At each site, approximately 200 L of soil material were collected randomly in a circle of 7 m in diameter in the top 20 cm depth using a spade and a shovel.

Vieusart is a typical loamy agricultural soil from the northern Wallonia, classified as a Luvisol according to the World Reference Base for Soil Resources (WRB; Mantel et al., 2023) and located on a sandy formation more or less clayey (Sint-Huibrechts-Hern formation) surmounted by a thick aeolian loess deposit (Brabant silt plateau; Herbosch and Blockmans, 2005). Sainte-Walburge is a loamy agricultural soil classified as a Luvisol/Cambisol, located on a clayey chalk formation (Gulpen Formation) surmounted by a red clay with flints, while Bressoux, whose soil type is not mapped, is classified as a Luvisol, located on alluvial deposits (Ancient Alluvium) containing sandy silt, sand, and clay (Barchy and Marion, 2000). Finally, Aubange is a loamy-stony agricultural soil classified as a Cambisol and located on the Aubange formation composed of a complex of sandstone, ferruginous and non-ferruginous calcareous sandstone, siltstone, and mudstone (Belanger et al., 2002). The four study sites are characterized by a temperate oceanic climate with an average annual air temperature comprised between 9.4 (Aubange) and 11.2 °C (Liège area) and an average annual precipitation between 790 (Vieusart) and 1100 mm (Aubange).

2.3.2. Experimental design

Soil–plant transfer of trace elements was conducted in greenhouse conditions (UCLouvain experimental greenhouses, Louvain-la-Neuve, Belgium) from April to July 2021 using maize (*Zea mays* L.). Collected soil samples were dried (25 °C in a drying room for seven days) and sieved at 1.2 cm. Approximately 15 kg of the sieved soil were mixed with 20 g of NPK 9-7-14 (equivalent to 240 kg_N ha⁻¹), and then potted (10 L pots of 30 cm in diameter and 30 cm height) before sowing one maize seed in each pot. For representativeness purpose, three replicates were considered. During the experiment, each pot was watered with 1 to 3 L of tap water per week depending on weather conditions. In each pot, a rhizon (19.21.21F, Rhizosphere, Wageningen, The Netherlands) connected to a 60-mL polypropylene syringe (BD Plastipak Luer Lock) was vertically inserted into the upper 10 cm of soil to collect soil solution (Arbalestrie et al., 2022).

2.3.3. Sampling procedure and sample preparation

Soil solutions were collected two times during the experiment (5 May and 22 June 2021). The collected samples were immediately acidified to reach 2% HNO₃ before ICP–MS analysis. Plant parts (roots, stems, and leaves) were sampled at the end of the experiment. Root samples were cleaned with pressurized tap water to remove soil residues and all plant samples were dried in a ventilated oven at 50 °C before grinding (Cyclotec 1093 Sample Mill, Foss A/S, Hillerød, Denmark).

2.3.4. Chemical analyses

Soil characterization

After sieving at 2 mm, soil samples were characterized for pH (pH_{H₂O} and pH_{KCl} using a 1:5 ratio), grain-size (sedimentation method; Pansu and Gautheyrou, 2006), and cation exchange capacity (CEC; ammonium acetate method at pH 7; Metson, 1956) analyses. After grinding (Vibratory Disc Mill RS 200, Retsch, Haan, Germany), soil total carbon and nitrogen contents were measured on 10 to 30 mg of soil samples by gas

chromatography (Elementar vario EL cube, Langenselbold, Germany), and mineralogical composition analyses were made by X-ray diffraction (XRD, Bruker D8 advance diffractometer, Bruker, Karlsruhe, Germany). All analyses were duplicated and due to the absence of inorganic carbon, we considered total carbon content as organic carbon content.

Trace element contents

To assess the element distribution in solid phase of each studied soil, a modified BCR three-step sequential extraction (Žemberyová et al., 2006) was performed on 1 g of <2 mm soil samples: (1) 40 mL of 0.11 mol L⁻¹ CH₃COOH (exchangeable fraction); (2) 40 mL of 0.5 mol L⁻¹ NH₂OH·HCl (reducible-iron/manganese oxides fraction); and (3) 2×10 mL of 8.8 mol L⁻¹ H₂O₂ before 50 mL of 1 mol L⁻¹ CH₃COONH₄ (oxidizable-organic matter and sulfides fraction). For each extraction step, soil samples were mixed with the extractant at 300 rpm for 16 h using a mechanical shaker (Universal Shaker SM 30 B, Edmund Bühler GmbH, Bodelshausen, Germany). The extracted solutions were then separated from the solid phase by: (1) centrifugation at 4000 rpm for 20 min (Centrifuge Jouan GR4.12, France); (2) filtration with 20-μm Whatman paper filters; and (3) filtration with 0.2-μm GHP Acrodisc (PSF and nylon, Pall). The precipitates were washed with 20 mL of Milli-Q water between every step. The residual fraction was obtained for each element by the difference between the total soil content and the sum of the other three fractions. Besides the BCR extraction, we performed a water extraction (i.e., 1 g of <2 mm soil samples with 40 mL of Milli-Q water following the same mixing and separating steps as done for the BCR extraction).

Total element contents in soil and plant samples were determined using total digestion on ca. 100 mg of ground samples with suprapure acids (HNO₃, HCl, and HF) and H₂O₂ mixture in a Savillex (Teflon bottle) in an ISO 6 cleanroom, as described in Arbalestrie et al. (2022). Quantification of 18 trace elements (As, Ba, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, Sc, Se, Sn, Sr, Ti, V, and Zn) and 14 REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) was performed by ICP–MS (iCAP Q ICP–MS, Thermo Fischer Scientific, Waltham, MA, USA) with an internal standard (Ru, In, and Re) for mass deviation correction. Procedure performance was evaluated using organic (lichen IAEA-336) and mineral (basalt BHVO-2) certified materials. The average recovery ($C_{\text{measured}} / C_{\text{certified}} \times 100$) was 100±20%, except for Ni, Mo, Lu, Er, Tm, Se and Sn in IAEA-336 (56, 62, 71, 76, 76, 155 and 163%, respectively) and for Pb, Sc, Sb and As in BHVO-2 (69, 79,

195, and 303%, respectively). A river water standard (SLRS-6) was added to check ICP-MS performance and the average recovery was around 100±20%, except for Pb (77%), Zn (127%), Cd (147%), Sn (156%), and Se (202%). No contamination was evidenced during the digestion process (average blank concentrations <1% of the sample concentration, except for Cd and Ti that reached 2%). Limit of detection were estimated to <1 ng kg⁻¹, except for Cr, Cu, Mn, Pb, Sr, and V (<0.01 µg kg⁻¹), Ba and Zn (<0.1 µg kg⁻¹), and Ti (<1 µg kg⁻¹).

2.3.5. Data processing and statistical analyses

To evaluate the transfer of trace elements between soil or plant-available compartments and plant parts, transfer factors (TF) from one compartment to another were calculated as follows (Adriano, 2001; Antoniadis et al., 2017; Marchiol et al., 2004):

$$TF_{A-B} = \frac{C_B}{C_A}$$

with C_A and C_B , the trace element contents in compartment A and B, respectively, which can be soil, root, stem, leaf, shoot (i.e., biomass-weighted average of stems and leaves), plant (i.e., biomass-weighted average of roots, stems, and leaves), and plant-available trace element compartments (soil solution, soil water-extract, and BCR exchangeable fraction).

REE were displayed as normalized profiles using the following reference materials: (1) UCC (upper continental crust; Rudnick and Gao, 2014) for soil samples (Cidu et al., 2013) and (2) the local soil for BCR extraction, soil water-extract, root, stem, leaf, and soil solution samples (Brioschi et al., 2013). All graphs were produced using the same log scale to aid comparisons. REE indices frequently used in the literature have been calculated from the measured concentrations (Arbalestrie et al., 2022; Miao et al., 2008; Wyttenbach et al., 1998): (1) Ce and Eu anomalies calculated by dividing the normalized value by the expected value (obtained by averaging the values of the elements immediately before and after in the periodic table, and noted Ce* and Eu*, respectively) and (2) light REE/ heavy REE (LREE/HREE) ratio using La to Eu (LREE) and Gd to Lu (HREE) normalized contents. Only anomaly values of <0.80 or >1.2 were

considered as significant negative or positive anomalies, respectively (Krzciuk and Gałuszka, 2020).

The software R 4.0.4 (R Core Team, 2021) was used for statistical analyses: non-parametric Wilcoxon test and the principal component analysis (PCA). The latter being carried out on centered log-ratio transformed element concentrations (*clr* function of the *rgr* package) to determine the correlations between elements (Garrett, 2013). All plots were performed using the *ggplot2* package (Wickham, 2016).

2.4. Results and discussions

2.4.1. Soil characterization

The uncontaminated soil (Vieusart) was classified as a loamy soil (USDA classification) with average $\text{pH}_{\text{H}_2\text{O}}$ and pH_{KCl} of 6.5 and 5.8, respectively (Table III-2). Organic carbon and total nitrogen contents were 1.3 and 0.13%, respectively, and CEC reached $11.1 \text{ cmol}_c \text{ kg}^{-1}$ with a base saturation of 100%. These characteristics are representative of the slightly acidic fertile soils of the Wallonia silty plateau widely used for agriculture (Goidts and van Wesemael, 2007).

The two anthropogenically contaminated soils (Sainte-Walburge and Bressoux) were also loamy soils with average $\text{pH}_{\text{H}_2\text{O}}$ of 7.8 and 7.0, respectively, and average pH_{KCl} of 6.8 and 6.1, respectively. Organic carbon content of the two soils reached 11.1 and 15.8%, respectively, inducing a higher CEC compared to the uncontaminated soil (15.2 and $26.9 \text{ cmol}_c \text{ kg}^{-1}$, respectively), with a base saturation of 100 and 92%, respectively. The presence of industrial artifacts, such as coal, clinker, slag, and construction debris, frequently found in the soils of the Liège region, could explain the higher pH (e.g., through the release of OH^- ions during the hydrolysis of compounds, such as CaO, found in various artifacts) and organic carbon content (e.g., through coal residues) compared to the uncontaminated soil. Indeed, an increase in soil pH was observed in the presence of slag on metal-contaminated soils in China (Wen et al., 2020). Furthermore, Hardy et al. (2017) showed that the charcoal CEC could reach up to $>400 \text{ cmol}_c \text{ kg}^{-1}$, and thus could contribute to the increase of soil CEC and carbon/nitrogen (C/N) ratio.

The naturally-enriched soil (Aubange) was classified as sandy clay loam soil with average $\text{pH}_{\text{H}_2\text{O}}$ and pH_{KCl} of 7.3 and 6.2, respectively. These higher pH values can be explained by the presence of ferruginous and non-ferruginous calcareous sandstone in the parent material (Belanger et al., 2002). Organic carbon (2.4%) and total nitrogen (0.23%) contents were slightly higher than the uncontaminated soil. Finally, CEC reached $20.8 \text{ cmol}_c \text{ kg}^{-1}$, with a base saturation of 78%, which may result from Fe and Mn oxyhydroxides present in the Aubange formation providing negative charges in this pH range (Belanger et al., 2002; Vandeuren et al., 2023). Soil mineralogy analysis highlighted a large presence of goethite, which was not observed along the anthropogenic contamination gradient (i.e., from Vieusart to Sainte-Walburge to Bressoux) revealing a homogeneous mineralogy (Appendix VI.1, Figure VI.1).

Table III-2 - Summary table (means and standard deviations in brackets, n = 2) of soil physico-chemical parameters.

	pH _{H2O}	pH _{KCl}	C _{tot}	N _{tot}	C/N	Clay	Silt	Sand	CEC	Ca	K	Mg	Na	Saturation
	[-]		[%]		[-]	[%]			[cmol _c kg ⁻¹]					[%]
Uncontaminated (Vieusart)	6.5 (0.01)	5.8 (0.01)	1.3 (0.05)	0.13 (0.01)	10.1 (0.32)	19 (0)	47 (1)	34 (1)	11.1 (0.32)	9.52 (0.02)	0.47 (0.03)	1.35 (0.01)	0.06 (0.02)	100 (4)
Moderately contaminated (Sainte-Walburge)	7.8 (0.02)	6.8 (0.01)	11.1 (0.10)	0.35 (0.01)	31.9 (0.23)	22 (1)	50 (1)	29 (1)	15.2 (0.68)	15.9 (0.30)	1.08 (0.00)	0.96 (0.01)	0.05 (0.00)	100 (7)
Highly contaminated (Bressoux)	7.0 (0.01)	6.1 (0.0)	15.8 (0.40)	0.52 (0.01)	30.7 (0.97)	18 (0)	34 (0)	48 (0)	26.9 (3.80)	20.0 (0.50)	1.01 (0.06)	3.79 (0.06)	0.07 (0.01)	92 (11)
Naturally-enriched (Aubange)	7.3 (0.03)	6.2 (0.0)	2.4 (0.49)	0.23 (0.01)	10.8 (1.85)	24 (0)	25 (0)	51 (0)	20.8 (1.20)	13.6 (0.54)	1.00 (0.00)	1.69 (0.05)	0.04 (0.00)	78 (2)

2.4.2. Assessing trace element transfer through soil–plant transfer factors

Trace element contents in soil

Average trace element contents in the uncontaminated soil (Vieusart; Appendix VI.1, Table VI-3) ranged from Cd ($0.27 \pm 0.01 \text{ mg kg}^{-1}$) to Ti ($1680 \pm 120 \text{ mg kg}^{-1}$), including values close to those found in French uncontaminated agricultural soils (Baize, 2000b). REE contents, represented as the sum of REE (ΣREE), was $116 \pm 0 \text{ mg kg}^{-1}$, close to those of the upper Earth's crust (150 mg kg^{-1} ; Brioschi et al., 2013; McLennan, 1989). Trace element contents measured in both anthropogenically contaminated soils (Sainte-Walburge and Bressoux; Appendix VI.1, Table VI-3) were on average 3.8- and 11.5-times higher than the uncontaminated soil, respectively, ranging from Cd ($1.85 \pm 0.22 \text{ mg kg}^{-1}$) to Ti ($2510 \pm 468 \text{ mg kg}^{-1}$) in the moderately contaminated soil (Sainte-Walburge) and from Mo ($4.14 \pm 0.26 \text{ mg kg}^{-1}$) to Zn ($1270 \pm 50 \text{ mg kg}^{-1}$) in the highly contaminated soil (Bressoux). These exceeding values compared to those from uncontaminated soils (Vieusart and literature data; Baize, 2000) may result from short- and long-term atmospheric deposition from metal, textile, and coal industries widespread in this region since the 18th century. The increasing anthropogenic contamination gradient (i.e., from Vieusart to Bressoux) was observed for all elements considered, except for Ti and ΣREE that showed lower value in the highly contaminated soil than in the two other soils. Indeed, these elements are mostly related to lithologic sources instead of anthropogenic ones (Cornu et al., 1999; Kabata-Pendias, 2011). Finally, the naturally-enriched soil (Aubange; Appendix VI.1, Table VI-3) showed trace element contents ranging from Cd ($0.422 \pm 0.004 \text{ mg kg}^{-1}$) to Mn ($8840 \pm 230 \text{ mg kg}^{-1}$), which were on average 6.2-times higher than the uncontaminated soil. The elements with the highest Aubange/Vieusart content ratios (i.e., Mn, As, Mo, Ni, and Co; up to 30) could be associated in Aubange with soil Fe and Mn oxyhydroxides present in the bedrock (Belanger et al., 2002; Vandeuren et al., 2023). The same observation applied to exclusively lithogenic elements, such as REE (Aubange/Vieusart content ratio of 2), likely results from a large content of these elements in oxyhydroxides (Laveuf et al., 2008).

Trace element contents in plants

Trace elements measured in plant parts of maize grown in uncontaminated and contaminated soils consistently showed higher values in roots compared to leaves and stems. For the uncontaminated soil (Vieusart; Appendix VI.1, Table VI-3), root contents ranged from Sb ($0.33 \pm 0.07 \text{ mg kg}^{-1}$) to Ti ($784 \pm 138 \text{ mg kg}^{-1}$) and were on average 82- and 34-times more concentrated than in stems and leaves, respectively. These values were within the range of those observed for agricultural plants in the literature (Angelone and Bini, 1992; Bañuelos and Ajwa, 1999). The anthropogenically contaminated soils (Sainte-Walburge and Bressoux; Appendix VI.1, Table VI-3) showed trace element contents in plant samples that were more concentrated than the uncontaminated soil: on average, 1.2- and 1.4-times in roots, 2.7- and 6.1-times in stems, and 1.4- and 2.2-times in leaves, for Sainte-Walburge and Bressoux, respectively. For the naturally-enriched soil (Aubange; Appendix VI.1, Table VI-3), however, trace element contents in plants were less contrasted than for the uncontaminated soil.

Transfer of trace elements along the soil–root–shoot continuum

Among trace elements considered in our study, only six of them are presented for transfer factors along the soil–root–shoot continuum ($TF_{\text{soil–plant}}$, $TF_{\text{soil–root}}$, and $TF_{\text{root–shoot}}$) because of their expected contrasted environmental fates related to distinct origins, chemical behaviors, and bioavailabilities (Figure III.7): Ti, Co, Zn, Cd, Pb, and As. We compared the transfer capacity between the four uncontaminated and contaminated studied soils. For a given soil, transfer factors showed distinct orders of magnitude depending on the element considered, highlighting different bioavailabilities or mobilities. For instance, both Cd and Zn were highly transferred from soil to plant ($TF_{\text{soil–plant}} > 0.1$; Figure III.7A), but Cd was preferentially accumulated in roots (Figure III.7B) while Zn was in shoots (Figure III.7C). This results from distinct biological processes that regulate the transport of elements to and within the plant (i.e., tolerance mechanism, involvement in metabolite functions, antagonistic and synergistic behaviors; Bañuelos and Ajwa, 1999; Chibuike and Obiora, 2014; Gupta et al., 2019).

Considering multiple soil contamination levels, we observed a decrease of transfer factors by a factor of 3 following the contamination gradient (i.e., from Vieusart to Bressoux; Figure III.7A), suggesting either a lower trace element bioavailability in contaminated soils or a biological saturation

mechanism during root uptake as mentioned by Prasad et al. (2006). Furthermore, for a similar contamination level, the naturally-enriched soil (Aubange) presented a lower $TF_{\text{soil-plant}}$ compared to the moderately contaminated soil (Sainte-Walburge) showing a lower bioavailability, as illustrated by As that was the least transferred element ($TF_{\text{soil-plant}} < 0.01$) despite its highest soil content ($143 \pm 5 \text{ mg kg}^{-1}$). Thus, both soil contents and transfer factors are limited to predict the proportion of soil elements that can be uptake by plants, which constitutes a challenge in contaminated soils.

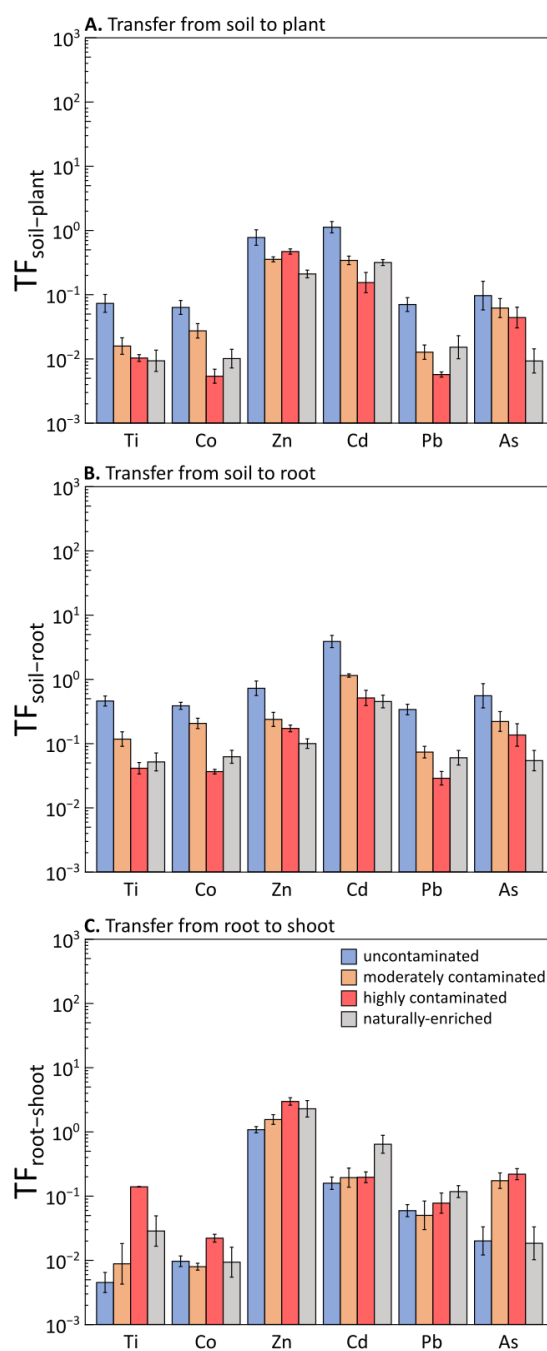


Figure III.7 - Transfer factors (TF; log scale) of Ti, Co, Zn, Cd, Pb, and As from uncontaminated and contaminated soils to maize: from soil to plant ($TF_{\text{soil-plant}}$; A), from soil to root ($TF_{\text{soil-root}}$; B), and from root to shoot ($TF_{\text{root-shoot}}$; C).

2.4.3. Assessing trace element transfer through plant-available compartments

Plant-available trace element compartments

Soil solutions

Soil solution concentrations (Appendix VI.1, Table VI-3) did not show significant differences between both sampling dates ($p > 0.05$, Wilcoxon test). Thus, only samples collected in 5 May 2021 (i.e., first sampling date) will be discussed in this section. Trace elements presented increasing concentrations along the contamination gradient: lowest values were reported in Vieusart (from Sn with $0.03 \pm 0.01 \mu\text{g L}^{-1}$ to Sr with $1400 \pm 480 \mu\text{g L}^{-1}$), close to those generally found in uncontaminated soils (Kabata-Pendias, 2004; Moreno-Jiménez et al., 2011), while they were on average 7.6- and 12.0-times higher in anthropogenically contaminated soils (Sainte-Walburge and Bressoux, respectively). This highlights the higher pool of trace elements mobilized in contaminated soils, suggesting a greater potential transfer from soil to groundwater. Since it was not observed considering $\text{TF}_{\text{soil-plant}}$ (Figure III.7A), we hypothesize that: (1) $\text{TF}_{\text{soil-plant}}$ is not representative of the real transfer resulting from not considering the bioavailable soil fraction; (2) plants do not uptake the full bioavailable fraction due to a biological saturation mechanism; and/or (3) soil solutions collected by rhizons do not fully represent a bioavailable fraction, partly because of the presence of colloids not available to plants (Arbalestrie et al., 2022). Finally, although soil concentrations in the naturally-enriched soil (Aubange) were on average 6.2-times higher than in the uncontaminated soil, soil solution concentrations only reached on average 2.4-times higher values. This suggests that only a small fraction of these elements was mobilizable, explaining the lowest $\text{TF}_{\text{soil-plant}}$ compared to the uncontaminated soil (Figure III.7A).

Soil water-extracts

Besides soil solutions, we performed soil water-extracts (Appendix VI.1, Table VI-7) corresponding to a second plant-available compartment. The uncontaminated soil (Vieusart) showed a wide range of soil water-extract contents, ranging from $0.7 \pm 0.5 \mu\text{g kg}^{-1}$ (Sc) to $229 \pm 30 \mu\text{g kg}^{-1}$ (Sr). This followed roughly the same element order as for the soil solutions although no comparison of absolute values was possible between concentrations in a solution and extractable contents. Again, increasing contents were observed

along the contamination gradient (up to 10-times higher on average from Vieusart to Bressoux), indicating a higher pool of trace elements potentially available to plants in trace element-rich soils. Surprisingly, the extraction of trace elements from the naturally-enriched soil (Aubange) was similar as observed for the moderately contaminated soil (6-times higher than the uncontaminated soil). This indicates distinct exchange processes between water percolation in the soil (soil solution) and active extraction (soil water-extract). Note that extraction with Milli-Q water, which lacks ionic strength, facilitates the extraction of trace elements.

Three-step sequential extraction

The modified BCR three-step sequential extraction, including a third plant-available compartment (i.e., the exchangeable soil fraction), was reported for Ti, Co, Zn, Cd, Pb, and As with contrasted trace element distributions (Figure III.8). Those differences mainly resulted from the origin of the elements: lithogenic elements linked to parent material weathering, such as Ti and Co, vs anthropogenic elements linked to both long-term atmospheric deposition and industrial artifacts, such as Zn, Cd, Pb, and As. Indeed, Ti (Figure III.8A), similar to Sc, Cr, Sb, and Sn (Appendix VI.1, Table VI-7) and, to a lesser extent, Co (Figure III.8B), similar to V and Ni (Appendix VI.1, Table VI-7), were mostly found in the residual fraction regardless of the soil considered (>99% for Ti and between 43 and 81% for Co), attesting their lithogenic origin with a low bioavailability in the environment (Kabata-Pendias, 2011; Malandrino et al., 2011). In the naturally-enriched soil (Aubange), results highlighted an unusual strong influence of the parent material on some trace elements such as Zn and As (residual proportion >85%; Figure III.8C and F), explaining the limited bioavailability despite their high total content from the Aubange formation due to ore deposits (Belanger et al., 2002; Vandeuren et al., 2023).

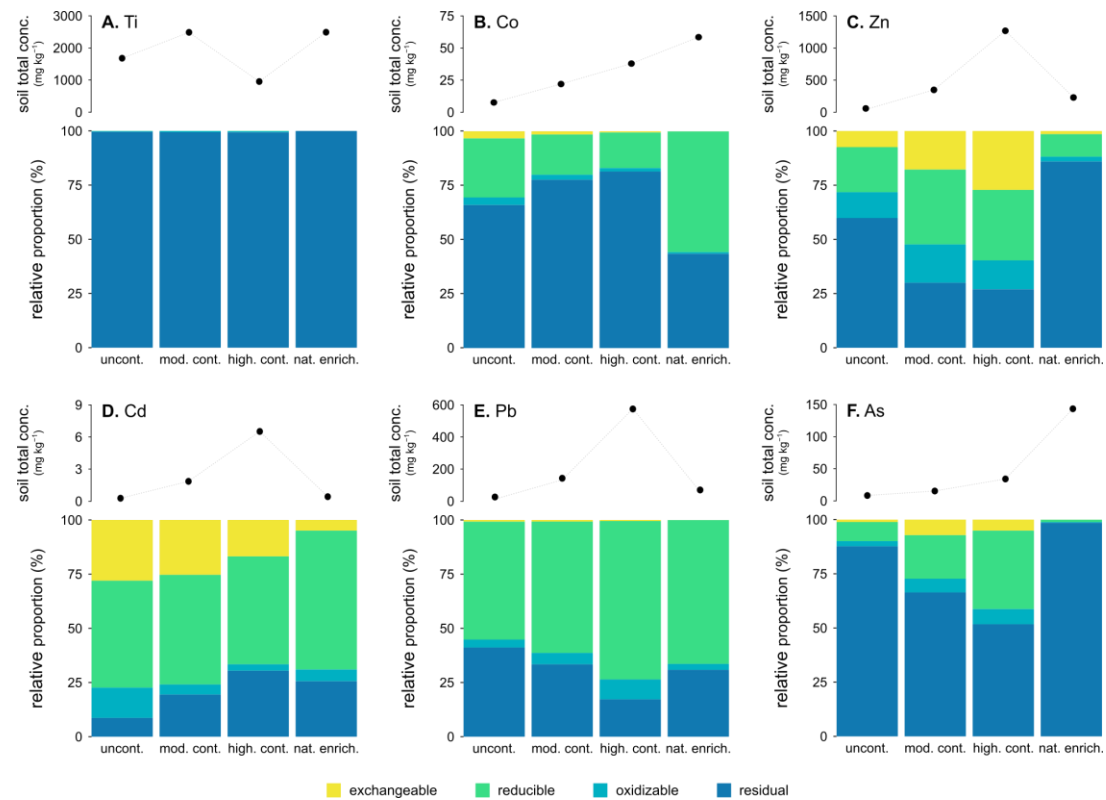


Figure III.8 - Titanium (A), Co (B), Zn (C), Cd (D), Pb (E), and As (F) total concentration and fractionation in the uncontaminated (Vieusart), anthropogenically-contaminated (moderately, Sainte-Walburge and highly, Bressoux), and naturally-enriched (Aubange) soils. Element fractionation was performed using the modified BCR three-step sequential extraction and total acidic digestion.

Conversely, anthropogenic elements showed increasing proportions of short-term (i.e., exchangeable) and long-term (i.e., reducible and oxidizable) mobile fractions from the uncontaminated soil to the anthropogenically contaminated ones, as observed for Zn (Figure III.8C), similar to Cu, Sr, and Ba (Appendix VI.1, Table VI-7), Pb (Figure III.8E), and As (Figure III.8F). For instance, Zn is more likely to be found in readily available form in topsoil of anthropogenically contaminated soils because of its industrial production and emission (e.g., smelter; Shen et al., 2017). These pool of manmade trace elements may interact with soil constituents (sorption on soil organic matter and oxyhydroxides; Akkajit and Tongcumpou, 2010; Perelomov and Kandeler, 2006; Pueyo et al., 2008; Sánchez-España and Yusta, 2019), as illustrated with higher reducible and oxidizable fractions compared to the uncontaminated soil. These elements, however, presented different chemical behaviors associated to distinct mobilities: Cd (Figure III.8D), similar to Mn (Appendix VI.1, Table VI-7), had a highest proportion of exchangeable fraction (on average 19%) resulting from its strong mobility (Malandrino et al., 2011; Prokop et al., 2003), unlike Pb (on average 0.5%; Ahmadipour et al., 2014). These contrasted trends in highly enriched elements (Bressoux/Vieusart content ratio > 20) following the contamination gradient (i.e., increasing available fraction for Pb and Zn vs increasing residual fraction for Cd) highlight that trace elements were not supplied by the same manmade materials (e.g., coal, clinker, or slag residues) or not the same weathering degrees due to distinct environmental physico-chemical parameters. Thus, no assumption is valid for estimating the available fraction from the total content in contaminated soils without a direct evaluation, such as a sequential extraction.

Comparison of plant-available trace element compartments

To better compare the three plant-available trace element compartments, we performed a PCA including all compartments of the soil–plant continuum (Figure III.9). The first dimension of the PCA (35% of the data variance) differentiated the plant-available compartments (with positive scores, linked to Sr, Ni, Ba, Sb, Co, and Zn) from the soil–plant compartments (with negative scores, linked to Ti, Cr, Sn, Mn, and Pb). These contrasted trends likely result from a higher solubility of the first pool of elements (cf. BCR results; Appendix VI.1, Table VI-7), facilitating their mobilization during the exchange with solution (for soil solution) or the extraction process (for water-extract and BCR exchangeable fraction). Thus, we assume that soil solution is the least

representative compartment because it overestimates mobile elements, unlike water-extract that is geochemically closer to the soil-plant compartments.

The second dimension (26% of the data variance) revealed a gradient following both: (1) soil-plant compartments (soil > roots > stems > leaves with decreasing scores); and (2) soil contamination gradient (Aubange ~ Vieusart > Sainte-Walburge > Bressoux with decreasing scores). This distribution was influenced by trace elements: Σ REE, V, and Sc (positive scores) weakly accumable to plant (low $TF_{\text{soil-plant}}$) opposed to Cu, Cd, Zn, and Mo (negative scores) highly accumable (high $TF_{\text{soil-plant}}$) and/or highly enriched (Bressoux/Vieusart content ratio > 20). Along this second dimension, water-extract presented the geochemical signatures furthest from the plant compartments and therefore from the bioavailable fraction compared to the BCR exchangeable fraction and the soil solution. This indicates that, despite a better geochemical representativeness (less influenced by soluble elements), soil water extract cannot fully reflect the bioavailable fraction to plant.

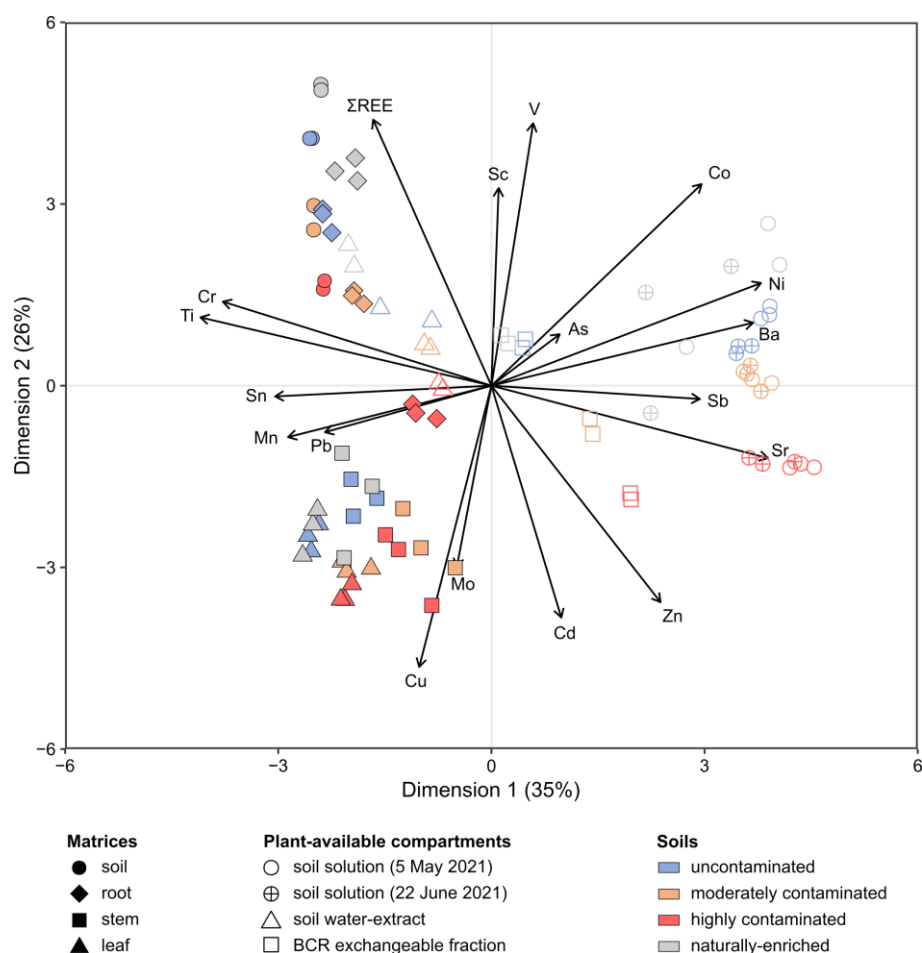


Figure III.9 - Principal component analysis (PCA) of soil–plant compartments and plant-available trace element compartments for the uncontaminated, anthropogenically contaminated, and naturally-enriched soils. Selenium was not considered in the PCA due to missing data in soil solution samples.

Transfer from plant-available compartments to plant

As done for the total soil content, we calculated the transfer factor from the three previously mentioned plant-available compartments to plant (Figure III.10). Firstly, the transfer from soil solution to plant ($TF_{\text{soil solution-plant}}$; Figure III.10A) showed high variability between both trace elements (up to three orders of magnitude between Ti and Co) and soils (up to two orders of magnitude for Pb). Titanium, particularly, showed unexpected high transfers due to its low concentration in soil solution (i.e., low solubility; Figure III.8 and Figure III.9) that artificially overestimated the $TF_{\text{soil solution-plant}}$. This confirms

that soil solution is not fully representative of the available fraction to the plant when comparing trace elements. Secondly, soil water extract ($TF_{\text{soil water extract-plant}}$; Figure III.10B) highlighted less differences between both trace elements and soils. Contaminated soils showed systematically lower transfer than the uncontaminated one (up to 26 times for Pb), probably linked to the biological saturation mechanism previously mentioned. Finally, when considering the first BCR sequential extraction step ($TF_{\text{BCR exchangeable fraction-plant}}$; Figure III.10C), transfers were almost similar between trace elements for a given soil (except for Ti), indicating a consistency of the bioavailable fraction. Using this relevant plant-available compartment, we clearly identified distinct transfer processes occurring in soils depending on the contamination level, reinforcing the evidence of a physiological aspect (i.e., biological saturation mechanism or plant accommodation in naturally-enriched environments) that should be independent of any protocol bias.

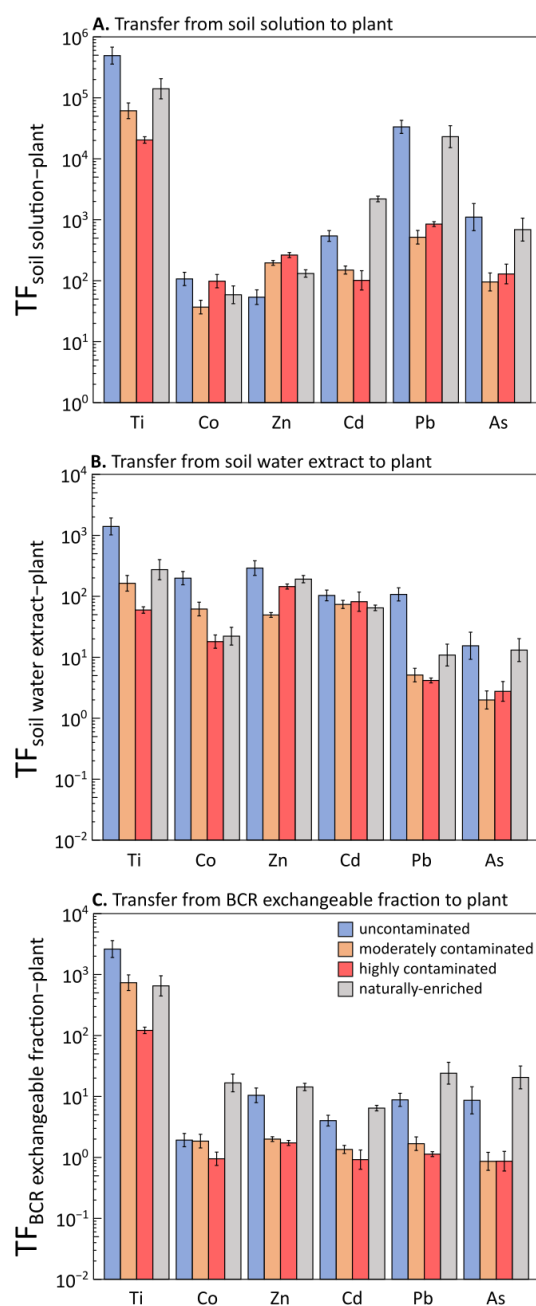


Figure III.10 - Transfer factors (TF; log scale) of Ti, Co, Zn, Cd, Pb, and As in maize in uncontaminated and contaminated contexts: from soil solution to plant ($TF_{\text{soil solution-plant}}$; A), from soil water extract to plant ($TF_{\text{soil water extract-plant}}$; B), and from first BCR sequential extraction step to plant ($TF_{\text{BCR exchangeable fraction-plant}}$; C).

Insight of rare earth elements to validate the plant-available compartment relevance

To evaluate the relevance of the three plant-available trace element compartments, we studied REE (Figure III.11). UCC-normalized REE patterns were compared between soil and plant (Figure III.11A-D). While we observed differences between the four soils studied (e.g., positive Ce anomaly of 1.4 and a low LREE/HREE ratio of 0.81 in the naturally-enriched soil compared to the other soils), both compartments represented similar patterns, as shown by the flat plant REE patterns using a soil-normalization (Figure III.11I). This observation done on contrasted soils confirms findings by Arbalestrie et al. (2022) who highlighted a clear correlation between soil and plant REE patterns.

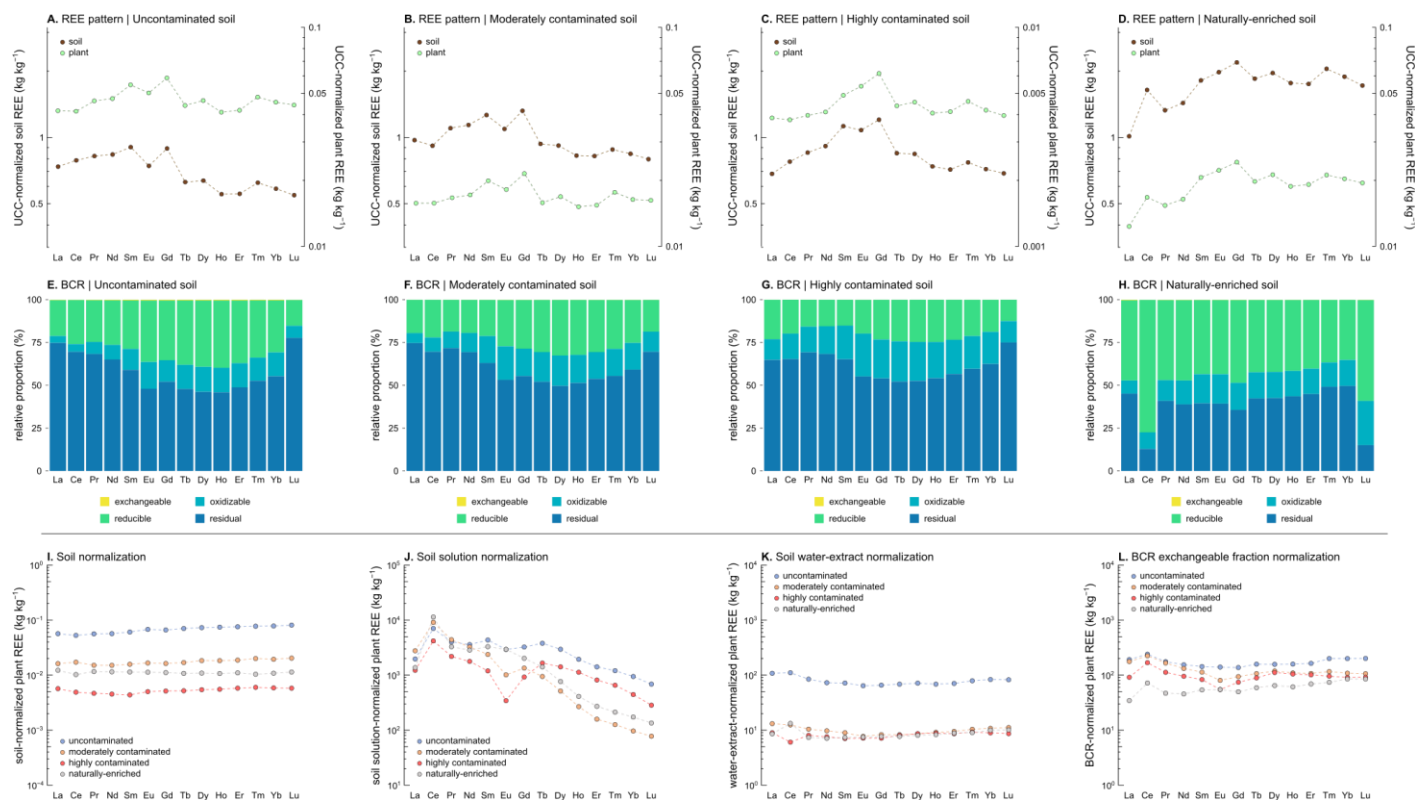


Figure III.11 - UCC-normalized pattern profiles and fractionation (modified BCR tree-step sequential extraction) of rare earth elements (REE) from the uncontaminated (A, E), anthropogenically contaminated (B, F and C, G), and naturally-enriched (D, H) soils. Plant REE pattern profiles were normalized by: soil (I), soil solution from 5 May 2021 (J), soil water-extract (K), and BCR exchangeable fraction (L).

Yet, all REE were weakly present in the exchangeable fraction (<1%) regardless of the soil considered, as shown by the modified BCR three-step sequential extraction (Figure III.11E-H). Indeed, REE were mostly present in the residual fraction (generally >50%, except in the naturally-enriched soil where Ce and Lu reached 13 and 15%, respectively), with a systematic relative middle REE depletion (except for the naturally-enriched soil with a higher contribution of the reducible fraction: from 35% for Yb to 77% for Ce). The higher reducible proportion of Ce in the naturally-enriched soil (Figure III.11H) may result from its lithological origin and the oxidative scavenging of Ce onto Mn/Fe oxyhydroxides in a low organic carbon-content soil (Bau and Koschinsky, 2009; Liu et al., 2017; Ratié et al., 2023), promoting pronounced positive Ce anomalies in both soil and plant (i.e., high relative bioavailability; Figure III.11D). Despite similar trends between REE along the contamination gradient (i.e., Vieusart < Sainte-Walburge < Bressoux), we observed a slight relative decrease of reducible fraction while the oxidizable fraction slightly increased (Figure III.11E-G). This was not observed by Rao et al. (2010), which might indicate that the contamination level is not the only parameter influencing the distribution of REE in soils. Indeed, other factors such as mineralogy, climate, topography, redox conditions, and organic matter could explain the differences between soils (Davranche et al., 2008; Khorasanipour and Rashidi, 2020). In this case, the relative increase in the oxidizable fraction in contaminated soils might be due to the higher carbon content in these soils.

We then compared the REE patterns between the three plant-available compartments and plant (Figure III.11J-L). The soil solution-normalized REE patterns (Figure III.11J) showed: (1) a relative HREE depletion (LREE/HREE ratios ranging from 2.0 in the uncontaminated soil to 8.7 in the moderately contaminated soil); and (2) a positive Ce (up to 4.9 in the naturally-enriched soil) and negative Eu (up to 0.32 in the highly contaminated soil) anomalies. These might be explained by the irrigation tap water (specific REE indices: LREE/HREE = 0.26, Ce anomaly = 0.25, Eu anomaly = 0.66) that influenced the soil solution composition when collected by rhizon (Arbalestrie et al., 2022).

Conversely, both soil water-extract- and BCR exchangeable fraction-normalized REE patterns presented flatter profiles (i.e., LREE/HREE and Ce and Eu anomalies around 1, with some exceptions for Ce anomaly for the BCR exchangeable fraction normalization). Yet, the flatter the pattern profile, the more representative the compartment is of the trace element plant-availability. We thus assume that both soil water-extract and BCR

exchangeable fraction better reflect the soil bioavailable fraction to plant concerning the chemical reactivity illustrated by REE (sorption to organic matter or oxyhydroxides, leaching, redox sensitivity, etc.).

2.5. Conclusion

Transfers of trace elements from uncontaminated and contaminated agricultural soils to plant were evaluated in a greenhouse experiment using three plant-available compartments (soil solution, soil water-extract, and BCR exchangeable fraction). Using trace element concentrations and REE signatures, we investigated the predictability of trace element transfers from soil to plant. Transfer factors highlighted distinct transfer depending on the element and soil considered. This transfer diminished along the contamination gradient, suggesting a biological saturation mechanism or plant accommodation during root uptake. Predicting the proportion of soil elements that plants can absorb remains challenging in contaminated soils, as both soil content and transfer factors have limitations in this regard. A comparison between the three plant-available compartments revealed that: (1) although the soil solution exhibited a high transfer potential, it demonstrated a significant variability among the elements, mainly by overestimating the transfer of highly soluble elements and by a potential contamination of irrigation water; (2) the soil water-extract appeared geochemically closer to the plant bioavailable compartments; and (3) the BCR exchangeable fraction exhibited nearly uniform transfer for all contaminant elements for a given soil. REE analysis confirmed these observations and showed that both soil water-extracts and BCR exchangeable fraction are the most relevant compartments for predicting soil–plant transfer.

3. Role of exogenous organic matter quality on trace element transfer

3.1. Abstract

Trace elements, although present in small amounts in the environment, can pose significant risks to human and environmental health when their concentrations exceed critical thresholds. In agricultural soils, exogenous organic matter input can significantly influence the dynamics of trace elements through modification of soil organic matter chemistry, offering potential lever to address these environmental and public health concerns. This study aimed to: (1) evaluate the influence of three exogenous organic matters (cattle manure, green waste compost, and cover crop restitution) on trace element transfer from soil to plants; and (2) conduct a detailed characterization of the applied organic matters. Experiments were conducted both in controlled greenhouse and field conditions considering various trace element contamination contexts in Wallonia, Belgium. Results indicated that the application of exogenous organic matter increased or decreased trace element transfer to soil solutions and plant parts compared to no application modality, suggesting that organic matter served both as a source and retention surface for trace elements. Cattle manure and green waste compost application had the most significant influence, likely due to higher carbon input. Soil properties, however, were identified as key factors controlling the impact of organic matter on trace element transfer. Field and greenhouse experiments yielded different results, with greenhouse conditions likely promoting faster organic matter decomposition and enhancing trace element leaching. Comprehensive chemical characterizations (^{13}C solid-state NMR, Rock-Eval, and Py-GCMS) of both soil and exogenous organic matters revealed that organic matter quality mostly control trace element transfer to soil solution. These findings underline the importance of intrinsic soil characteristics in optimizing trace element management through organic matter inputs.

3.2. Introduction

Trace elements are chemical elements found in small amounts in the environment, typically less than 0.1% in the continental crust (e.g., As, Cd, Cu, Pb, Zn). Despite their low content, they may present adverse effects for human and environmental health above a certain threshold. Originating from both natural (e.g., bedrock weathering) and anthropogenic (e.g., through long-range atmospheric deposition) sources, agricultural soils are also influenced by farming practices, including organic amendments, fertilizers (e.g., Cd and Zn), and phytosanitary products such as fungicides containing Cu (Komárek et al., 2013; Lambert et al., 2007). Yet, trace element present in soils can be transferred to plants, providing a potential pathway for human consumption. The dynamics within the soil–plant system remain insufficiently understood, particularly regarding the factors that influence their retention or transfer. Increased soil retention of essential elements can limit their bioavailability, potentially leading to deficiencies in human populations (Adamo et al., 2014). Conversely, the mobilization of potentially harmful elements via the soil solution can increase toxicity risks for living organisms. A balance is then required between these two opposing processes, which depends on the element considered (He et al., 2005).

Application of exogenous organic matter (e.g., manure, animal slurry, compost, cover crop restitution, and sewage sludge) in agricultural soils is often recommended to improve soil chemical and physical fertility. Beyond their origins, organic matters exhibit significant diversity and can be categorized according to their chemical properties and agronomic potential (Lashermes et al., 2010). Yet, exogenous organic matter input can significantly influence the dynamics of trace elements through modifying the soil organic matter (SOM) chemistry, offering potential lever to address environmental and public health concerns (Montagne et al., 2007). Indeed, SOM is a key parameter in the bioavailability of trace elements (Ondrasek et al., 2019), as it constitutes a reactive surface that enables the retention of trace elements in the soil (Ahmad and Prasad, 2012). This is primarily attributed to its diverse functional groups, such as carboxyl and phenolic groups, which have strong affinities for trace elements depending on pH conditions, thereby regulating their biogeochemical cycling in the environment (Adusei-Gyamfi et al., 2019; Xia et al., 1997). However, declining organic matter levels in European agricultural soils are reducing this retention capacity (Virto et al., 2015),

leading to the migration of these elements out of the soil-plant system (e.g., groundwater contamination, micronutrient loss, etc.) and thus to potential deficiencies in essential trace elements (Jones et al., 2017).

In this context, the aim of this study was twofold: first, to assess the influence of applying three types of exogenous organic matters (cattle manure, green waste compost, and cover crop restitution) on the transfer of trace elements from soil to plants under varying environmental contexts and trace element concentrations, both in controlled greenhouse experiment and under real field conditions; and second, to conduct a detailed characterization of the applied organic matters (including chemical and structural composition) to better understand their role in the transfer of trace elements.

3.3. Materials and methods

3.3.1. Study area and soil sampling

The study area considered four study sites with distinct environmental contexts and varying trace element contents (Wallonia, Belgium), including: (1) Vieusart as an uncontaminated site from Walloon Brabant (UCLouvain experimental farm); (2) Sainte-Walburge and (3) Bressoux as two anthropogenically contaminated sites located in the province of Liège that showed a gradient of trace element content with industrial artifacts from 18th-century metal, textile, and coal industries (e.g., coal, clinker, slag, and construction debris); and (4) Aubange as a naturally-enriched (i.e., lithogenic enrichment) site situated in the Belgian Lorraine in the province of Luxembourg.

Vieusart is characterized by a loamy agricultural soil typical of northern Wallonia, classified as a Luvisol according to the World Reference Base for Soil Resources (WRB; Mantel et al., 2023) and located on a sandy formation with clay variations (Sint-Huibrechts-Hern formation) covered by a thick layer of aeolian loess deposit (Brabant silt plateau; Herbosch and Blockmans, 2005). Sainte-Walburge is marked by a loamy agricultural soil classified as a Luvisol/Cambisol and located on a clayey chalk formation (Gulpen Formation) surmounted by a red clay with flints, while Bressoux has a sandy loam agricultural soil classified as a Luvisol and located on alluvial deposits (Ancient

Alluvium; Barchy and Marion, 2000). Finally, Aubange is characterized by a loamy-stony agricultural soil classified as a Cambisol and located on the Aubange formation composed of a complex of sandstone, ferruginous and non-ferruginous calcareous sandstone, siltstone, and mudstone (Belanger et al., 2002). The four sites studied have a temperate oceanic climate, with average annual air temperatures ranging from 9.4 °C in Aubange to 11.2 °C in the Liège region, and average annual precipitation ranging from 790 mm in Vieusart to 1100 mm in Aubange.

The experiment was carried out on both controlled (greenhouse) and real (in situ, field) conditions. The greenhouse experiment was conducted for 88 days on the soil samples from the four sites described above: Vieusart (50°40'47" N, 4°38'8" E), Sainte-Walburge (50°39'52" N, 5°35'20" E), Bressoux (50°38'15" N, 5°36'39" E), and Aubange (49°34'34" N, 5°46'5" E). At each site, approximately 200 L of soil material were randomly collected from the top 20-cm depth within a 7-m diameter circle using a spade and a shovel. Given that the majority of agricultural soils in Wallonia (Belgium) are free from trace element contamination, and to ensure representativity, the field experiment was conducted exclusively at the uncontaminated site of Vieusart (50°40'15" N, 4°37'54" E) over two consecutive years.

3.3.2. Exogenous organic matter

Three distinct exogenous organic materials were considered for both experiments, i.e., cattle manure, green waste compost, and cover crop restitution (considered as exogenous even though it is usually already present on the plot). Cattle manure, primarily composed of hay, straw, and animal excrement, was collected from the experimental farm of UCLouvain. Green waste compost (<15 mm) was obtained from the composting platform in Basse-Wavre (Walloon Brabant) and resulting of the composting of green waste materials, such as garden waste, dead leaves, grass clippings, branches, and plant debris. Cover crop restitution considered in this study were plant fragments (crop residues) that remained in the field post-harvest. Depending on the experiment, various mixtures of three plant species were used as cover crop restitution. For the greenhouse experiment, the residues consisted of common oat (*Avena sativa*), field mustard (*Sinapis arvensis*), and lacy phacelia (*Phacelia tanacetifolia*), all collected from the same uncontaminated site as the soil material in Vieusart. In the two in-situ consecutive years experiment,

the residues restituted directly to the field were composed of sorghum (*Sorghum bicolor* × *Sorghum sudanense*), Egyptian clover (*Trifolium alexandrinum*), and common sunflower (*Helianthus annuus*) in the first year, and Egyptian clover (*Trifolium alexandrinum*), lacy phacelia (*Phacelia tanacetifolia*), and lopsided oat (*Avena strigosa*) in the second year.

3.3.3. Greenhouse experiment

Influence of exogenous organic matter application on trace element transfer from uncontaminated and gradually contaminated soils soil to plant (maize, *Zea mays*) was first conducted in controlled conditions (UCLouvain experimental greenhouses, Louvain-la-Neuve, Belgium) from April to July 2021 (88 days). Collected soil materials were dried (25 °C in a drying room for seven days) and sieved at 1.2 cm. Approximately 15 kg of the sieved soil were mixed with 20 g of NPK 9-7-14 (equivalent to 240 kg_N ha⁻¹) and exogenous organic matters (if applied: 245 g of cattle manure or green waste compost corresponding to 35 t ha⁻¹ or 35 g of cover crop restitution corresponding to 5 t ha⁻¹), and then potted (10 L pots of 30 cm in diameter and 30 cm in height) before sowing one maize seed in each pot. For representativeness purpose, three replicates per soil were considered, totaling 48 pots (4 sites × 4 modalities × 3 replicates). During the experiment, each pot was watered with 1 to 3 L per week of tap water according to the weather conditions. In each pot, a rhizon (19.21.21F, Rhizosphere, Wageningen, The Netherlands) connected to a 60-mL polypropylene syringe (BD Plastipak Luer Lock) was installed vertically in the top 10 cm of the soil (Argo et al., 1997) to collect soil solution. Average greenhouse ambient temperature and air humidity were 22.9±4.2 °C and 61±13%, respectively.

Soil solutions were collected three times during the experiment (5th May, 26th May, and 22nd June 2021) for trace element analysis (except for the solutions collected on 26th May dedicated for dissolved organic carbon analysis). Plant samples were collected once at the end of the experiment by separating the roots, stems, and leaves of maize as well as a sample of soil (few grams) from each pot after the experiment (mixed or not with exogenous organic matter) for further SOM characterization.

3.3.4. Field experiment

The in-situ experiment aimed to study, in real conditions, the influence of exogenous organic matter application on the transfer of trace elements from soil to plant over two consecutive years, on two different crops (spring barley, *Hordeum vulgare*, and maize, *Zea mays*). The experiments were carried out from 24th March to 29th July 2022 (year 1) and from 8th May to 20th September 2023 (year 2) on the selected plot (74 m × 46 m) of the uncontaminated site of Vieusart. A part of the plot was divided into four distinct land strips (74 m long and 3 m wide) corresponding to exogenous organic matter application modalities. A first land strip was not amended with organic matter, constituting the control. Then, the last three strips were amended on 24th March 2022 and 8th May 2023, using agricultural machinery, with cattle manure (45 t ha⁻¹), green waste compost (48 t ha⁻¹), and the restitution of cover crop (8 t ha⁻¹). Each strip was subdivided into three sampling areas (3 m × 1 m sampling sub area), distributed to cover all the heterogeneity of the strip.

Soil, soil solution, and plant samples were collected in each sub-area. Soil samples were collected once before starting of the experiment (23rd March 2022) at two different depths (0-30 cm and 30-50 cm), using an auger. For each depth, six samples per sub-area were collected and then merged into a composite sample representative of the sub-area. Soil solution samples were collected six times (23rd May 2022, 25th May 2022, 9th November 2022, 13th January 2023, 26th July 2023, and 13th September 2023) using five rhizons per sub-area, installed vertically in the top 10-cm soil depth and separated from each other by 1 m. The five soil solution samples collected were merged into a composite sample to ensure sufficient volume for trace element analysis (except for the solutions collected on 25th May dedicated for dissolved organic carbon analysis). The first-year plant sampling (i.e., spring barley) were performed twice (25th May 2022 and 25th July 2022) collecting about twenty specimens per sub-area, while the second-year plant sampling (i.e., maize) were only carried out at the end of the vegetation growth (20th September 2023) collecting one specimen per sub-area.

3.3.5. Sample preparation

Collected soil and exogenous organic matter samples were dried (25 °C in a drying room for seven days), sieved (<2 mm), and ground using a soil grinder (Vibratory Disc Mill RS 200, Retsch, Haan, Germany). For plant material, shoot samples (i.e., stems and leaves) were gently cleaned with distilled water while root samples were cleaned with pressurized tap water to remove soil residues. All plant samples were dried in a ventilated oven at 50 °C. Plant parts were then separated and weighed before grinding (Cyclotec 1093 Sample Mill, Foss A/S, Hillerød, Denmark). Collected soil solution samples were immediately acidified to reach 2% HNO₃ by adding suprapure 65% HNO₃ before trace element analysis, except for soil solutions intended for dissolved organic carbon analysis.

3.3.6. Chemical analyses

Soil and soil organic matter characterization

After sieving at 2 mm, soil samples were characterized for pH, grain-size, and cation exchange capacity analyses (see data chapter 2). Soil organic matter samples were characterized after grinding for soil total carbon and nitrogen contents, ¹³C solid-state nuclear magnetic resonance (¹³C-NMR), pyrolysis-gas chromatography-mass spectrometry (Py-GCMS), and Rock-Eval analyses.

Exogenous organic matter characterization

Ground exogenous organic matter samples were characterized for soil total carbon and nitrogen contents, Py-GCMS, and Rock-Eval analyses.

Trace element concentrations

Trace element concentrations in solid samples were measured in an ISO 6 cleanroom using approximately 100 mg of ground samples digested with a mixture of suprapure acids (HNO₃, HCl, HF) and H₂O₂ in a Savillex Teflon bottle, following the procedure outlined by Arbalestrie et al. (2022). Trace elements (As, Ba, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, Sc, Se, Sn, Sr, Ti, V, and Zn) and rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) concentrations in all samples (solid and liquid) were quantified using inductively coupled plasma mass spectrometry (ICP-MS; iCAP Q ICP-MS,

Thermo Fischer Scientific, Waltham, MA, USA) at the Earth and Life Institute analytical platform (MOCA, UCLouvain, Belgium). The performance of the acidic digestion procedure was evaluated using certified organic (lichen IAEA-336) and mineral (basalt BHVO-2) reference materials. The average recovery, calculated as $(C_{\text{measured}} / C_{\text{certified}}) \times 100$, was $100 \pm 20\%$, except for the elements Ti, V, Cr, Ni, Se, Sn, Er, Tm, and Lu in IAEA-336 (134, 134, 132, 128, 130, 161, 79, 76, and 74%, respectively), and for Sb, As and Se in BHVO-2 (237 and 300, 374%, respectively). To assess the performance of the ICP-MS, a river water standard (SLRS-6) was included, resulting in an average recovery of approximately $100 \pm 20\%$, except for Sc (no data), Cd (163%), Sn (214%), and Se (190%). No contamination was detected during the digestion process, as indicated by average blank concentrations being less than 1% of the sample concentrations. Limits of detection were estimated to be below $0.01 \mu\text{g kg}^{-1}$, except for Ti, Zn, Se, and Mo, which were below $0.1 \mu\text{g kg}^{-1}$.

3.3.7. Data processing and statistical analyses

We calculated several indices derived from the py-GC-MS (Loh et al., 2008; Thevenot et al., 2010) and Rock-Eval (Behar et al., 2001; Derenne and Qu  n  a, 2015) analyses, in order to characterize either the degree of decomposition of lignin or either thermal stability of organic matter in samples.

The acid-to-aldehyde (Ad-to-Al) ratios of combined vanillyl and syringyl units which increase as decomposition of lignin progresses :

$$(\text{Ad}/\text{Al}) = \frac{\text{Ad}_v + \text{Ad}_s}{\text{Al}_v + \text{Al}_s}$$

The pyrolyzable carbon (PC) index represents the total amount of carbon ($\text{mg}_C/\text{g}_{\text{sample}}$) released by the sample during the pyrolysis phase:

$$\text{PC} = (\text{S1} + \text{S2}) \times 0.083 + \left(\frac{\text{S3} \times 12}{440} \right) + \left(\frac{\text{S3CO} + \frac{1}{2} \text{S3}'\text{CO}}{280} \times 12 \right)$$

The residual carbon (RC) index represents the total amount of carbon ($\text{mg}_C/\text{g}_{\text{sample}}$) released by the sample during the oxidation phase:

$$\text{RC} = \left(\frac{\text{S4CO}_2 \times 12}{440} \right) + \left(\frac{\text{S4CO} \times 12}{280} \right)$$

Total organic carbon (TOC) of a sample ($\text{mg}_C/\text{g}_{\text{sample}}$) was obtained by combining the contributions from pyrolyzable carbon (PC) and residual carbon (RC) produced during pyrolysis and oxidation, respectively.

The hydrogen index (HI), analogous to the hydrogen/carbon ratio, provides an indication of the proportion of hydrogenated compounds present in the sample ($\text{mg}_{\text{hydrocarbons}}/\text{g}_{\text{TOC}}$).

$$\text{HI} = \frac{\text{S2} \times 100}{\text{TOC}}$$

The oxygen index (OI), analogous to the oxygen/carbon ratio, reflects the degree of oxidation of the organic matter within the sample ($\text{mg}_{\text{CO}_2}/\text{g}_{\text{TOC}}$).

$$\text{OI} = \frac{\text{S3} \times 100}{\text{TOC}}$$

Statistical analyses were performed using R version 4.0.4 (R Core Team, 2021). For testing statistically significant differences, the parametric Student's *t*-test test was applied with a significance level of $\alpha = 0.05$. All results have been presented using the *ggplot2* R package (Wickham, 2016) or Excel. The influence of experimental modalities was assessed comparing exogenous organic matter application modality and control modality. An increase of the value was considered as a “positive effect” and a decrease as a “negative effect”.

3.4. Results and discussions

3.4.1. Transfer of trace elements following exogenous organic matter application

Greenhouse experiment

We first investigated the influence of exogenous organic matter application (i.e., cattle manure, green waste compost, and cover crop restitution) on trace element concentrations in different compartments: shoots (Figure III.12), roots (Figure III.13), and soil solutions (Figure III.14). Considering shoot contents (Figure III.12), the effect was either negative (i.e., decreased contents) or positive (i.e., increased contents) in the exogenous organic matter application modalities compared to the control (i.e., no application)

depending on the soil and trace element considered. For instance, the uncontaminated soil (i.e., Vieusart) mostly displayed positive effects, especially for Ba, Mo, and Se. Note that only few statistically significant effects ($p < 0.05$) were observed. Surprisingly, both anthropogenically contaminated soils showed distinct trends: the highly contaminated soil (i.e., Bressoux) predominantly exhibited negative effects across most trace elements (about 30% of element/modality combinations with $p < 0.1$; e.g., Co, Cu, and Mo), while the moderately contaminated soil (i.e., Sainte-Walburge) predominantly presented positive effects (about 40% of element/modality combinations with $p < 0.1$; e.g., Ba, Cu, Mo, and Zn). Results showed that the type of soil, and related soil physical and chemical characteristics, was the main factor for controlling the effect of exogenous organic matter application on trace element transfer to plant. Roots also displayed a soil-dependent behavior (i.e., mostly negative effects in the uncontaminated soil and positive effects in both anthropogenically contaminated and naturally-enriched soils; Figure III.13). However, Mo always exhibited a positive effect, whatever the soil considered (except for Aubange without significant differences). Finally, effects of exogenous organic matter application on soil solution concentrations (Figure III.14) showed predominantly positive effects across all four soils, particularly for Cu, Mo, and Sn. This indicates a higher mobilization of trace elements into natural waters after application of exogenous organic matter. Note that soil solutions ($<0.15 \mu\text{m}$) also include colloids, specifically produced by exogenous organic matter, that are not necessarily available for plants.

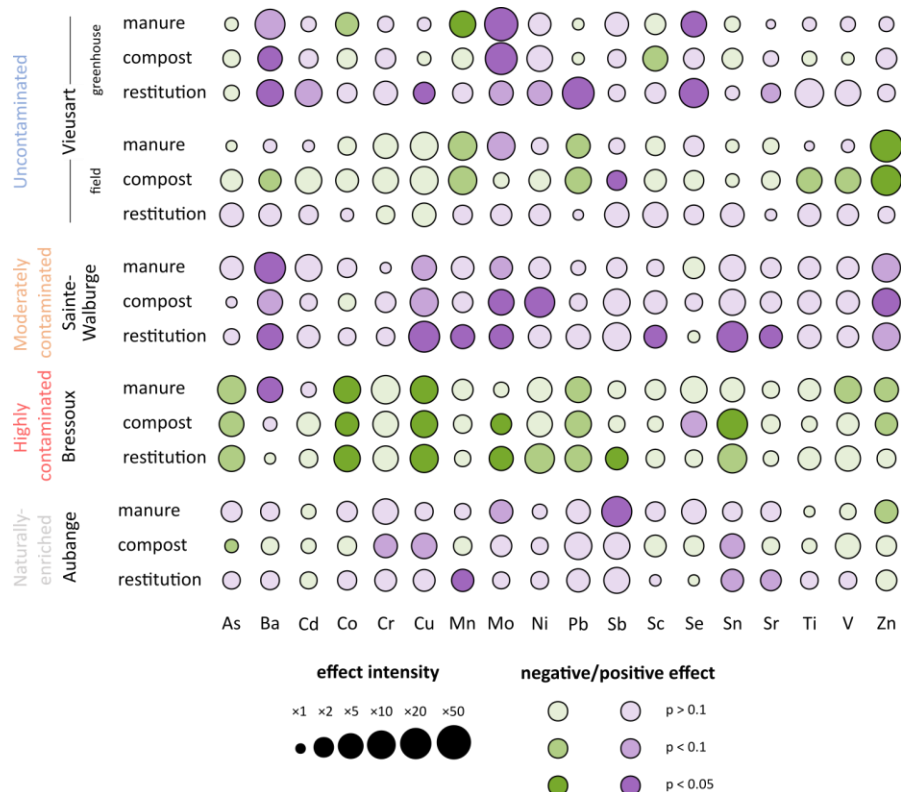


Figure III.12 - Negative (i.e., decrease) or positive (i.e., increase) effects of exogenous organic matter application on trace element contents in shoots (maize; $n = 3$) in uncontaminated (Vieuxart), anthropogenically contaminated (Sainte-Walburge and Bressoux), and naturally-enriched (Aubange) soils from a greenhouse experiment (except for Vieuxart where both greenhouse and field experiments were considered). The effect intensity corresponds to the effect ratio between exogenous organic matter application modality and control modality, whether positive or negative.

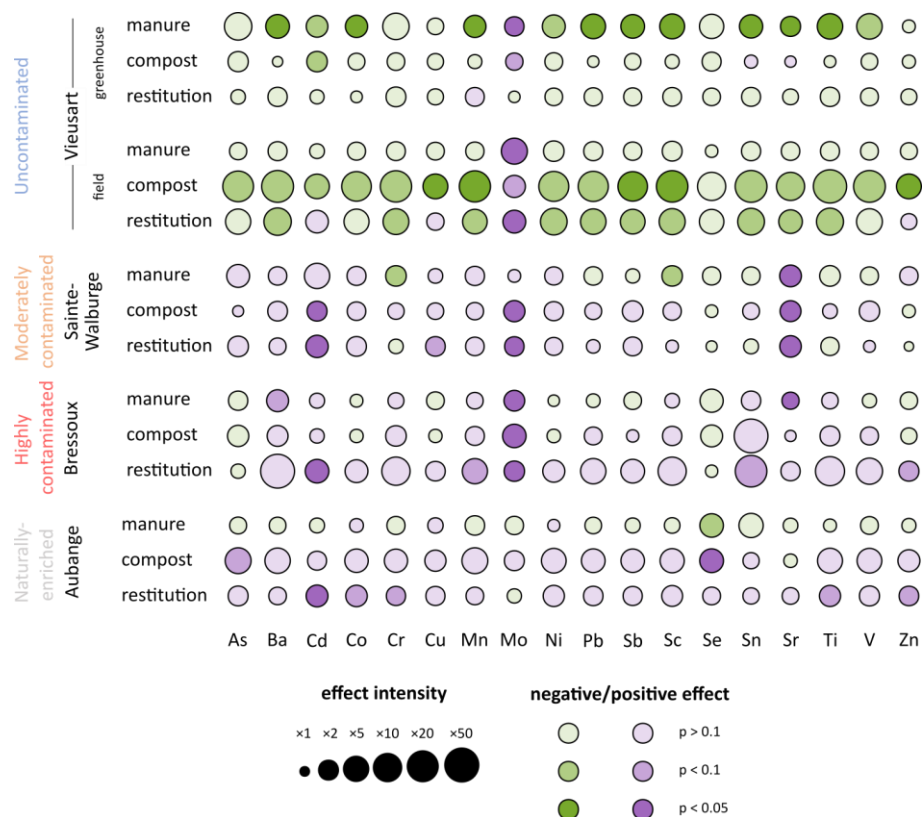


Figure III.13 - Negative (i.e., decrease) or positive (i.e., increase) effects of exogenous organic matter application on trace element contents in roots (maize; $n = 3$) in uncontaminated (Vieusart), anthropogenically contaminated (Sainte-Walburge and Bressoux), and naturally-enriched (Aubange) soils from a greenhouse experiment (except for Vieusart where both greenhouse and field experiments were considered). The effect intensity corresponds to the effect ratio between exogenous organic matter application modality and control modality, whether positive or negative.

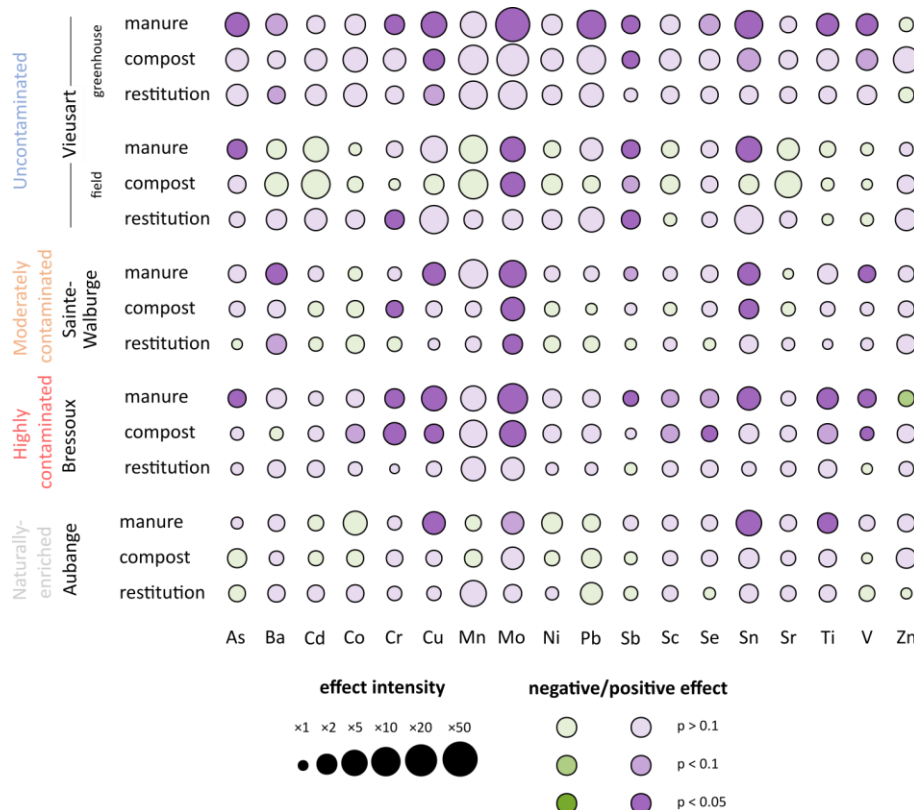


Figure III.14 - Negative (i.e., decrease) or positive (i.e., increase) effects of exogenous organic matter application on trace element concentrations in soil solution (maize; n = 3) in uncontaminated (Vieuxart), anthropogenically contaminated (Sainte-Walburge and Bressoux), and naturally-enriched (Aubange) soils from a greenhouse experiment (except for Vieuxart where both greenhouse and field experiments were considered). The effect intensity corresponds to the effect ratio between exogenous organic matter application modality and control modality, whether positive or negative.

These observations can be attributed to the dual role of organic matter, which acts both as a source of trace elements and as a retention surface capable of adsorbing trace elements (Karabcová et al., 2015). Indeed, exogenous organic matters are frequently responsible for trace element input in agricultural soils (Azimi et al., 2004; Benke et al., 2008; Juste and Robert, 2000). This could explain the consistent positive effects observed in the soil solutions (up to 35 times the control concentration for Mo). The contribution of water-extractable trace elements from exogenous organic matters, compared to those from the soil, exhibited a wide range depending on the elements and soil types (Faridullah et al., 2012; Sushkova et al., 2021). In some cases, these contributions were substantial (up to 100%), as observed for Zn suggesting

that the cattle manure provided an exchangeable Zn pool at least as large as that of uncontaminated soil (Appendix VI.1, Table VI-9). Note that the contribution of total trace elements from organic matter was low compared to the soil one (maximum observed was 6% of Cu from the green waste compost in Vieusart; Appendix VI.1, Table VI-10).

Conversely, exogenous organic matter can interact with trace elements, modifying their mobility through two primary mechanisms: (1) complexation with insoluble organic compounds, leading to a decrease in the element mobility (Bataillard et al., 2003), which may explain the reduction in soil solution concentrations following the addition of exogenous organic matter (not observed here, except for Zn in Bressoux after cattle manure application); and (2) complexation with dissolved organic matter, leading to increase the element mobility (Li et al., 2015; Tang et al., 2019), which makes trace elements available for root uptake. Since soil solutions had predominantly positive effects, while plant showed contrasting influence, we hypothesize that the trace element contribution by exogenous organic matter always affects soil solutions (mainly for Cu, Mo, and Sn), whereas organic matters may counteract this new pool of elements by complexing both initial and newly added trace elements in some soils, thus limiting the plant accumulation.

In addition, the application of exogenous organic matter may influence soil properties, such as reducing soil pH (Carrillo-González et al., 2006; Mench, 1998), that in turn alter the trace element availability through speciation changes (Pérez-Esteban et al., 2014). In this study, the application of exogenous organic matter increased the $\text{pH}_{\text{H}_2\text{O}}$ by an average of 0.28 pH unit, from -0.1 (cover crop in Vieusart and Bressoux) to $+0.8$ (green waste compost in Sainte-Walburge; Appendix VI.1, Table VI-12). The highest effect was observed in Sainte-Walburge. This may contribute to an increased mobility for cationic trace elements (Carrillo-González et al., 2006), as observed in shoots in Saint-Walburge.

Field experiment

The influence of exogenous organic matter application on trace element transfer was also investigated in field conditions for the uncontaminated soil (Vieusart). Results for shoots revealed different behaviors in terms of both effect type and intensity compared to the greenhouse experiment (Figure III.12). Specifically, the field results demonstrated predominantly negative

effects (i.e., lower concentrations after exogenous organic matter application compared to the control), particularly for Mn, Pb, and Zn. Similarly, the effects of exogenous organic matter application on root contents were largely negative for multiple elements (i.e., Ba, Cr, Cu, Mn, Ni, and Pb; Figure III.13). Conversely, few differences were observed in soil solution concentrations (Figure III.14) between field and greenhouse experiments, with both showing positive effects (i.e., larger trace element mobilization). These observed differences could be attributed to the distinct conditions between the two experiments. Indeed, higher temperatures recorded in the greenhouse (reaching a maximum of 37.2 °C) may accelerate organic matter decomposition rates (Erhagen et al., 2013), and more frequent watering could have amplified leaching of elements, both resulting in element release out of the soil-plant system. This implies that results obtained in our greenhouse experiment may be partly biased, exacerbating the effect of trace element mobilization.

3.4.2. Organic matter quantity and quality

Soil organic matter characterization

Organic carbon contents measured in soil samples from the greenhouse experiment showed a wide range resulting from high values in both anthropogenically contaminated soils (11.1 and 15.8% for Sainte-Walburge and Bressoux, respectively; Table III-3). On average, they reached 7-times the organic carbon content from the uncontaminated and naturally-enriched soils (1.3 and 2.4%, respectively; Table III-3). Only the last two soils showed values within the range of organic carbon contents generally observed in European agricultural soils (Matschullat et al., 2018). This discrepancy between uncontaminated/naturally-enriched soils and both anthropogenically contaminated soils may result from the charcoal load found in contaminated soils. The dissolved organic carbon (DOC) concentration in uncontaminated soil without organic matter application was $9.6 \pm 2.5 \text{ mg L}^{-1}$. In comparison, DOC concentrations were 1.4-, 1.8-, and 0.8-times higher in moderately contaminated, highly contaminated, and naturally-enriched soils, respectively. The ^{13}C -NMR performed on after-experiment soil samples from the greenhouse experiment revealed a clear difference between uncontaminated and anthropogenically contaminated soils (Figure III.15A), including higher O-alkyl C in the uncontaminated soil (50%) and aromatic C in

both contaminated soils (up to 55%). This confirms the charcoal contribution in the anthropogenically contaminated soils (Kögel-Knabner, 1997; Song and Schobert, 1996; Yang et al., 2021) and explained the C/N ratios much higher than those observed in European soils (ca. 30, i.e., 3-times the ratio in the uncontaminated soil; Matschullat et al., 2018). Although alkyl C/O-alkyl C ratios showed distinct values between uncontaminated and contaminated soils (0.45, 0.96, and 1.05, respectively), it is difficult to draw any conclusions due to the distinct nature of soil organic matter.

Results from the Rock-Eval pyrolysis showed lower HI and OI values in the anthropogenically contaminated soils (30-40 $\text{mg}_{\text{hydrocarbons}}/\text{g}_{\text{Corg}}$ and 40-50 $\text{mg}_{\text{CO}_2}/\text{g}_{\text{Corg}}$, respectively) compared to the uncontaminated and naturally-enriched soils (90-110 $\text{mg}_{\text{hydrocarbons}}/\text{g}_{\text{Corg}}$ and 310-760 $\text{mg}_{\text{CO}_2}/\text{g}_{\text{Corg}}$, respectively; Table III-3). The similar trends between both indices were not expected following the natural decomposition process of soil organic matter (Disnar et al., 2003). Indeed, decreasing HI and increasing OI result from dehydrogenation and oxidative transformation of organic compounds during the decomposition, respectively (Sebag et al., 2016). In our study, the anthropogenically contaminated soils only reflected a high aromaticity (Figure III.15A), resulting in lower hydrogen/carbon ratios (Bandara et al., 2005; Kögel-Knabner, 1997), and thus lower HI values. Furthermore, the absence of carbon loss (i.e., carbon retained in the aromatic rings) enable relatively low OI to be maintained. These two indices therefore fail to highlight the different degrees of organic matter maturation between these soils. The RC values confirmed the presence of more recalcitrant organic compounds (i.e., degraded at higher temperatures) in the contaminated soils (>10%, while it reached <1% in the uncontaminated soil; Table III-3).

Finally, the Ad/Al ratios from the GC-MS pyrolysis, considering both vanillyl and syringyl units, showed increasing values from the uncontaminated (1.69) soil to the highly anthropogenically contaminated soil (2.32). The lowest Ad/Al ratio was observed in the naturally-enriched soil (1.35; Table III-3). This may suggest a higher degree of lignin degradation in contaminated soils, reflected by the oxidation of aldehydes to acids (Kögel-Knabner, 2000). However, since no information was available on the complete organic matter amendment used in recent years, we cannot evaluate the turnover rate of soil organic matter in these four soils.

Table III-3 - Chemical parameters (n=2) and indices (n=3) calculated for soil organic matter and exogenous organic matter.

		C	N	C/N	$\frac{Ad_v + Ad_s}{Al_v + Al_s}$	HI	OI	PC	RC
		[%]		[-]		[mg _{hydrocarbons} /g _{TOC}]	[mg _{CO2} /g _{TOC}]	[wt%]	[wt%]
Soil samples	Uncontaminated (Vieusart)	1.30 (0.05)	0.13 (0.01)	10.1 (0.3)	1.69 (-)	107 (-)	312 (-)	0.2 (-)	0.7 (-)
	Moderately contaminated (Sainte-Walburge)	11.1 (0.1)	0.35 (0.01)	31.9 (0.2)	1.82 (-)	32 (-)	38 (-)	0.45 (-)	9.5 (-)
	Highly contaminated (Bressoux)	15.8 (0.4)	0.52 (0.01)	30.7 (1.0)	2.32 (-)	41 (-)	54 (-)	0.9 (-)	14.1 (-)
	Naturally-enriched (Aubange)	2.4 (0.5)	0.23 (0.01)	10.8 (1.9)	1.35 (-)	94 (-)	761 (-)	0.4 (-)	0.9 (-)
Exogenous organic matter samples	Cattle manure	37.7 (0.5)	3.00 (0.05)	12.7 (0.4)	1.49 (-)	289 (23)	247 (33)	10.5 (0.8)	20.8 (1.0)
	Green waste compost	27.3 (0.1)	1.90 (0.04)	14.5 (0.2)	2.74 (-)	252 (8)	176 (14)	6.7 (0.1)	17.0 (0.1)
	Cover crop restitution	39.4 (0.2)	2.60 (0.06)	15.3 (0.5)	1.97 (-)	336 (6)	311 (10)	13.3 (0.3)	20.0 (0.5)

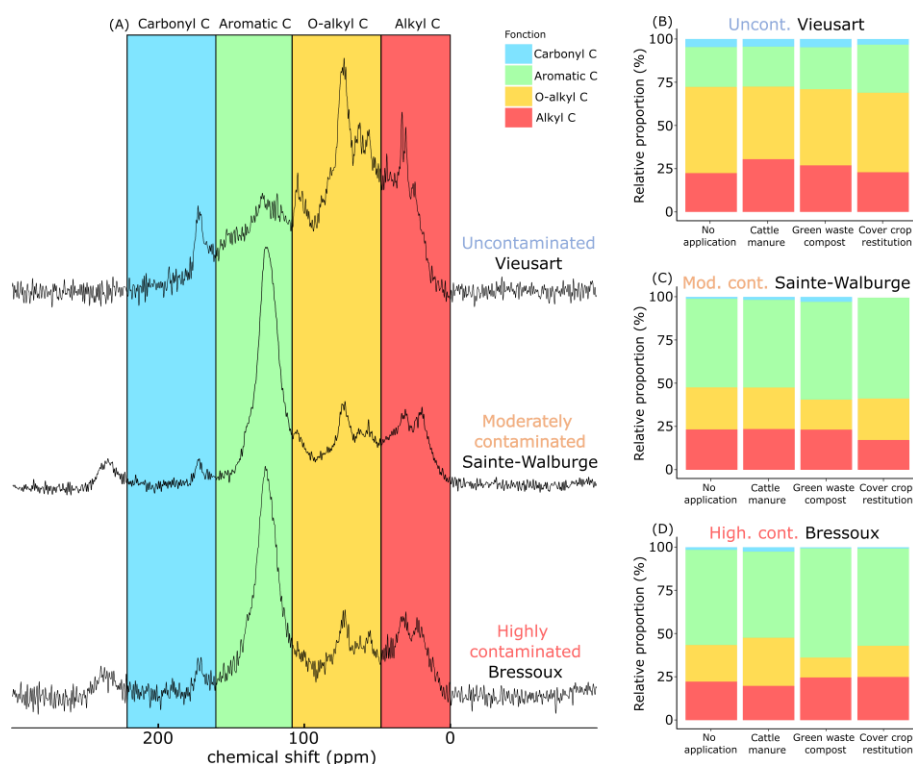


Figure III.15 - ^{13}C -NMR spectra for the uncontaminated (Vieuxart), moderately (Sainte-Walburge), and highly (Bressoux) contaminated soils for the no organic matter application modality (A) and relative proportion of Carbonyl C, Aromatic C, O-alkyl C and Alkyl C in uncontaminated (B), moderately (C) and highly (D) contaminated soils for the organic matter application modalities.

Exogenous organic matter characterization

The organic carbon content of exogenous organic matters was comparable for cattle manure and cover crop restitution ($31.3 \pm 1.8\%$ and $33.3 \pm 0.8\%$, respectively; Table III-3). These values were notably higher than the organic carbon content of the green waste compost ($23.7 \pm 0.2\%$), as observed in previous studies (Fronning et al., 2008; Hartz et al., 2000). However, C/N ratios were close together in the three exogenous organic matters, ranging from 12.7 for cattle manure to 15.3 for cover crop restitution. These values fell between those of fresh green cuttings (7-15; Matschullat et al., 2018) and more decomposed organic matter (ca. 20; Matschullat et al., 2018), and suggests a relatively faster decomposition state for cattle manure compared to the other two materials (Hartz et al., 2000). The cation exchange capacity (CEC) was determined exclusively for cattle manure and green waste

compost, with measured values of 37 ± 8 and 55 ± 1 $\text{cmol}_c \text{ kg}^{-1}$, respectively ($n = 2$). For all soil, the application of exogenous organic matter consistently resulted in higher DOC concentrations compared to the control without organic matter application. The extent of this increase varied depending on the exogenous organic matter applied: cattle manure showed a DOC concentration approximately 6-times greater, green waste compost led to a 3- to 4-fold increase, while cover crop residues generally had no effect (except in Aubange, where DOC concentration doubled). The HI and OI values were lower in the green waste compost ($252 \pm 8 \text{ mg}_{\text{hydrocarbons}}/\text{g}_{\text{Corg}}$ and $176 \pm 14 \text{ mg}_{\text{CO}_2}/\text{g}_{\text{Corg}}$, respectively; Table III-3) compared to the other organic matters, highlighting a lower content of hydrogen-rich organic compounds and a less pronounced decomposition degree. However, they were close to data from fresh organic materials (Sebag et al., 2016). Finally, Ad/AI ratios showed values within the same range as those observed in soils, ranging from 1.49 for cattle manure to 2.74 for green waste compost (Table III-3). This suggests a higher degree of lignin degradation in the green waste compost resulting from the maturation process before obtaining compost.

Influence of exogenous organic matter application on soil organic matter characterization

For each soil, the application of cattle manure and green waste compost consistently resulted in a slight increase in organic carbon content compared to the no application modality (ranging from $+0.5 \pm 0.1\%$ for uncontaminated/naturally enriched soils to $+1.2 \pm 1.6\%$ for both anthropogenically contaminated soils). In contrast, the restitution of cover crop residues did not modify organic carbon content, except for the moderately contaminated soil (i.e., Sainte-Walburge), where an average increase of $+2 \pm 1\%$ was observed. In general, many indices and parameters revealed greater differences between soils than between the modalities. This can be illustrated by ^{13}C -NMR spectroscopy (Figure III.15B-D), which showed that, for a given soil, the organic matter application did not lead to significant differences compared to the absence of application: e.g., from 42 (cattle manure) to 50% (no application) for O-alkyl C in Vieusart, from 52 (no application) to 58% (cover crop restitution) for aromatic C in Sainte-Walburge, and from 50 (cattle manure) to 63% (green waste compost) for aromatic C in Bressoux. This highlights the dominant influence of the contrasted soil

considered on organic matter signature compared to those of the exogenous organic matter application.

However, certain indices, such as HI, OI, PC, and Ad/Al, exhibited differences between application modalities. A comparison between before and after the experiment considering the no application modality, revealed that PC and HI values remained quite consistent, varying from -7 to +15%. In contrast, Ad/Al ratio showed more variable data, potentially due to the lack of replicates and the less integrative nature of this indicator. The maximum increase was observed in Sainte-Walburge (+74%, higher oxidation state), despite no convincing explanation. The application of exogenous organic matter to soil actually generates a mixture of signatures from both exogenous and soil organic matters. A comparison between the observed and the theoretical expected results revealed discrepancies depending on the index considered. For instance, the observed PC reached up to -92% compared to the expected value for cattle manure application, particularly in Vieusart. In Aubange, where the soil contribution was lower, the more pronounced effect of exogenous organic matter that would be expected was not observed. This suggests that the exogenous organic matter was either rapidly degraded during the experiment, or promoted the decomposition of soil organic matter (i.e., priming effect).

To further investigate the effects of exogenous organic matter application, delta (Δ) values were calculated for various indices obtained from pyrolysis-GC-MS and Rock-Eval analyses. These Δ values were determined for each after-experiment soil sample by calculating the difference between the observed data after exogenous organic matter application and the no application modality. Results showed variable influences on Ad/Al ratio (one replicate; Figure III.16A), both between modalities and soils. Indeed, all modalities in Vieusart exhibited a decrease in Ad/Al ratio (ranging from -0.31 for both cattle manure and green waste compost to ca. 0 for cover crop restitution) compared to the no application modality. This trend was also observed in Sainte-Walburge, but with a greater order of magnitude (from -0.11 to -1.60 for green waste compost and cattle manure, respectively). These findings suggest a lower degree of organic matter degradation when exogenous organic matter was applied. In contrast, the addition of exogenous organic matter in Bressoux tended to increase the Ad/Al ratio (up to +1.23 for cover crop restitution), except for cattle manure that resulted in a slight

decrease (-0.11). A possible explanation is that exogenous organic matter promotes lignin degradation through microorganism stimulation (Liu et al., 2023; Ngo, 2014), except in soils with more recalcitrant SOM, such as in Bressoux (e.g., due to the presence of charcoal). However, the same trend was not observed in Sainte-Walburge, which also has a non-negligible charcoal content. Finally, in Aubange, the application of exogenous organic matter induced minimal impact on the Ad/Al ratio (<0.1), except for green waste compost that led to a slight increase ($+0.28$).

More consistent trends were observed in HI and PC in response to exogenous organic matter application. Indeed, we generally observed an increase in HI values after manure and compost application across all soils (except for compost in Aubange; Figure III.16B), indicating higher proportion of hydrogen-rich compounds. However, no definitive conclusions can be drawn regarding the application modalities due to uncertainties in the data, likely attributable to the high variability in the composition of organic matter (Sebag et al., 2016). The experiment also led to an increase in PC content across all soils (Figure III.16C), showing higher values in anthropogenically contaminated soils. Surprisingly, lower values were found for the cover crop restitution modality, despite the fact that this exogenous organic matter had the highest PC value compared to the other two sources.

In summary, only few differences were highlighted in soil organic matter characterization after application of exogenous organic matter. This may result from a single application, which does not reveal any contrasting effects. However, repeated application in the field could produce more effective results. However, it is important to note that the organic matter applications did not contribute equally to the same amount of carbon. Indeed, if we normalize these effects by carbon unit of the exogenous organic matter and considering the organic carbon originally present in the soil, cover crop restitution exacerbated trends, mainly in Sainte-Walburge and Bressoux.

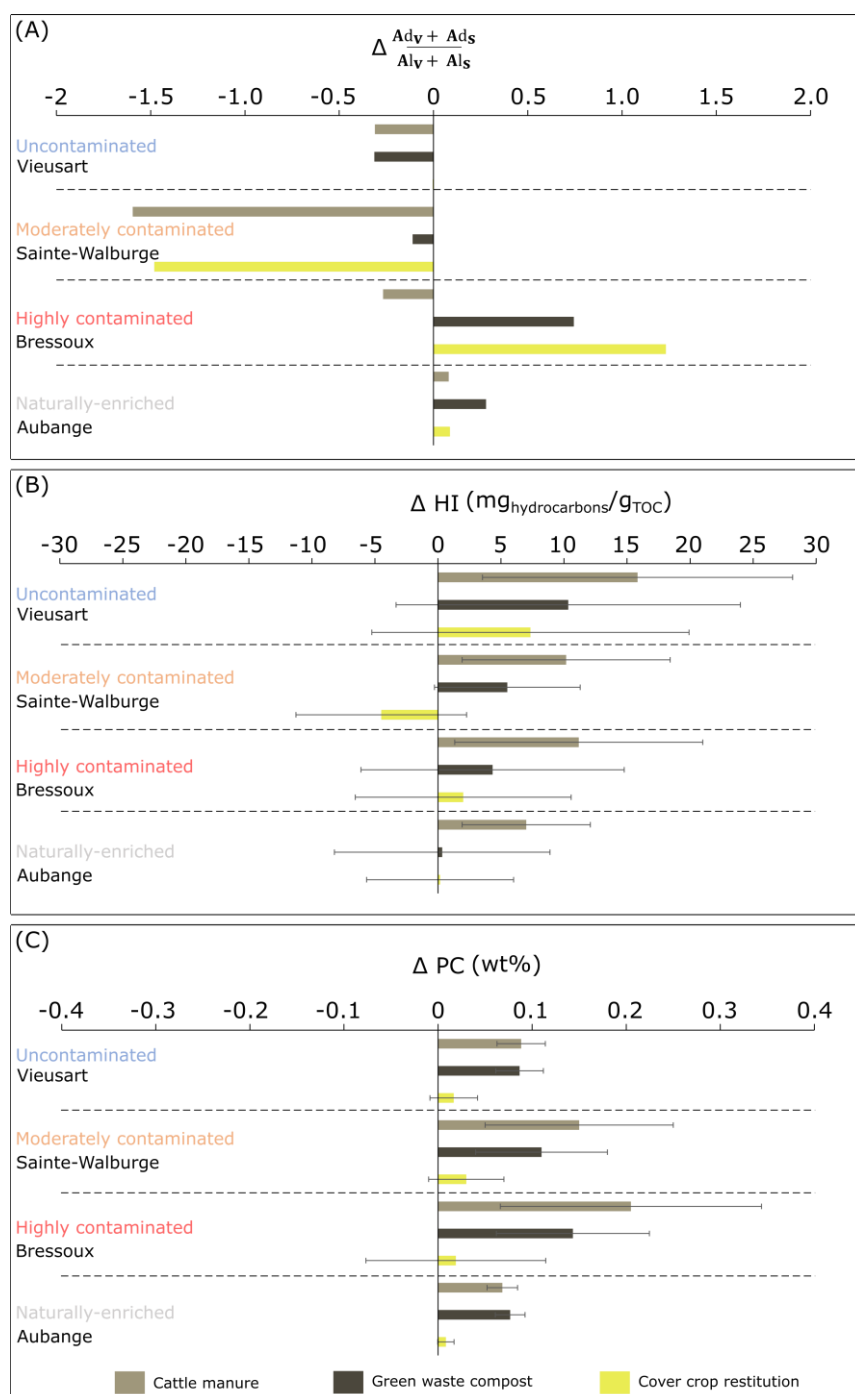


Figure III.16 – Effect of exogenous organic matter application on the acid-to-aldehyde ratio ($Ad_v + Ad_s / Al_v + Al_s$) of combined vanillyl (v) and syringyl (s) units (A), hydrogen index (HI; B), and the pyrolyzable carbon content (PC; C) compare to the no organic matter application modality.

3.4.3. Coupling trace elements and organic matter

We finally coupled the trace element concentrations in soil solutions (Δ concentration) or trace element contents in plant shoots (Δ content) and the specific organic matter characterization (Δ index) both influenced by application of exogenous organic matter to assess the role of organic matter in trace element dynamics. For the soil solution, several elements (e.g., Cu, Sn, and Sb) exhibited a positive correlation with dissolved organic carbon (Appendix VI.1; Table VI-13), suggesting either a mobilization of these trace elements by additional DOC produced by exogenous organic matter, or a potential contribution of trace elements by DOC (Li et al., 2015; Tang et al., 2019). However, this trend appeared to be highly dependent on the specific soil considered and their physical and chemical characteristics. For example, in the uncontaminated soil, Cu was more released in the soil solution for a similar Δ DOC after application of the three exogenous organic matters (Figure III.17A). In contrast, Cu released was independent on the soil considered when studying HI, indicating that changing soil organic matter characteristics may influence the mobilization of these pool of elements in the soil solution (Figure III.17B). Conversely, certain elements (e.g., Zn or Sr) showed no correlation with any of the tested indices (Figure III.17C).

However, heterogeneity was expected in effects on trace element contents and organic matter characteristics, resulting from high soil heterogeneity and since the properties of organic matter and trace elements significantly influence binding kinetics and preferences, largely determined by atomic size and valence electrons (Adusei-Gyamfi et al., 2019). Indeed, soil organic matter is a complex mixture of organic compounds containing various chemical functional groups capable of binding cations, such as trace elements, due to high affinity (e.g., phenolic groups) or high density (e.g., carboxylic groups; Adusei-Gyamfi et al., 2019; Stevenson, 1994). Specifically, phenolic groups form stronger bonds with Cu and Pb, but weaker ones with Cd and Zn. The latter tend to preferentially bind to amine-containing sites and smaller, less aromatic molecules (Cabaniss, 2011, 2009). Furthermore, the exogenous organic matter addition also affects the HI: fresher organic matter typically shows a higher HI, as it is richer in polysaccharides, waxes, lignin, and other biopolymers that contain higher hydrogen content relative to carbon (Disnar et al., 2003). The chemical functions from the organic compounds capable of

binding trace elements then vary with the degree of organic matter decomposition.

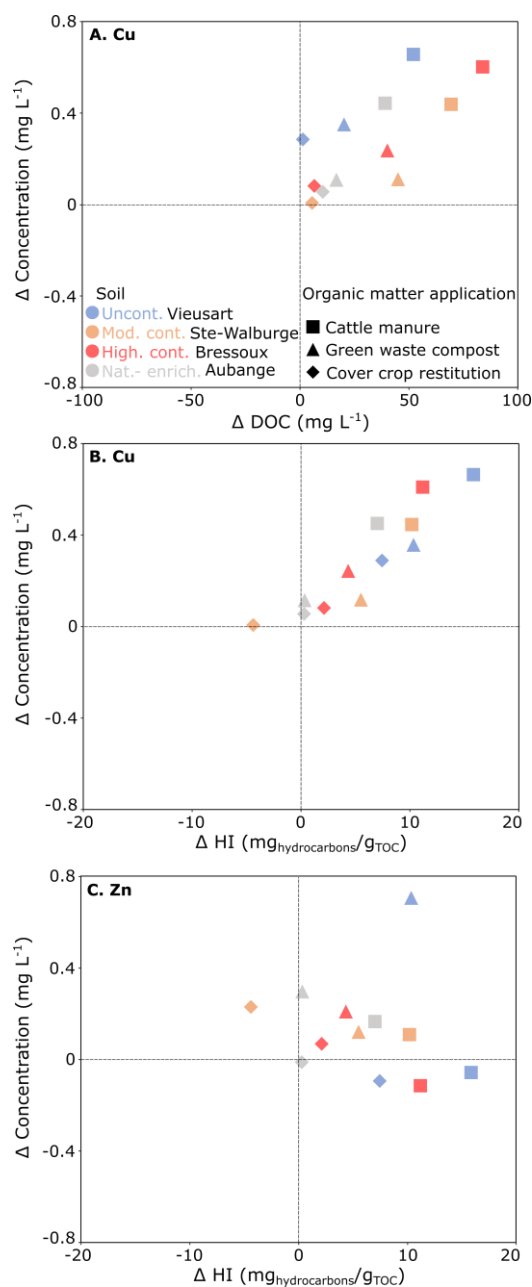


Figure III.17 – Relationships between trace element concentrations in soil solutions (Δ concentration) and organic matter characteristics (Δ index) in exogenous organic matter application modalities compared to no application modality: Cu vs Δ dissolved organic matter (DOC; A), Cu vs Δ hydrogen index (HI, B), and Zn vs Δ HI (C).

However, the relationships observed in the soil solution were no longer evident in the plant shoots. Overall, most trace element contents follow a similar trend, without showing a clear correlation with the indices, such as PC or HI. In contrast, a negative correlation with the Ad/Al ratio was observed for several trace elements (Cu, Zn, Cr, Sn, Ba, etc.). As the Ad/Al ratio increased (indicating greater lignin degradation compared to the no application modality), trace element accumulation in the plant decreased, suggesting a loss of trace element availability with organic matter degradation. This was observed for Cu, Zn, and Cd (Figure III.18A-C) in Bressoux following the application of green waste compost and cover crop restitution. A similar effect was noted for Zn and Cd in Aubange across all modalities of exogenous organic matter application. Conversely, as the Ad/Al ratio decreased (indicating reduced lignin degradation compared to the control), trace element accumulation in plant shoots increased, suggesting an increase in the pool of available trace elements and their uptake by the plant. This trend was particularly pronounced for Cu, Zn, and Cd (Figure III.18A-C) in the uncontaminated soil of Vieusart and the moderately contaminated soil of Sainte-Walburge for all modalities of exogenous organic matter application.

The increase in Δ concentration with a decrease in the Δ Ad/Al ratio on one hand, and the decrease in Δ concentration with an increase in the Δ Ad/Al ratio on the other hand, relative to the control, was challenging to explain and appeared again to be soil-dependent, despite observing opposite trends in soils with similar characteristics, such as the two anthropogenically contaminated soils of Sainte-Walburge and Bressoux. It is important to note that in both cases (soil solution and plant), there was a correlation between the different trace elements; i.e., what was observed for one trace element generally held true for the others as well.

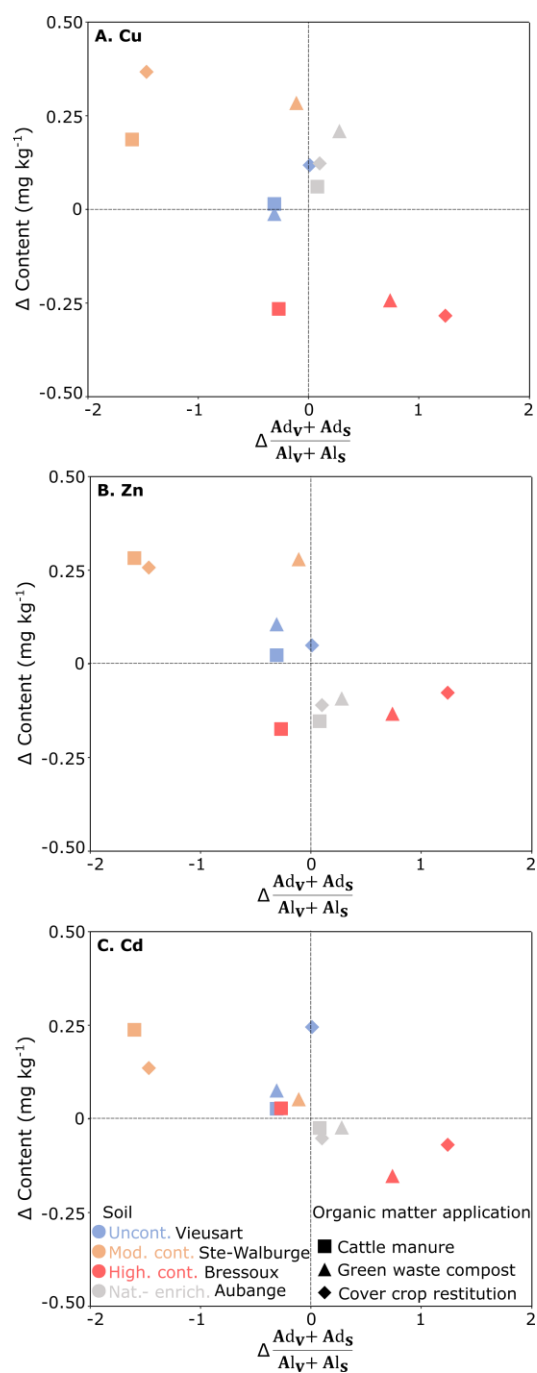


Figure III.18 - Relationships between trace element contents in plant shoots (Δ content) of Cu (A), Zn (B), and Cd (C) and acid-to-aldehyde ratios (Ad/Al) of the organic matter considering both vanillyl (v) and syringyl (s) units in exogenous organic matter application modalities compare to no application modality.

3.5. Conclusion

The influence of exogenous organic matter (cattle manure, green waste compost, and cover crop restitution) application on the transfer of trace elements from soil to plants under varying soil contamination contexts were assessed in both controlled greenhouse experiment and field conditions. The results demonstrated that the application of exogenous organic matter had both positive (increasing) and negative (decreasing) effects on trace element concentrations in soil solutions and plants. The observed differences in trace element contents in plant shoots indicated that soil properties were the main factor controlling the effect of exogenous organic matter application on trace element transfer to plants. In contrast, the consistent positive effects observed in soil solutions highlighted the dual role of organic matter, acting as a source of trace elements and as a retention surface capable of adsorbing trace elements. The contrasting trends observed between soil solutions and plant shoots following organic matter application led to the hypothesis that the trace element input from exogenous organic matter always affects soil solutions (notably for elements such as Cu, Mo, and Sn). However, in certain soils, exogenous organic matter may mitigate this new pool of elements by complexing both native and newly added trace elements, thereby limiting plant accumulation. Moreover, field experiments showed different outcomes compared to greenhouse experiment, which could be attributed to distinct experimental conditions. The higher temperatures and more frequent watering in the greenhouse likely accelerated the decomposition of organic matter ultimately promoting the leaching of trace elements in the soil-plant system.

In addition, a comprehensive characterization of both soil and exogenous organic matters, including chemical composition, was conducted to better understand the role of organic matter in the transfer of trace elements. The results revealed distinct signatures for soil organic matter, enabling differentiation between anthropogenically contaminated soils and naturally-enriched/uncontaminated soils. It was highlighted that soil properties were the primary factor controlling the transfer of trace elements. In contrast, while exogenous organic matter exhibited fewer differences than soil organic matter, certain parameters (such as the HI and Ad/Al ratio) showed contrasting influences on the behavior of trace elements within the soil-plant

system. These effects depended not only on the properties of the trace elements but also on the nature of the exogenous organic matter applied.

4. Influence of exogenous organic matter on metal isotope transfer

4.1. Abstract

Trace elements, including Cu, Pb, or Zn, play a critical role in agroecosystems, influencing both plant and human health. However, their dynamics in the soil-plant continuum remain poorly understood because of the multiple complex processes involved, difficult to extrapolate under different conditions (e.g., uncontaminated vs. contaminated). In addition, agricultural practices, such as application of exogenous organic matter, constitute a key factor influencing trace element availability and transfer in agroecosystems. For instance, organic matter provides reactive surfaces that can further modify trace element dynamics. Yet, non-conventional stable metal isotopes can be used to trace biological and physicochemical processes governing element transfer in soil-plant system. This study aimed to investigate the impact of exogenous organic matter application (cattle manure and green waste compost) on the isotope fractionation of Cu, Zn, Fe, and Pb in agricultural soils. A greenhouse experiment was conducted using maize (*Zea mays*) grown on uncontaminated, anthropogenically contaminated, and a naturally-enriched soils from Wallonia, Belgium. Results revealed that exogenous organic matter application influenced Cu and Zn isotope fractionation between soil and plant compartments, but both direction and magnitude depended on soil, element, and exogenous organic matter considered. Sorption and complexation processes involved minerals (e.g., Fe and Mn oxyhydroxides) and organic surfaces (including different decomposition degrees). Additionally, initial soil Zn and Pb isotope signatures, shaped by pedogenetic and anthropogenic processes, further modulated fractionation. Biological mechanisms, such as siderophore production under Zn or Fe deficiency and metal tolerance strategies under contamination, also impacted element uptake and isotope behavior. These findings underscore the complex interplay between soil characteristics, organic matter application, and plant physiological responses in determining trace element dynamics in agroecosystems. Understanding these processes is essential for optimizing agricultural practices to address both trace element deficiencies and contamination risks.

4.2. Introduction

Dynamics of trace elements in agroecosystems, including metals, metalloids, and non-metals with low content in the environment, may present health issues for human populations with a critical global concern (Alloway, 2012). Indeed, insufficient levels in food products of essential elements, such as copper (Cu) and zinc (Zn), pose significant risks to human health (Muthayya et al., 2013). On the other hand, exceeding threshold values in soils lead to increase the foodstuff content and affect various biochemical processes (Rai et al., 2019). Some elements, such as lead (Pb), have a particular concern since they have no role in biological function and are therefore exclusively toxic (Kushwaha et al., 2018). In agricultural soils, trace elements primarily originate from the parent material but human activities can contribute significantly to elevated trace element levels (Adriano, 2001; He et al., 2005). Indeed, global soil trace element contents have steadily risen over time, largely driven by anthropogenic inputs from industrial and agricultural activities (Komárek et al., 2013; Lambert et al., 2007). Studying the distribution and behavior of trace elements across different environmental compartments is challenging due to their complex physicochemical properties and diverse sources. Moreover, their dynamics within the soil-plant system—which forms the basis of human nutrition—remain poorly understood, particularly concerning the factors governing their retention or transfer in agroecosystems (Antoniadis et al., 2017; Chojnacka et al., 2005).

Among the key factors influencing trace element availability and transfer in agroecosystems, soil organic matter (SOM) plays a crucial role by providing reactive surfaces that enhance trace element retention in soils (Ahmad and Prasad, 2012; Ondrasek et al., 2019). However, declining SOM levels in European agricultural soils (Capriel, 2013; Hanegraaf et al., 2009; Knotters et al., 2022) are reducing this retention capacity, facilitating the mobility of trace elements in the soil-plant system. This may result in potential deficiencies of essential trace elements, a trend projected to accelerate with climate change scenarios (Semba et al., 2022). Conversely, agricultural practices, such as the application of exogenous organic matter, which is often employed to enhance soil chemical and physical properties, can significantly influence trace element dynamics (Montagne et al., 2007; cf. Data chapter 3). It is vital to evaluate the impact of organic matter on trace element behavior, considering both retention processes that may lead to deficiencies and transfer processes that

could increase contamination risks. However, it is not always easy to identify the processes involved simply by examining and comparing soil and plant contents.

For several decades, non-conventional stable isotopes have been widely utilized to trace biological and physicochemical processes governing the uptake and transport of elements within plants. For instance, Cu isotopes have been employed to investigate processes involved in the transfer between soil and plant parts (Ryan et al., 2013; Weinstein et al., 2011; Zheng et al., 2024). The isotopes of iron (Fe), a crucial nutrient for organisms often limited due to its insoluble form in soil, also provide important insights into plant strategies for Fe acquisition, some of which induce Fe isotope fractionation while others do not (Guelke and von Blanckenburg, 2007; Wigganhauser et al., 2022). Moreover, metal isotopes may help to identify sources of elements, particularly in contaminated soils. Indeed, Weiss et al. (2007) and Mattielli et al. (2009) demonstrated that Zn isotopes are valuable tracers for identifying atmospheric contamination sources, including those from mining and smelting operations. Additionally, Pb isotopes have proven to be effective in tracing industrial emissions of Pb (Cloquet et al., 2006; Gelly et al., 2019; Komárek et al., 2008).

In this context, we aimed to: (1) investigate the isotope fractionation of Cu, Zn, Fe, and Pb in the soil-plant continuum in uncontaminated and contaminated soils; and (2) assess the impact of exogenous organic matter application on these isotope fractionations. To achieve this, a greenhouse experiment was conducted with maize plants grown in three distinct agricultural soils and amended with two types of exogenous organic matter: cattle manure and green waste compost.

4.3. Materials and methods

4.3.1. Study area and soil sampling

The study was carried out on three agricultural soils located in Wallonia, Belgium, covering distinct environmental contexts and trace element contents: (1) Vieusart (50°40'47" N, 4°38'8" E) as a typical uncontaminated soil in Walloon Brabant (UCLouvain experimental farm); (2) Bressoux

(50°38'15" N, 5°36'39" E) as an anthropogenically contaminated soil in the province of Liège, exhibiting significant trace element contaminations (e.g., Pb and Zn) with industrial artifacts from 18th century metal, textile, and coal industries (e.g., coal, clinker, slag, and construction debris); and (3) Aubange (49°34'34" N, 5°46'5" E) characterized by a lithogenic enrichment of trace elements (e.g., As, Cr, Fe, and Ni) in the Belgian Lorraine. At each site, approximately 200 L of soil material were randomly collected within a 7-m diameter circle at a depth of 20 cm using spades and shovels.

Vieusart represents a typical loamy agricultural soil in northern Wallonia, classified as a Luvisol according to the World Reference Base for Soil Resources (WRB; Mantel et al., 2023), situated on a sandy formation (Sint-Huibrechts-Hern formation), underlaying by a substantial aeolian loess deposit (Brabant silt plateau; Herbosch and Blockmans 2005). Bressoux is a loamy agricultural soil classified as a Luvisol and situated on alluvial deposits (Ancient Alluvium) containing a mixture of sandy silt, sand, and clay (Barchy and Marion, 2000). Aubange is a loamy-stony agricultural soil classified as a Cambisol and located on the Aubange formation, which comprises a complex composition of sandstone, ferruginous and non-ferruginous calcareous sandstone, siltstone, and mudstone (Belanger et al., 2002). All three research sites had a temperate oceanic climate, with an average annual air temperature ranging from 9.4 °C in Aubange to 11.2 °C in Bressoux. The annual precipitation from 790 mm in Vieusart to 1100 mm in Aubange.

4.3.2. Experimental design

Two distinct exogenous organic materials were considered: cattle manure and green waste compost. Cattle manure, primarily composed of hay, straw, and animal excrement, was collected from the experimental farm of UCLouvain. Green waste compost (size <15 mm) was obtained from the composting platform in Basse-Wavre (Brabant Wallon) and resulting of the composting of green waste materials such as garden waste, dead leaves, grass clippings, branches, and plant debris. Average (n=2) total carbon (C) content reached 37.7±0.5 and 27.3±0.1% for cattle manure and green waste compost, respectively, and cation exchange capacity (CEC) reached 37±8 and 55±1 cmol_c kg⁻¹, respectively.

The transfer of Cu, Zn, Fe, and Pb from soils to plant (maize, *Zea mays*) was monitored in greenhouse conditions (UCLouvain experimental greenhouses, Louvain-la-Neuve, Belgium) from April 12th to July 9th 2021. The 200 L of soil material collected on each of the three sites were dried (25 °C in a drying room for seven days) and sieved at 1.2 cm (characteristics of the soil samples were detailed in chapter 2). Approximately 15 kg of the sieved soil were mixed with 20 g of NPK 9-7-14 (equivalent to 240 kg_N ha⁻¹) and exogenous organic matters (245 g of cattle manure or green waste compost to reach 35 t ha⁻¹, except for the no application modality), and then potted (10 L pots of 30 cm in diameter and 30 cm height) before sowing one maize seed in each pot, totaling 9 pots (3 soils × 3 modalities). During the experiment, each pot was watered with 1 to 3 L per week of tap water according to the weather conditions.

4.3.3. Sampling procedure and sample preparation

Plant parts (roots and leaves) were sampled at the end of the experiment (i.e., 88 days) following the end of the plant growth. Root samples were meticulously cleansed using pressurized tap water to eliminate soil residues. Subsequently, all plant samples were dried in a ventilated oven set at a temperature of 50 °C. Then the plant samples were ground using a Cyclotec 1093 Sample Mill, manufactured by Foss A/S in Hillerød, Denmark.

4.3.4. Chemical analyses

Element content

Total Cu, Zn, Fe, and Pb contents in soil, exogenous organic matter, and plant samples were determined after acid digestion in an ISO 6 cleanroom using suprapure acids (HNO₃, HCl, and HF) and H₂O₂ mixture in Teflon vessel (Savillex) as described in Arbalestrie et al. (2022).

Iron concentrations were determined by ICP-OES (iCAP 6500 Thermo Fisher Scientific, Waltham, MA, USA), while quantification of Cu, Zn, and Pb was done using an ICP-MS (iCAP Q ICP-MS, Thermo Fisher Scientific, Waltham, MA, USA) with an internal standard (Ru, In, and Re) for mass deviation correction. Procedure performance was evaluated using organic (lichen IAEA-336) and mineral (basalt USGS BHVO-2) certified materials. The average recovery

($C_{\text{measured}} / C_{\text{certified}} \times 100$) was $100 \pm 20\%$, except for Pb (69%) in BHVO-2. No contamination was evidenced during the digestion process (average blank concentrations $<1\%$ of the sample concentration). Limit of detection were estimated to $<0.01 \mu\text{g kg}^{-1}$, except for Zn ($<0.1 \mu\text{g kg}^{-1}$).

Isotopes

Between 500 and 2000 mg of ground soil, exogenous organic matter, and plant samples were gradually calcinated in an oven (Carbolite ELF 11/14B Economy Chamber Furnace, Carbolite®, England) up to 800°C for 14 h. Then, the calcined samples underwent microwave-assisted acid digestion with the addition of 14 mL of 14 M HNO_3 and 1 mL of 40 % HF for 80 minutes at 190°C , followed by a classic digestion (1-2 days) in a Teflon beaker (Savillex), using subboiled acids (HNO_3 , HCl, HF) and H_2O_2 , in an ISO 6 cleanroom (G-Time Laboratory, Université Libre de Bruxelles, Belgium). The heating plate temperature was set at 90°C for the evaporation processes.

Copper, Zn, Fe, and Pb isotopes purification was performed using a four-steps column chromatography (Triskem AC-142-TK column, Bio-Rad Mini Bio-Spin® and custom-made column) with ion exchange resins (Bio-Rad, AG® 1-X8 Anion Exchange Resin, analytical grade, 100–200 and 200–400 mesh, chloride form), following a modified protocol from Vanderstraeten et al. (2020): (1) Cu, Zn, Fe, and Pb were purified from sample matrices on 1 mL of the AG1-X8 200–400 mesh resin in AC-142-TK column (2 mL volume, 7 mm inner diameter; 4 mm column outlet outer diameter; 2 mm column outlet inner diameter); (2) Zn was purified a second time on the same resin in the same column after cleaning steps; (3) Cu was purified on 0.5 mL of a new AG1-X8 200–400 mesh resin in Mini Bio-Spin® column (1.2 mL volume; 3.3 cm length; 2.8 cm bed height), and (4), Pb was purified on 0.2 mL of the AG1-X8 100–200 mesh resin in custom-made column (end of 60-mL polypropylene syringe; 3.5 cm diameter; 2.5 cm bed height). Each purified collected sample was evaporated on a hot plate at 90°C , then re-dissolved in 1 mL of 14 M HNO_3 and 100 μL of H_2O_2 . The solution was subsequently evaporated again prior to multiple collector - inductively coupled plasma - mass spectrometry (MC-ICP-MS) analysis. A soil sample (highly contaminated soil, Bressoux) was processed in duplicate to evaluate the reproducibility and effectiveness of the entire protocol.

Zinc, Cu, Fe and Pb isotopic ratios were measured using a Nu Plasma II MC-ICP-MS (Nu Instruments). For each sample, at least three replicates were

measured for Cu, Zn, Fe, and Pb. Detailed analytical parameters and mass bias correction methodologies were more precisely developed in Vanderstraeten et al. (2020). The isotopic compositions of three certified reference materials (Hawaiian basalt USGS BHVO-2, San Joaquin soil NIST SRM 2709a, and apple leaves NIST SRM 1515) were analyzed to evaluate the performance of the protocol (Table III-4).

Table III-4 - Cu, Zn, Fe, and Pb isotopic signatures (2SD in brackets) in the certified materials.

Certified material	$\delta^{65}\text{Cu}$ [‰]	$\delta^{66}\text{Zn}$ [‰]	$\delta^{56}\text{Fe}$ [‰]	$^{207}\text{Pb}/^{206}\text{Pb}$ [-]
USGS BHVO-2	0.32 (0.00)	0.02 (0.02)	0.11 (0.06)	0.8351 (0.000)
NIST SRM 2709a	0.22 (0.03)	0.17 (0.05)	0.15 (0.03)	0.8328 (0.000)
NIST SRM 1515	-0.22 (0.01)	-0.13 (0.01)	-0.32 (0.03)	0.8203 (0.000)

4.3.5. Data processing and statistical analyses

The isotopic ratios obtained through MC-ICP-MS analysis were normalized using internationally recognized standard solutions: NIST SRM 976 ($\delta^{65}\text{Cu} = 0.94\text{‰}$), JMC Lyon ($\delta^{66}\text{Zn} = -0.12\text{‰}$), and IRMM-014 ($\delta^{56}\text{Fe} = 0.00\text{‰}$). Throughout the analyses, repeated measurements of an in-house standard solutions containing 400 ppb Zn and Cu yielded mean values of $\delta^{66}\text{Zn} = 0.00 \pm 0.02\text{‰}$ ($n = 20$) and $\delta^{65}\text{Cu} = 0.00 \pm 0.02\text{‰}$ ($n = 23$). Isotope ratios were reported using the delta (δ) notation:

$$\delta^{65}\text{Cu} (\text{‰}) = \left[\frac{(^{65}\text{Cu}/^{63}\text{Cu})_{\text{Sample}}}{(^{65}\text{Cu}/^{63}\text{Cu})_{\text{NIST SRM 976}}} - 1 \right] \times 1000$$

$$\delta^{66}\text{Zn} (\text{‰}) = \left[\frac{(^{66}\text{Zn}/^{64}\text{Zn})_{\text{Sample}}}{(^{66}\text{Zn}/^{64}\text{Zn})_{\text{JMC Lyon}}} - 1 \right] \times 1000$$

$$\delta^{56}\text{Fe} (\text{‰}) = \left[\frac{(^{56}\text{Fe}/^{54}\text{Fe})_{\text{Sample}}}{(^{56}\text{Fe}/^{54}\text{Fe})_{\text{IRMM-014}}} - 1 \right] \times 1000$$

The difference between two δ values of two compartments was characterized by the notation Δ :

$$\Delta^X = \delta_{\text{Compartment 1}}^X - \delta_{\text{Compartment 2}}^X$$

where X may represent Cu, Zn, or Fe, with compartment 1 comprising roots or leaves, and compartment 2 consisting of soil or roots.

4.4. Results and discussion

4.4.1. Element contents in soil and plant samples

Average Cu, Zn, Fe, and Pb contents in soil samples showed distinct environmental context from the uncontaminated soil of Vieusart (11.9 ± 0.2 , 44.4 ± 0.0 , ~ 25000 , and 20.3 ± 0.1 mg kg⁻¹, respectively; Table III-5) to the anthropogenically contaminated soil of Bressoux (248 ± 6.2 , 1270 ± 54 , ~ 38000 , and 587 ± 10.8 mg kg⁻¹, respectively; Table III-5). The elevated levels observed in Bressoux compared to Vieusart (from 1.5- for Fe to 30-times higher for Zn and Pb) are likely attributable to both short- and long-term atmospheric deposition from regional industries (e.g., metal, textile, and coal) since the 18th century. In the naturally-enriched soil of Aubange, soil contents were in-between the two previously studied soils (14.8 ± 0.1 , 232 ± 0.5 , ~ 204000 , and 65.9 ± 1.1 mg kg⁻¹, respectively; Table III-5). The higher contents in this soil result from the elevated Fe and Mn oxyhydroxide content (Belanger et al., 2002; Vandeuren et al., 2023), supported by the high Fe content (i.e., 8-times higher than in Vieusart).

Element contents in plant samples generally showed higher Cu and Zn values in leaves than in roots (up to 8 times higher Cu in leaves in Aubange). The elevated Cu and Zn levels in leaves can be attributed to their essential roles in biochemical processes (Gupta et al., 2016; Yruela, 2009), promoting their translocation from roots to shoots (Palmer and Guerinot, 2009). In contrast, Pb contents were consistently higher in roots than in leaves, ranging from 4-times higher in Aubange to 8 times higher in Vieusart. The non-linear relationship observed between soil and plant compartments from uncontaminated to contaminated contexts may result from a biological saturation mechanism (Prasad et al., 2006) or cellular detoxification and tolerance processes to prevent toxicity symptoms (Hall, 2002; Wintz et al.,

2002), by limiting the translocation to leaves in contaminated sites. This is particularly pronounced for elements with no biological function known (Kushwaha et al., 2018).

Table III-5 - Total Cu, Zn, Fe, and Pb concentrations and Cu, Zn, Fe, and Pb isotopic signatures (means and standard deviations in brackets for highly contaminated soil, n = 2) in all samples. Average calculated 2SD for Cu, Zn, and Fe ratios were <0.05 and <10⁻⁴ for Pb ratios.

Compartment	Site	Modality	Cu	$\delta^{65}\text{Cu}$	Zn	$\delta^{66}\text{Zn}$	Fe	$\delta^{56}\text{Fe}$	Pb	$^{208}\text{Pb}/^{207}\text{Pb}$
			[mg kg ⁻¹]	[‰]	[mg kg ⁻¹]	[‰]	[%]	[‰]	[mg kg ⁻¹]	[-]
Soil	Uncontaminated (Vieusart)	-	11.9 (0.2)	0.13	44.4 (0.0)	0.08	2.5	-0.07	20.3 (0.1)	2.466
Soil	Highly contaminated (Bressoux)	-	248 (6.2)	0.14 (0.03)	1268 (54.0)	0.47 (0.11)	3.8	0.12 (0.04)	587 (10.8)	2.441 (0.001)
Soil	Naturally-enriched (Aubange)	-	14.8 (0.1)	-0.01	231.5 (0.5)	0.29	20.4	-0.44	65.9 (1.1)	2.471
Roots	Uncontaminated (Vieusart)	No application	23.3	-2.91	43.0	0.15	-	-0.23	8.5	2.465
Roots	Uncontaminated (Vieusart)	Cattle manure	16.1	-2.28	33.4	0.31	-	-0.06	3.0	2.461
Roots	Uncontaminated (Vieusart)	Green waste compost	15.7	-3.00	29.9	0.26	-	-0.03	5.7	2.460
Roots	Highly contaminated (Bressoux)	No application	70.7	-0.82	246.0	0.50	-	0.08	13.7	2.443
Roots	Highly contaminated (Bressoux)	Cattle manure	56.5	-0.59	162.2	0.69	-	0.03	12.2	2.443
Roots	Highly contaminated (Bressoux)	Green waste compost	72.3	-2.59	180.3	0.67	-	0.13	20.1	2.442
Roots	Naturally-enriched (Aubange)	No application	3.2	-2.59	20.1	0.19	-	-0.44	3.2	2.463

Roots	Naturally-enriched (Aubange)	Cattle manure	3.8	-2.06	26.3	0.29	-	-0.47	5.0	2.458
Roots	Naturally-enriched (Aubange)	Green waste compost	5.1	-2.29	31.3	0.20	-	-0.37	6.8	2.466
Leaves	Uncontaminated (Vieusart)	No application	32.6	-1.08	67.4	0.48	-	0.04	1.1	2.446
Leaves	Uncontaminated (Vieusart)	Cattle manure	33.2	-0.08	59.0	0.48	-	0.26	1.2	2.444
Leaves	Uncontaminated (Vieusart)	Green waste compost	22.2	-0.01	50.2	0.32	-	0.16	0.9	2.446
Leaves	Highly contaminated (Bressoux)	No application	59.4	-0.59	418.7	0.04	-	0.17	2.1	2.444
Leaves	Highly contaminated (Bressoux)	Cattle manure	33.1	-1.17	452.6	-0.04	-	0.39	1.2	2.444
Leaves	Highly contaminated (Bressoux)	Green waste compost	29.7	-1.82	400.3	0.12	-	0.16	1.2	2.448
Leaves	Naturally-enriched (Aubange)	No application	24.9	-1.54	53.5	0.59	-	0.03	0.8	2.459
Leaves	Naturally-enriched (Aubange)	Cattle manure	28.1	-1.35	60.2	0.37	-	-0.02	2.4	2.454
Leaves	Naturally-enriched (Aubange)	Green waste compost	44.3	-1.16	67.9	0.38	-	-0.01	1.9	2.450
Cattle manure	-	-	18.4 (0.3)	-2.42	99.6 (0.4)	0.34	-	0.11	3.7 (0.0)	2.456
Green waste compost	-	-	27.8 (0.3)	-1.15	165.6 (2.4)	0.03	-	0.08	35.6 (0.8)	2.447

4.4.2. Isotopic behavior in the uncontaminated soil

Copper, zinc, and iron

Copper, Zn, and Fe isotopic composition were first determined in the uncontaminated soil (i.e., Vieusart) prior to the greenhouse experiment (Figure III.19). The isotope signatures exhibited $\delta^{65}\text{Cu}$ (Figure III.19A), $\delta^{66}\text{Zn}$ (Figure III.19B), and $\delta^{56}\text{Fe}$ (Figure III.19C) of $+0.13\pm0.05$, $+0.08\pm0.05$, and $-0.07\pm0.04\text{‰}$, respectively, values close to those observed in the surface horizons of many uncontaminated European Cambisols (Fekiacova et al., 2015, 2013). In maize, roots presented values of -2.91 ± 0.05 , $+0.15\pm0.00$, and $-0.23\pm0.05\text{‰}$ for $\delta^{65}\text{Cu}$, $\delta^{66}\text{Zn}$, and $\delta^{56}\text{Fe}$, respectively. This showed a depletion in heavier isotopes relative to the soil for Cu ($\Delta^{65}\text{Cu}_{\text{roots-soil}} = -3.03\pm0.10\text{‰}$; Figure III.20A) and, to a lesser extent, Fe ($\Delta^{56}\text{Fe}_{\text{roots-soil}} = -0.16\pm0.09\text{‰}$; Figure III.20C), while this trend was not observed for Zn that only showed a slight enrichment in heavier isotopes in roots compared to the soil ($\Delta^{66}\text{Zn}_{\text{roots-soil}} = +0.07\pm0.02\text{‰}$; Figure III.20B).

The limited Fe isotope fractionation observed between soil and roots may be explained by the ability of maize to employ both Fe acquisition strategies. Indeed, maize typically utilizes strategy II, which involves the release of phytosiderophores for mobilizing Fe(III) from soil and transporting Fe(III)-phytosiderophore complexes directly into the roots, a process that does not induce significant isotope fractionation between soil and roots (Guelke and von Blanckenburg, 2007; Wiggerhauser et al., 2022). However, maize may also adopts strategy I as an additional mechanism for Fe acquisition (Li et al., 2018), corresponding to Fe(III) reduction to Fe(II) in the rhizosphere before the uptake. Since this second strategy generates an isotope fractionation by preferentially incorporating lighter isotopes into the roots ($\Delta^{56}\text{Fe}_{\text{plant-soil}}$ of -1.8‰ ; Guelke and von Blanckenburg, 2007), we assume that this strategy was limited during the experiment.

Although various trends are reported in the literature (Wiggerhauser et al., 2022), several studies also showed a depletion of heavier Cu isotopes in roots relative to the soil (Li et al., 2016; Ryan et al., 2013; Weinstein et al., 2011; Zheng et al., 2024). Note that the activation of strategy I under Fe-sufficient conditions may influence the fractionation of other elements, such as Cu (Ryan et al., 2013; Wiggerhauser et al., 2022). Finally, the slight enrichment

in heavier Zn isotopes in roots relative to soil is consistent with previous studies (Jouvin et al., 2012; Smolders et al., 2013; Weiss et al., 2004) and can be attributed to two main Zn absorption pathways: (1) ZIP (Zn-regulated, Fe-regulated transporter-like protein) that promotes a slightly heavier Zn isotope uptake; and (2) complexation with phytosiderophores in strategy II that preferentially uptake heavier Zn isotopes (Jouvin et al., 2012).

Isotope signatures in maize leaves reached -1.08 ± 0.05 , $+0.48 \pm 0.04$, and $+0.04 \pm 0.02\text{‰}$ for $\delta^{65}\text{Cu}$, $\delta^{66}\text{Zn}$, and $\delta^{56}\text{Fe}$, respectively (Figure III.19). The three elements therefore exhibited consistent enrichments in heavier isotopes from roots to leaves ($\Delta^{65}\text{Cu}_{\text{leaves-roots}} = +1.82 \pm 0.10\text{‰}$, $\Delta^{66}\text{Zn}_{\text{leaves-roots}} = +0.33 \pm 0.04\text{‰}$, and $\Delta^{56}\text{Fe}_{\text{leaves-roots}} = +0.26 \pm 0.07\text{‰}$; Figure III.20). This observation contrasted with the general trend reported in the literature (Couder et al., 2015; Houben et al., 2014; Jouvin et al., 2012; Moynier et al., 2009; Weiss et al., 2004), although alternative patterns were suggested in certain species for Cu (Ryan et al., 2013), Zn (Viers et al., 2007), and Fe (Wiggenhauser et al., 2022). The contrasting trends may result from distinct conditions (e.g., uncontaminated vs contaminated or different plant species). Note also that some of these studies consider the whole “shoots” instead of a specific aboveground plant part such as leaves in our study.

Lead

The $^{208}\text{Pb}/^{207}\text{Pb}$ ratio obtained in the uncontaminated soil (2.466; Table III-5) exhibited values close to those of natural rocks (e.g., limestone and schist) and minerals (e.g., galena and pyrite) reported by several authors in Wallonia, Belgium (Figure III.21A-B; Cauet, 1985; Cauet and Weis, 1983). This suggests that the Pb isotope signature in this soil originated from lithogenic sources, as expected due to the absence of known contamination at this site. In the $^{208}\text{Pb}/^{207}\text{Pb}$ vs $^{206}\text{Pb}/^{207}\text{Pb}$ relationship (Figure III.21A-B), soil and plant samples were located between the two end-members: (1) natural background sources (Asmerom and Jacobsen, 1993; Hemming and McLennan, 2001; Millot et al., 2004; Sonke et al., 2008); and (2) urban and industrial sources (Petit, 1977; Petit et al., 1984; Sonke et al., 2008, 2002). In contrast to the soil with an exclusively natural signature, the leaves were closer to the anthropogenic end-member, which may result from an isotope fractionation from soil to plant due to the absence of contamination in the greenhouse. This fractionation was also observed in the literature due to the involvement of potential transport proteins (Wu et al., 2024).

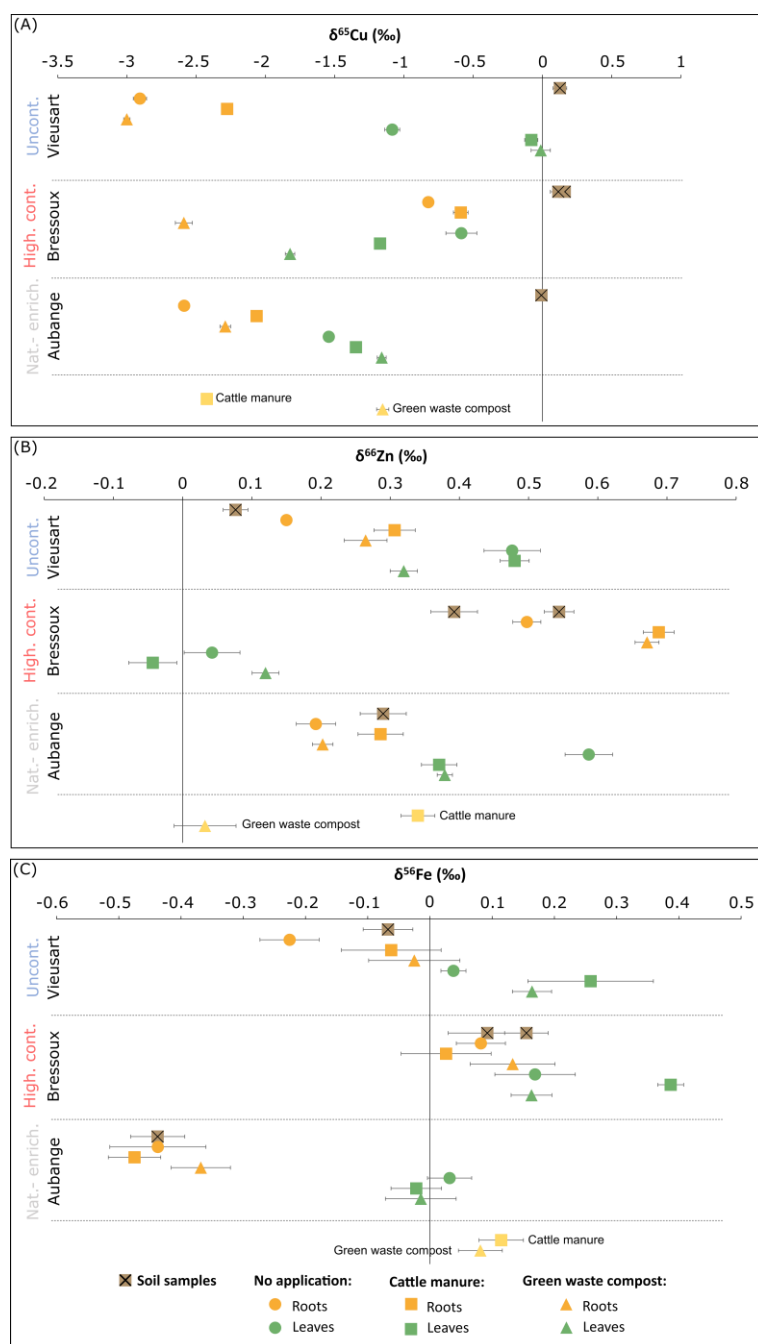


Figure III.19 - Cu (A), Zn (B), and Fe (C) isotopic signatures (2SD) in soils and plant parts for the uncontaminated, highly contaminated and naturally-enriched soils following exogenous organic matter application modalities: no application, cattle manure, and green waste compost.

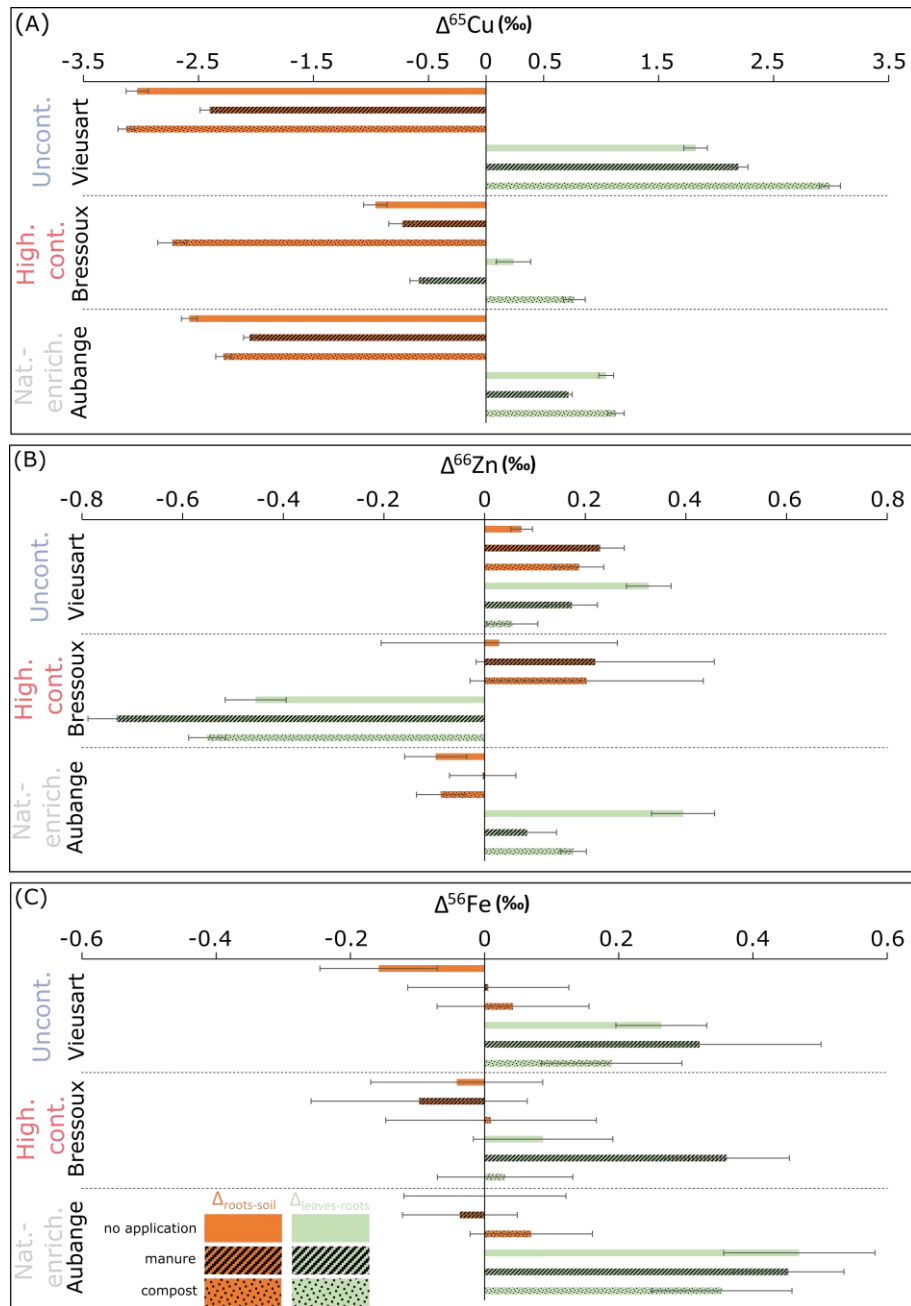


Figure III.20 - Δ⁶⁵Cu (A), Δ⁶⁶Zn (B), and Δ⁵⁶Fe (C) between soil and roots (Δ_{roots-soil}) and between roots and leaves (Δ_{leaves-roots}) for the uncontaminated, highly contaminated, and naturally-enriched soils following exogenous organic matter application modalities: no application, cattle manure, and green waste compost.

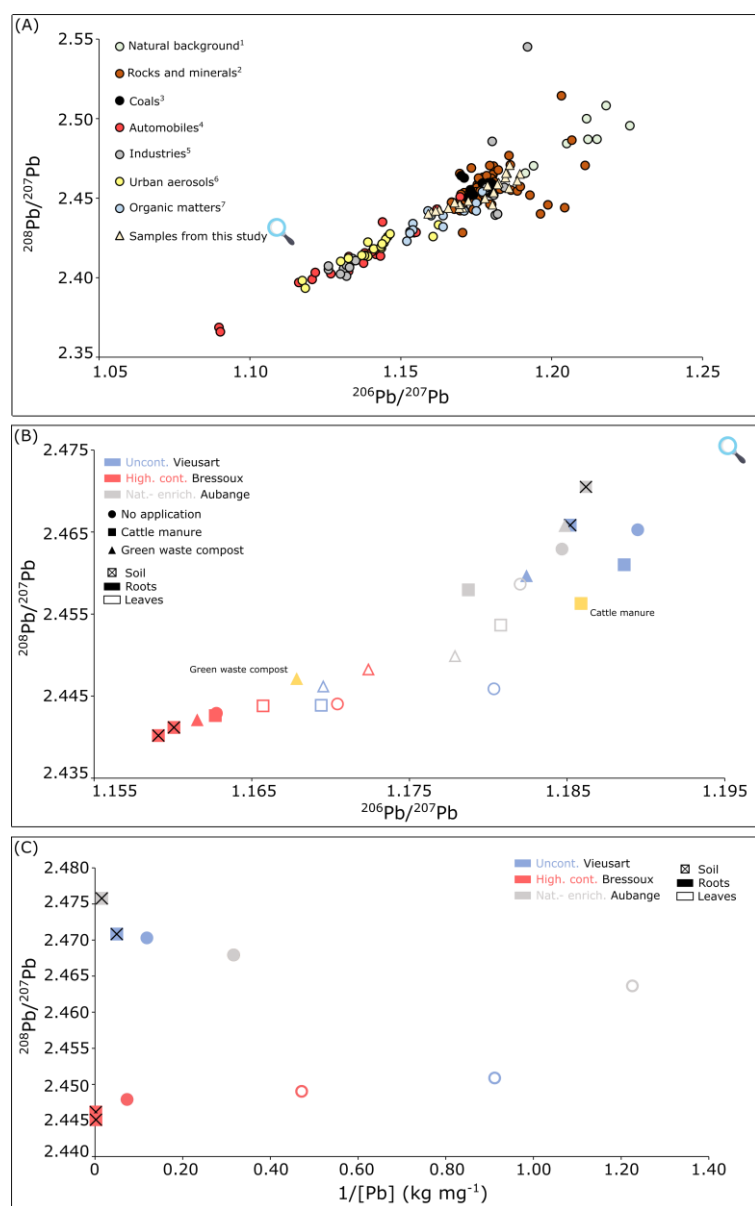


Figure III.21 - Mixing trend of literature data and all sampled from this study (A) and zoom (B) in a $^{208}\text{Pb}/^{207}\text{Pb}$ vs $^{206}\text{Pb}/^{207}\text{Pb}$ plot (‰), and $^{208}\text{Pb}/^{207}\text{Pb}$ vs $1/[\text{Pb}]$ plot for no exogenous organic matter application modality (C). Calculated 2SD for Pb ratios were $<10^{-4}$ for this study. ¹(Asmerom and Jacobsen, 1993; Hemming and McLennan, 2001; Millot et al., 2004; Petit et al., 1984; Sonke et al., 2008, 2002), ²(Cauet, 1985), ³(Walraven et al., 1997), ⁴(Petit, 1977), ⁵(Petit, 1977; Sonke et al., 2008, 2002), ⁶(Petit, 1977), ⁷(Walraven et al., 2013).

4.4.3. Isotopic behavior in contaminated soils

Copper, zinc, and iron

The $\delta^{65}\text{Cu}$, $\delta^{66}\text{Zn}$, and $\delta^{56}\text{Fe}$ values were then determined in the highly contaminated soil (i.e., Bressoux) and in the naturally-enriched soil (i.e., Aubange) prior to the greenhouse experiment (Figure III.19). Both soils exhibited $\delta^{65}\text{Cu}$ values (Figure III.19A) close to the uncontaminated soil, i.e., $+0.14 \pm 0.03\text{‰}$ ($n=2$) in Bressoux and $-0.01 \pm 0.03\text{‰}$ in Aubange. The lack of a significant difference in $\delta^{65}\text{Cu}$ values across the three soils could suggest either a predominantly geogenic origin, or similar isotope signatures for the additional anthropogenic sources (e.g., smelter). The elevated Cu contents in Bressoux supported the second option, although complexation with organic matter in surface horizons could occur in such organic-rich soil samples (Gelly et al., 2019). Conversely, the $\delta^{66}\text{Zn}$ values were higher in both contaminated soils compared to the uncontaminated one, reaching $+0.47 \pm 0.11\text{‰}$ ($n=2$) in Bressoux and $+0.29 \pm 0.03\text{‰}$ in Aubange (Figure III.19B). These contrasting trend with Vieusart may be attributed to both anthropogenic inputs and pedogenetic processes (Fekiacova et al., 2015). Indeed, post-depositional isotope fractionation, including direct processes such as sorption or indirect processes like plant uptake, could alter the Zn isotopic composition at the soil surface (Juillot et al., 2011; Mattielli et al., 2009). Finally, $\delta^{56}\text{Fe}$ presented distinct signatures depending on the soil considered: higher values in Bressoux ($+0.12 \pm 0.04\text{‰}$) and lower value in Aubange ($-0.44 \pm 0.04\text{‰}$) compared to Vieusart (Figure III.19C). In the absence of soil hydromorphy, the lower $\delta^{56}\text{Fe}$ value can be related to the soil Fe oxyhydroxides, which is supported by the strong negative correlation between the $\delta^{56}\text{Fe}$ of bulk soil samples and the oxide-bound Fe content evidenced by Fekiacova et al. (2013).

Similar to observations at Vieusart, maize roots showed a depletion in heavier Cu isotopes relative to the soil in both contaminated soils ($\Delta^{65}\text{Cu}_{\text{roots-soil}} = -0.96 \pm 0.10\text{‰}$ in Bressoux and $-2.58 \pm 0.10\text{‰}$ in Aubange; Figure III.20A). This suggests the possible reduction of Cu(II), potentially occurring at the plasma membrane surfaces of root cells (Jouvin et al., 2012). This pattern was also consistent with the Cu isotope fractionation during adsorption/complexation with soil surfaces, where heavier Cu isotopes preferentially complex with Fe and Mn oxyhydroxides or organic matter, leading to lighter isotopes available for plant uptake (Komárek et al., 2022). Maize leaves, however, exhibited an enrichment in heavier Cu isotopes relative to the roots ($\Delta^{65}\text{Cu}_{\text{leaves-roots}} =$

+0.24±0.15‰ in Bressoux and +1.04±0.06‰ in Aubange; Figure III.20A). Given the trends obtained in the three soils, Cu isotope fractionation was therefore controlled by the same biological processes between soil, roots, and leaves, despite distinct fractionation magnitudes linked to pedogenetic processes or constituent contents (Fekiacova et al., 2015; Jouvin et al., 2012).

In contrast to Vieusart, Aubange exhibited a slight depletion in heavier Zn isotopes in roots relative to the soil ($\Delta^{66}\text{Zn}_{\text{roots-soil}} = -0.10 \pm 0.06\text{‰}$; Figure III.20B). This likely result from preferential heavier Zn isotope adsorption onto Fe and Mn oxyhydroxide surfaces (Bryan et al., 2015; Juillot et al., 2011), as observed for Cu. The isotope fractionation is more pronounced in poorly crystalline phases, such as ferrihydrite, compared to more crystalline phases, such as goethite found in Aubange (Appendix VI.1, Figure VI.1; Juillot et al., 2011). However, no obvious fractionation was evidenced between soil and roots in Bressoux, particularly with the large uncertainties ($\Delta^{66}\text{Zn}_{\text{roots-soil}} = +0.03 \pm 0.23\text{‰}$; Figure III.20B). Finally, maize leaves showed opposite trends in contaminated soils: (1) enrichment in heavier Zn isotopes in leaves relative to roots in Aubange ($\Delta^{66}\text{Zn}_{\text{leaves-roots}} = +0.39 \pm 0.06\text{‰}$; Figure III.20B), as observed in Vieusart; and (2) depletion in heavier Zn isotopes in leaves relative to roots in Bressoux ($\Delta^{66}\text{Zn}_{\text{leaves-roots}} = -0.45 \pm 0.06\text{‰}$; Figure III.20B), consistent with findings obtained under similar Zn contamination conditions (Couder et al., 2015). Thus, this allows differentiating contaminated soils due to anthropogenic activities from those in which Zn has a primarily lithogenic origin.

Both contaminated soils showed little to no Fe isotope fractionation between soil and roots ($\Delta^{56}\text{Fe}_{\text{roots-soil}} = -0.04 \pm 0.13\text{‰}$ in Bressoux and $+0.00 \pm 0.12\text{‰}$ in Aubange; Figure III.20C). This supports that Fe acquisition strategy developed in maize, which involves phytosiderophores, does not induce isotope fractionation between soil and roots. Similarly, no significant Fe isotope fractionation was observed between the roots and the leaves in Bressoux ($\Delta^{56}\text{Fe}_{\text{leaves-roots}} = -0.09 \pm 0.10\text{‰}$), unlike in Aubange with heavier Zn isotope depletion ($\Delta^{56}\text{Fe}_{\text{leaves-roots}} = -0.47 \pm 0.11\text{‰}$). These differences are likely due to the considerable variability in Fe isotope fractionation between roots and shoots, as reported by Wigganhauser et al. (2022). Furthermore, since Fe remobilization within the plant involves the reduction of Fe(III) to Fe(II), Fe isotope fractionation may occur during this process as Fe is redistributed from older to newer plant tissues. As a result, this remobilization could alter the Fe

isotope composition of the leaves throughout the growing season (Kiczka et al., 2010; Wiggerhauser et al., 2022).

Lead

The Pb isotopic ratios ($^{208}\text{Pb}/^{207}\text{Pb}$; Table III-5) in both contaminated soils exhibited distinct values, with 2.441 ± 0.001 ($n=2$) in Bressoux and 2.471 in Aubange. The latter was closer to the value found in uncontaminated soils, suggesting also a lithogenic origin of Pb in Aubange. In contrast, the average value observed at Bressoux indicated that Pb contamination originated primarily from anthropogenic sources or ore deposit residues. In the $^{208}\text{Pb}/^{207}\text{Pb}$ vs $^{206}\text{Pb}/^{207}\text{Pb}$ plot (Figure III.21A-B), the soil of Bressoux was located between the anthropogenic end-member (i.e., automobiles, industrial activities, and urban aerosols) and the Belgian charcoal samples (Walraven et al., 1997). This likely reflects the presence of charcoal in this soil in addition to anthropogenic inputs from industrial activities. Comparing the three contrasting soils, whatever the initial Pb isotope signature, plants are surprisingly always found with signatures in-between both natural and anthropogenic end-members. This was observed in the $^{208}\text{Pb}/^{207}\text{Pb}$ vs $1/[\text{Pb}]$ plot (Figure III.21C), showing similar signatures when $1/[\text{Pb}]$ increased (root and leaf samples) despite two distinct sources in soils (Vieusart and Aubange with lithogenic origins vs Bressoux with anthropogenic origins).

4.4.4. Influence of exogenous organic matter application

The green waste compost showed total Cu, Zn, and Pb contents that were on average 1.9-times higher than in the cattle manure, ranging from Cu ($27.8 \pm 0.3 \text{ mg kg}^{-1}$) to Zn ($166 \pm 2.4 \text{ mg kg}^{-1}$; Table III-5). The effect of exogenous organic matter application on Cu, Zn, and Pb contents in plant parts varied depending on the soil and exogenous organic matter modality considered (cf. Data chapter 3).

Copper, zinc, and iron

Exogenous organic matters exhibited contrasted $\delta^{65}\text{Cu}$ and $\delta^{66}\text{Zn}$ values, with $\delta^{65}\text{Cu} = -2.42 \pm 0.02$ and $-1.15 \pm 0.04\text{‰}$ and $\delta^{66}\text{Zn} = +0.34 \pm 0.02$ and $+0.03 \pm 0.04\text{‰}$ for cattle manure and green waste compost, respectively

(Figure III.19A-B). This indicates a depletion in heavier Cu isotopes and an enrichment of heavier Zn isotopes, and contrasts with data reported in the literature for animal manure (Imseng et al., 2019; Ostermann et al., 2015). Iron isotope signature, however, showed quite similar values: $\delta^{56}\text{Fe} = +0.11 \pm 0.04$ and $+0.08 \pm 0.04\text{‰}$ for cattle manure and green waste compost, respectively (Figure III.19C).

The application of exogenous organic matter generated similar trends but different magnitude in Cu isotope fractionation between soil and roots ($\Delta^{65}\text{Cu}_{\text{roots-soil}}$; Figure III.20A) compared to the control modality (i.e., no application). These differences varied depending on the type of exogenous organic matter applied (i.e., cattle manure or green waste compost) and the soil considered. Indeed, a slight decrease in the magnitude of fractionation (Δ less negative) was observed in Vieusart following the application of cattle manure and similarly in Aubange for both exogenous organic matters. This suggests that these applications resulted in enrichment of heavier Cu isotopes in roots relative to the soil. This phenomenon implies a preferential complexation/adsorption of lighter Cu isotopes onto organic surfaces following the application of exogenous organic matter, leading to a depletion of these lighter isotopes in the soil solution available to plants, contrary to the observations reported in the literature (Komárek et al., 2022). In contrast, a greater increase in fractionation magnitude was observed in Bressoux with green waste compost application, showing a distinct isotope signature between soil and roots ($\Delta^{65}\text{Cu}_{\text{roots-soil}} = -2.73 \pm 0.13\text{‰}$) compared to no application ($\Delta^{65}\text{Cu}_{\text{roots-soil}} = -0.96 \pm 0.10\text{‰}$). This suggests preferential complexation/adsorption of heavier Cu isotopes onto organic surfaces (Bigalke et al., 2010b; Komárek et al., 2022). These inconsistent trends were also highlighted in the Cu isotope fractionation between roots and leaves ($\Delta^{65}\text{Cu}_{\text{leaves-roots}}$), showing either an increase or decrease in the magnitude of fractionation compared to the no application modality. For instance, the application of exogenous organic matter amplified the fractionation (i.e., result in a larger isotopic composition difference) between roots and leaves (Δ more positive), indicating a greater enrichment of heavier Cu isotopes in leaves relative to roots (e.g., $\Delta^{65}\text{Cu}_{\text{leaves-roots}} = +2.99 \pm 0.09\text{‰}$ for green waste compost) compared to the no application modality ($\Delta^{65}\text{Cu}_{\text{leaves-roots}} = +1.82 \pm 0.10\text{‰}$). However, with the application of cattle manure, we observed a fractionation in the opposite direction in Bressoux (Δ becoming negative), indicating a depletion of heavier Cu isotopes in leaves relative to roots ($\Delta^{65}\text{Cu}_{\text{leaves-roots}} = -0.58 \pm 0.08\text{‰}$). Given the isotope signatures of exogenous

organic matter, distinct from that of the soil, and knowing that isotope fractionations did not change direction after application of exogenous organic matter, we hypothesize that Cu transferred to the plant does not correspond to Cu originating from the exogenous organic matter.

As observed for Cu, the application of exogenous organic matter modified magnitude of Zn isotope fractionation between soil and roots ($\Delta^{66}\text{Zn}_{\text{roots-soil}}$; Figure III.20B) compared to the no application modality (Δ more positive), but variations occurred depending on the exogenous organic matter and the soil considered. However, the differences observed in Bressoux and Aubange did not reveal a clear trend due to the large uncertainties (2SD) associated with the data. In contrast, the application of both exogenous organic matters led to a decrease in the magnitude of Zn isotope fractionation between roots and leaves ($\Delta^{66}\text{Zn}_{\text{leaves-roots}}$ less positive) in Vieusart and Aubange, indicating greater depletion of heavier Zn isotopes in leaves relative to roots. In Bressoux, the Zn fractionation between roots and leaves increased (i.e., $\Delta^{66}\text{Zn}_{\text{leaves-roots}}$ more negative), also indicating a greater depletion of heavier Zn isotopes in leaves compared to roots following exogenous organic matter application. No consistent trend appears in Zn isotope fractionation along the soil-plant pathway following exogenous organic matter application. The enrichment or depletion of a specific isotope from one compartment to another seems to depend strongly on the nature of the complex formed between the organic surface and the element, and this nature also influences the magnitude of the observed fractionation (Jouvin et al., 2009; Komárek et al., 2022).

Finally, no significant differences were observed in the magnitude of Fe fractionation between soil and roots ($\Delta^{56}\text{Fe}_{\text{roots-soil}}$; Figure III.20C) or between roots and leaves ($\Delta^{56}\text{Fe}_{\text{leaves-roots}}$; Figure III.20C) following the application of exogenous organic matter. However, in Bressoux, the application of cattle manure decreased $\Delta^{56}\text{Fe}_{\text{leaves-roots}}$ value (Δ value more positive). Although Fe bound to the organic fraction of soils represents one of the major Fe reservoir for plants (Guelke et al., 2010), it appears that the application of exogenous organic matter (with similar initial $\delta^{56}\text{Fe}$ values) does not influence Fe isotope fractionation compared to the no application modality. This suggests that the plant strategy for Fe acquisition is the primary factor modulating Fe fractionation in the soil-plant system.

Lead

The Pb isotopic ratios ($^{208}\text{Pb}/^{207}\text{Pb}$; Table III-5) in both exogenous organic matters displayed distinct values: 2.456 for cattle manure and 2.447 for green waste compost. In the $^{208}\text{Pb}/^{207}\text{Pb}$ vs $^{206}\text{Pb}/^{207}\text{Pb}$ plot (Figure III.21B), the green waste compost was closer to the values associated with Bressoux. In contrast, the cattle manure exhibited a signature more aligned with the “natural” pole, corresponding to signatures from Vieusart and Aubange. However, these signatures may not represent typical values due to the wide range of Pb isotope compositions observed in animal manure (2.423 to 2.454; Walraven et al., 2013; Figure III.21A) that are largely influenced by the substantial quantities of animal feed imported from other countries (Bouwman et al., 2011), and given that green waste compost, primarily composed of dead leaves, grass clippings, branches, and plant debris from household waste, also exhibiting significant variations in the Pb isotope signatures. The Pb signatures in both roots and leaves (Figure III.21A, B) were, for the most part, consistent to the signature of the soil and exogenous organic matter mixture in which the plant has grown, confirming the use of Pb isotopes as tracers for identifying sources in the environment (Trimmel et al., 2024). However, as a greenhouse experiment, atmospheric deposition was limited.

4.4.5. Isotope contribution for a global understanding

In this study, Cu, Zn, Fe, and Pb isotopes were used to assess the impact of exogenous organic matter application on isotope fractionation in the soil-plant system, considering distinct environmental conditions and trace element contents. Although no general trend was consistent across elements and soils considered, the application of exogenous organic matter only influenced the magnitude of Cu and Zn fractionation between different compartments. This effect appeared to depend on the soil type, specific element, and nature of exogenous organic matter. Some studies report sorption or complexation capacity of heavy Cu and Zn isotopes onto Fe and Mn oxyhydroxides and organic surfaces (Bigalke et al., 2010b; Juillot et al., 2011). Nonetheless, the heterogeneous nature of the exogenous organic matter and its decomposition degree influence the fractionation factor (Jouvin et al., 2009; Opfergelt et al., 2017; Viers et al., 2015). Furthermore, the initial isotope signatures of soils, which can be attributed to both pedogenetic processes and anthropogenic inputs (as shown notably by Zn and

Pb isotopes), also impact isotope fractionation. This influence depends on the organic matter and Fe and Mn oxyhydroxide content (Jouvin et al., 2012; Smolders et al., 2013), and the speciation of trace elements. Moreover, biological processes related to plant uptake, which vary according to contamination levels, also play a role. For instance, Zn or Fe deficiency stimulates the production of siderophores impacting Cu, Zn, and Fe uptake, while elevated concentrations trigger tolerance mechanisms such as accumulation of Cu or Pb in roots (Ryan et al., 2013; Wigganhauser et al., 2022).

IV. Conclusions and perspectives

1. General conclusions

1.1. Transfer of trace elements in the soil-plant system: influence of soil and element properties

In this thesis, four agricultural soils from Wallonia (Belgium) were selected primarily based on their trace element contents and contrasted sources. The uncontaminated soil (i.e., Vieusart) was used as a control in greenhouse and field experiments, providing a baseline for comparison. The moderately contaminated soil (i.e., Sainte-Walburge) and the highly contaminated soil (i.e., Bressoux), in addition to displaying a gradient of anthropogenic trace element contents resulting from industrial activities dating back to the 18th century, also exhibited higher soil organic carbon content due to significant coal deposits. Finally, the naturally-enriched soil (i.e., Aubange) showed trace element contents similar to those of Sainte-Walburge, though originating from lithogenic sources (notably As, Cr, and Ni) and was characterized by elevated levels of Fe and Mn oxyhydroxides.

Whether in greenhouse or field conditions, heterogeneity (including both positive and negative effects) in the transfer of trace elements from soil to plant were observed, and appeared strongly dependent on the specific soil and trace element considered. Indeed, Sainte-Walburge and Bressoux exhibited higher trace element contents (such as Cu, Zn, and Pb) and they were distributed in all mobile fractions compared to Vieusart, which could be attributed to anthropogenic sources and high soil organic matter (SOM) content. In contrast, Aubange initially displayed a marked presence of certain elements (such as As, Sb, and Mo) mainly distributed in the residual fraction, suggesting reduced mobility and availability, despite relatively high total trace element contents. Moreover, the high content of Fe and Mn oxyhydroxides in Aubange contributed to the retention of these elements through adsorption or complexation.

The differences in the distribution of trace elements among the soil fractions underlie the contrasting mobility and availability of trace elements observed during the study of soil-to-plant trace element transfers in this thesis. Additionally, the role of trace elements in biological processes contributed to variations in their transfer. For example, essential elements such as Cu and Zn were more readily transferred to plants compared to exclusively toxic elements like Pb. The findings also indicated that, when essential elements were present at excessively high contents, a saturation mechanism likely occurred in maize, restricting further transfer of these elements to the plant, as illustrated with isotope results involving distinct transfer processes.

The geochemical relevance and representativeness of plant-available compartments (soil solution, soil water extract, and BCR exchangeable fraction) as intermediate compartments in the transfer of trace elements were then assessed by comparing REE-normalized patterns along the soil–plant continuum under both greenhouse and field conditions. The key findings revealed distinct REE patterns between soil or plant samples and the compartments across both experimental conditions. This indicates that these intermediate compartments in the soil–plant system do not serve as universal compartments for element bioavailability. Further comparison of the three plant-available compartments highlighted the following: (1) although soil solution exhibited the highest potential for element transfer, it also showed considerable variability across elements, tending to overestimate the transfer of highly soluble elements and potentially being influenced by irrigation water contamination; (2) the soil water extract was geochemically more comparable to soil–plant compartments but displayed transfer characteristics similar to those of the soil solution; and (3) the BCR exchangeable fraction effectively distinguished elements based on their mobility, showing a relatively uniform transfer pattern for all contaminant elements within a given soil.

REE analysis corroborated these findings, demonstrating that both soil water extracts and the BCR exchangeable fraction are the most reliable compartments for predicting soil–plant transfer. Furthermore, the distribution of REE revealed notable differences in extractability and transferability, despite their similar chemical properties. The commonly used indices in the literature (e.g., LREE/HREE ratio, Ce and Eu anomalies) have revealed that, in contrast to the light REE (LREE), heavy REE (HREE) were more readily extractable and consequently more easily transferred to plants, a pattern that deviates from previous studies. Furthermore, the distinct

extractabilities of Ce and Eu played a pivotal role in elucidating different transfer mechanisms from soil to plant, likely influenced by adsorption processes or complexation with organic matter and Fe and Mn oxyhydroxides.

1.2. Influence of exogenous organic matter application on trace element transfer

The application of exogenous organic matter (i.e., cattle manure, green waste compost, and cover crop restitution) was evaluated under both controlled greenhouse experiment and field conditions. The findings revealed that exogenous organic matter application exerted both increasing and decreasing trace element concentrations in soil solutions and trace element contents in plants parts, depending on the specific soil characteristics and the trace element considered. The observed heterogeneities in trace element content in plant shoots indicated that soil properties are the primary factor governing the influence of exogenous organic matter on trace element transfer to plants. In contrast, the consistently positive effects observed in soil solutions emphasized the dual function of organic matter, acting both as a source of trace elements and as a retention surface capable of adsorbing trace elements. Based on these observations, we suggest that exogenous organic matter consistently alters trace element dynamics in soil solutions, particularly for elements such as Cu, Mo, and Sn. However, in certain soils, exogenous organic matter may mitigate the availability of both native and newly introduced trace elements by forming complexes, thereby limiting their accumulation in plants. Such a multi-elemental study makes it possible to avoid any extrapolation on trace elements that are chemically close but do not behave in the same way in view of the results.

A comprehensive characterization of both soil and exogenous organic matter, including detailed chemical composition analysis, was conducted alongside an assessment of Cu, Zn, Fe, and Pb isotope fractionation within the soil-plant system. The goal was to better understand the influence of the heterogeneous nature of organic matter and its degree of decomposition on trace element transfer. The results revealed distinct chemical signatures in soil organic matter, enabling clear differentiation between anthropogenically contaminated soils and those naturally-enriched or uncontaminated. These findings confirmed that soil properties are the primary factors controlling

trace element transfer, followed by the specific trace element itself and the characteristics of the organic matter. Indeed, exogenous organic matter exhibited lower heterogeneity compared to soil organic matter, and the initial isotopic composition of soils—shaped by both pedogenic processes and anthropogenic inputs, particularly for Zn and Pb—also supports this observation.

Although the application of exogenous organic matter did not show a general trend in trace element transfer, certain parameters describing the degree of decomposition and the thermal stability of organic matter had significant impacts on trace element behavior within the soil-plant system. Furthermore, trace elements demonstrated varying affinities for functional groups within organic compounds. This was evidenced by isotope analysis, which showed no specific Cu signature originating from the exogenous organic matter, leading to the hypothesis that Cu transferred to the plant does not originate from the exogenous organic matter. Additionally, biological processes related to plant uptake, which vary depending on contamination levels, played a critical role. For example, Zn or Fe deficiencies can induce the production of siderophores, which influence Cu, Zn, and Fe uptake, while high concentrations of these elements can trigger tolerance mechanisms, such as Cu or Pb accumulation in roots.

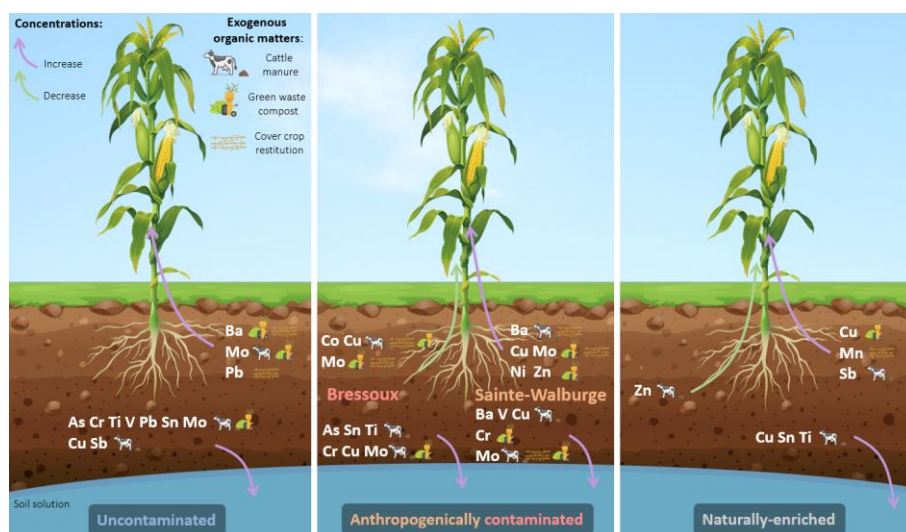


Figure IV.1 – Summary of exogenous organic matter influences on trace element transfers in various soil conditions.

1.3. Extrapolation and applicability

The effects of exogenous organic matter application have been evaluated across various environmental contexts, both in controlled greenhouse experiments and field conditions, resulting in diverse outcomes. Consequently, it is challenging to draw definitive conclusions or make recommendations based solely on soil contamination without considering the physico-chemical properties of the soil. Moreover, organic matter characterization and isotopic analyses were conducted on samples from the controlled greenhouse experiment, and special caution must be exercised when extrapolating these results to real-world conditions due to the inherent differences between experimental and natural environments. While greenhouse experiments are valuable for isolating and controlling specific factors, they do not capture the complexity of natural field conditions. Indeed, in greenhouse settings, plants were grown in pots containing a homogenized soil substrate, which differs in structure and compaction from field soil, potentially affecting water drainage and nutrient dynamics within the soil-plant system. Moreover, the climatic variability between the two experiments, such as higher temperatures and more frequent watering in the greenhouse, likely accelerated organic matter decomposition, potentially resulting in an overestimation of the outcomes. Additionally, differences in light exposure may have influenced plant growth. In the field, plants were exposed to increased biotic pressures (e.g., fungi, pathogens), intensified competition for resources (due to higher planting density and co-existence with other species), and greater atmospheric pollution, especially near urban areas and due to the use of pesticides in adjacent fields. Nevertheless, despite these differences, the greenhouse experiment allowed the isolation and amplification of specific mechanisms to identify and understand them more precisely, assuming their similarity between greenhouse and field conditions.

1.4. Agricultural implications

The experiments conducted on agricultural soils in greenhouses and fields were designed to closely align with current agricultural technologies and practices. Indeed, we focused on maize, one of the world's primary agricultural crops, and applied organic matters and other fertilizers at doses

typical of standard agricultural practices. The extended objective of this thesis was to contribute foundational insights into the health and environmental issues associated with deficiencies and excesses of trace elements, with the aim of facilitating discussions with farmers about whether to adapt their traditional methods without compromising their economic viability (costs and benefits). However, the primary findings of this thesis highlighted the significant influence of soil characteristics on the transfer of trace elements within the soil-plant system. Notably, soils that are similar in terms of physico-chemical properties (e.g., Sainte-Walburge and Bressoux) exhibited contrasting results in certain cases. This variability in outcomes does not always align with the findings reported in the literature; however, it introduces new trends concerning the influence of exogenous organic matter on the transfer of trace elements in agroecosystems. These findings pave the way for more sustainable agricultural strategies, optimizing soil management and natural resource use, while deepening our knowledge of the biogeochemical cycles of elements in the environment.

2. Perspectives

This thesis adopted a comprehensive approach by considering a variety of experimental conditions, including greenhouse and field experiments, diverse soils with contrasting environmental contexts and varying levels and origins of contamination, and a multitude of trace elements. The inclusion of 18 trace elements has facilitated a broader understanding of the transfer mechanisms of these elements, considering both antagonistic and synergistic effects among them but constraining a deeper understanding of the specific geochemical processes governing these transfers. In future studies, it may prove advantageous to concentrate on specific chemical elements that have demonstrated intriguing behaviors throughout this thesis. In particular, attention should be directed towards essential elements (Cu, Zn) and exclusively toxic elements (Pb), which are associated with public health concerns. Additionally, elements exhibiting significant interactions with organic matter, such as Mo, warrant investigation. Furthermore, it would be beneficial to compare two trace elements with distinct properties that have exhibited similar behaviors, or conversely, to explore elements with similar properties that demonstrate divergent behaviors. This would allow for a more in-depth exploration of the geochemical processes and underlying

mechanisms involved in the transfer of trace elements following the application of exogenous organic matter.

The variability in environmental contexts, particularly the soil organic matter content, has impeded the investigation of the exclusive influence of exogenous organic matter. In subsequent experiments, it may be valuable to compare soils with similar origins and contents of soil organic matter, as this would facilitate a clearer isolation of the impact of exogenous organic matter on the transfer of trace elements.

The use of stable isotopes and rare earth elements has partially alleviated the challenges encountered in studying trace element transfers in this thesis, particularly given the low concentrations and short experimental durations (three months in greenhouses and two seasons in the field). A multi-year study would allow for a more comprehensive consideration of the dynamics of organic matter and the impact of its degradation over time on the transfer of elements. Furthermore, to exacerbate the effects of organic matter application, it would be prudent to increase the application doses beyond conventional agricultural practices, thereby enhancing the contrast in observations.

Finally, if general trends emerge from these perspectives, it would be beneficial to model these organic matter-trace element interactions to simulate and predict, on a larger scale, the changes in trace element transfer resulting from the application of exogenous organic matter. In our study, we investigated several compartments, including soil, water, and plants, as well as various constituents. However, it is important to emphasize that these analyses primarily reveal correlations between organic functions and trace elements. To establish a more definitive relationship among these elements and constituents, the use of a synchrotron (particle accelerator) would enable a deeper investigation into the direct interactions and underlying mechanisms involved. Indeed, X-ray diffraction and X-ray absorption spectroscopy techniques from synchrotron would enable the examination of the local structure of trace elements in organic matter. These methods facilitate the determination of the oxidation states and coordination environments of trace elements, as well as their interactions with specific functional groups of organic matter, such as carboxyl, phenolic, or amine groups.

V. References

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VI. Appendices

1. Greenhouse experiment

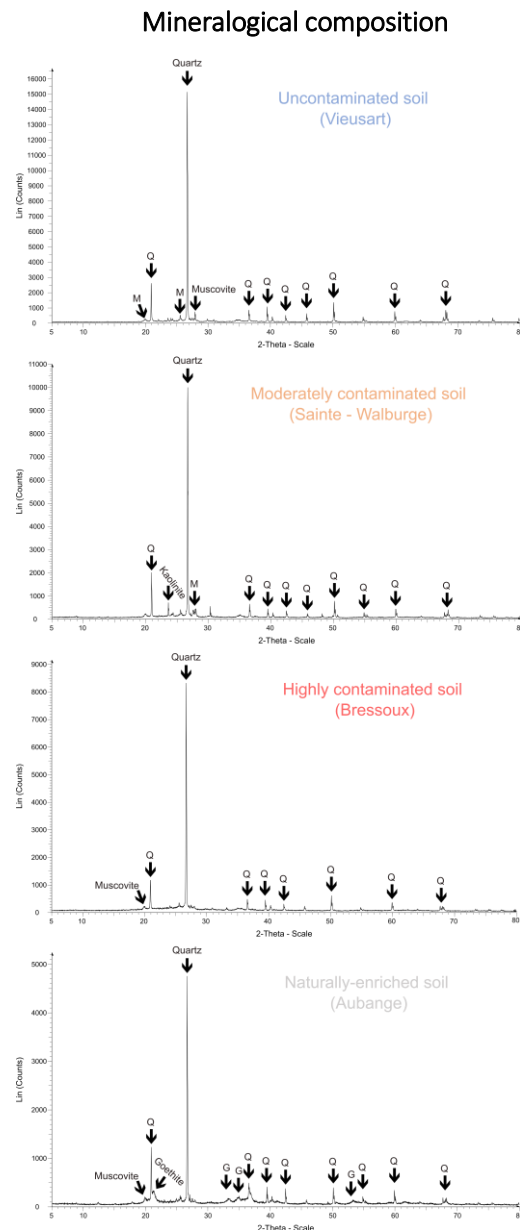
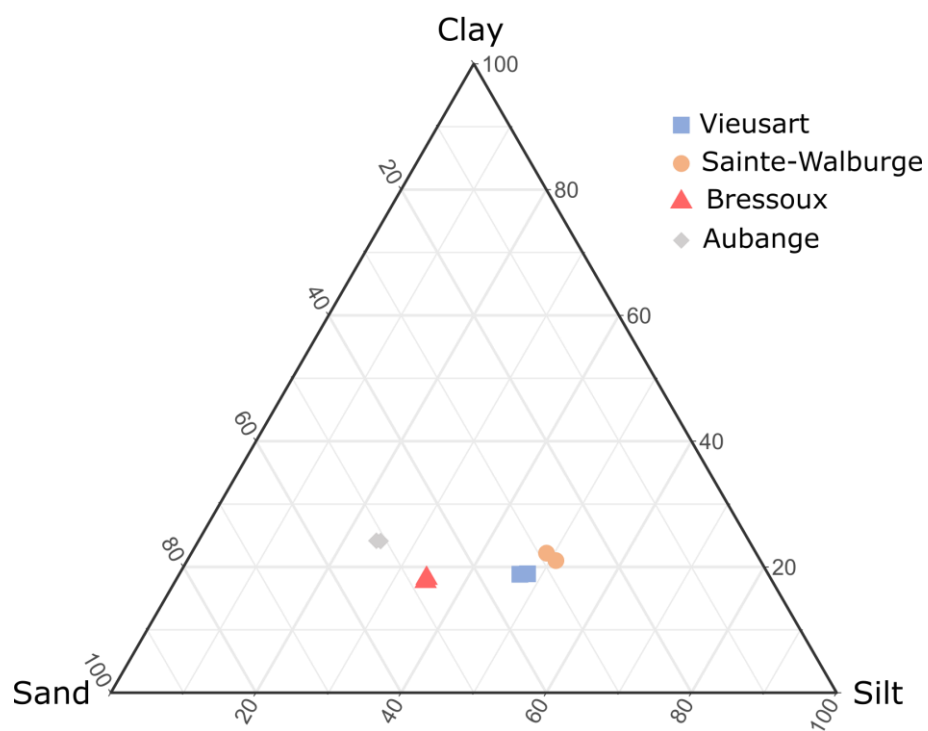


Figure VI.1 - X-ray diffraction (XRD) analysis of soil samples.

Textural diagram (%)



Total Al, Ca, Fe, K, P, S, Si contents

Total Al, Ca, Fe, K, P, S, Si contents of the soil and organic matter samples were determined using a portable X-ray fluorescence (pXRF) instrument (Niton™ XL3t GOLDD+ XRF Analyzer, Thermo Fisher Scientific). Ground samples were placed in circular plastic caps (2.5 cm in diameter) sealed with a 5 µm thick polypropylene film. The sample thickness was maintained at greater than 5 mm to minimize interference from fluorescence X-rays originating outside the sample. The total measurement duration per sample was set to 90 seconds. Each sample was analyzed twice using both internal calibration modes specific to the XL3t GOLDD+ analyzer, namely *Mining* and *Soil*. For each element, the calibration mode yielding the highest measurement precision and the strongest correlation with the reference protocol was selected to construct the geochemical dataset. Indeed, the reference protocol employed elemental analysis via inductively coupled plasma atomic emission spectroscopy (ICP-AES, Thermo Scientific™ iCAP™ 6500) after alkaline fusion. The R^2 values and regression coefficients for the ICP-AES versus pXRF comparison are provided in (Table VI-1). R^2 values exceeded 0.7 for all elements except S (0.49), with regression lines closely aligned with the equivalence line ($y=x$), demonstrating satisfactory agreement between the methods.

To align pXRF values with those from other studies or standards⁹ (soil for soil samples and vegetation/litter for organic matter samples; Table VI-1), the reported pXRF content were adjusted using the slope and intercept of the corresponding linear regression model (Table VI-2).

⁹ Data compiled into a proprietary database owned by the laboratory (doctoral theses of Elisabeth Mauclet, Arthur Monhonval, and Aubry Vandeuren).

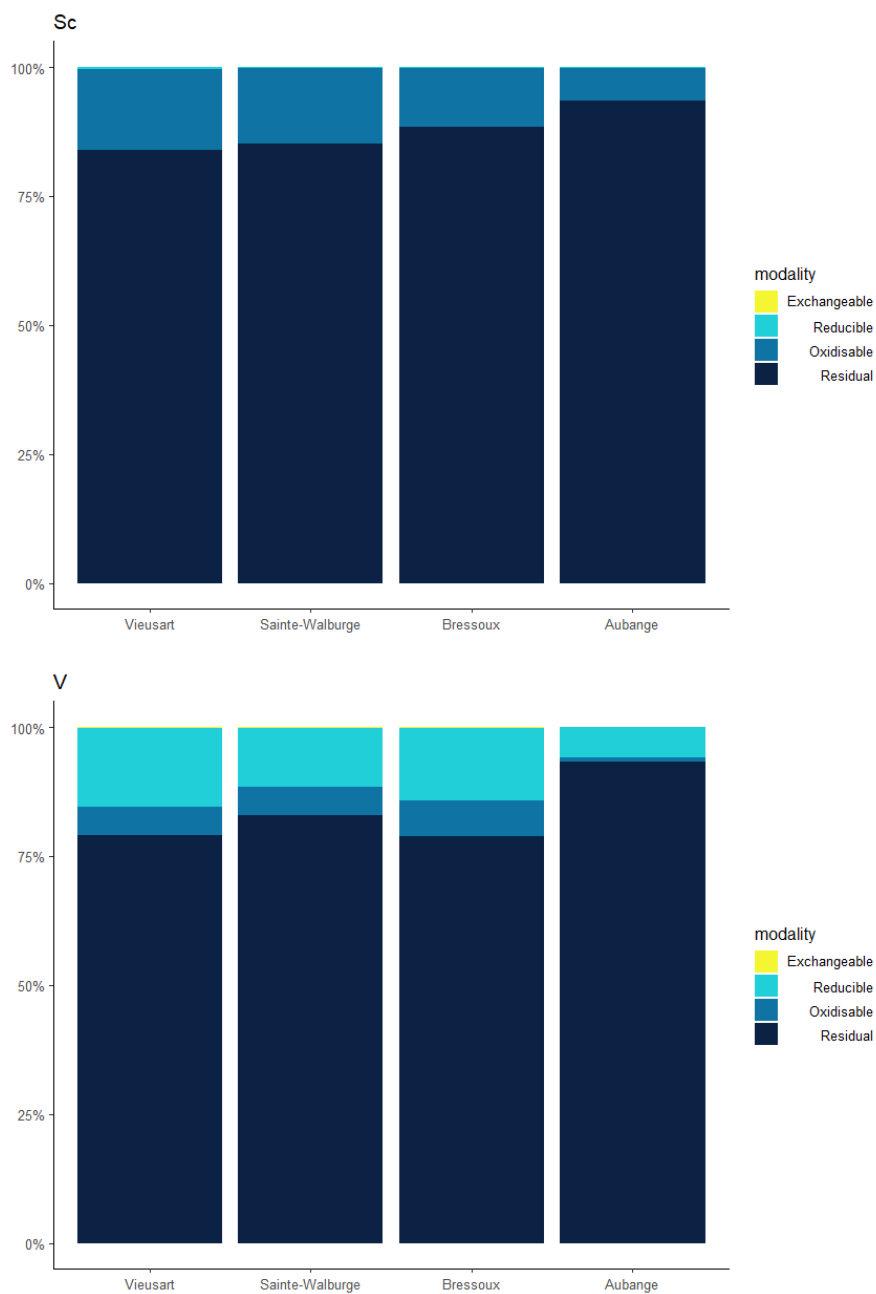
Table VI-1 - The R² values and regression coefficients for the ICP-AES versus pXRF comparison.

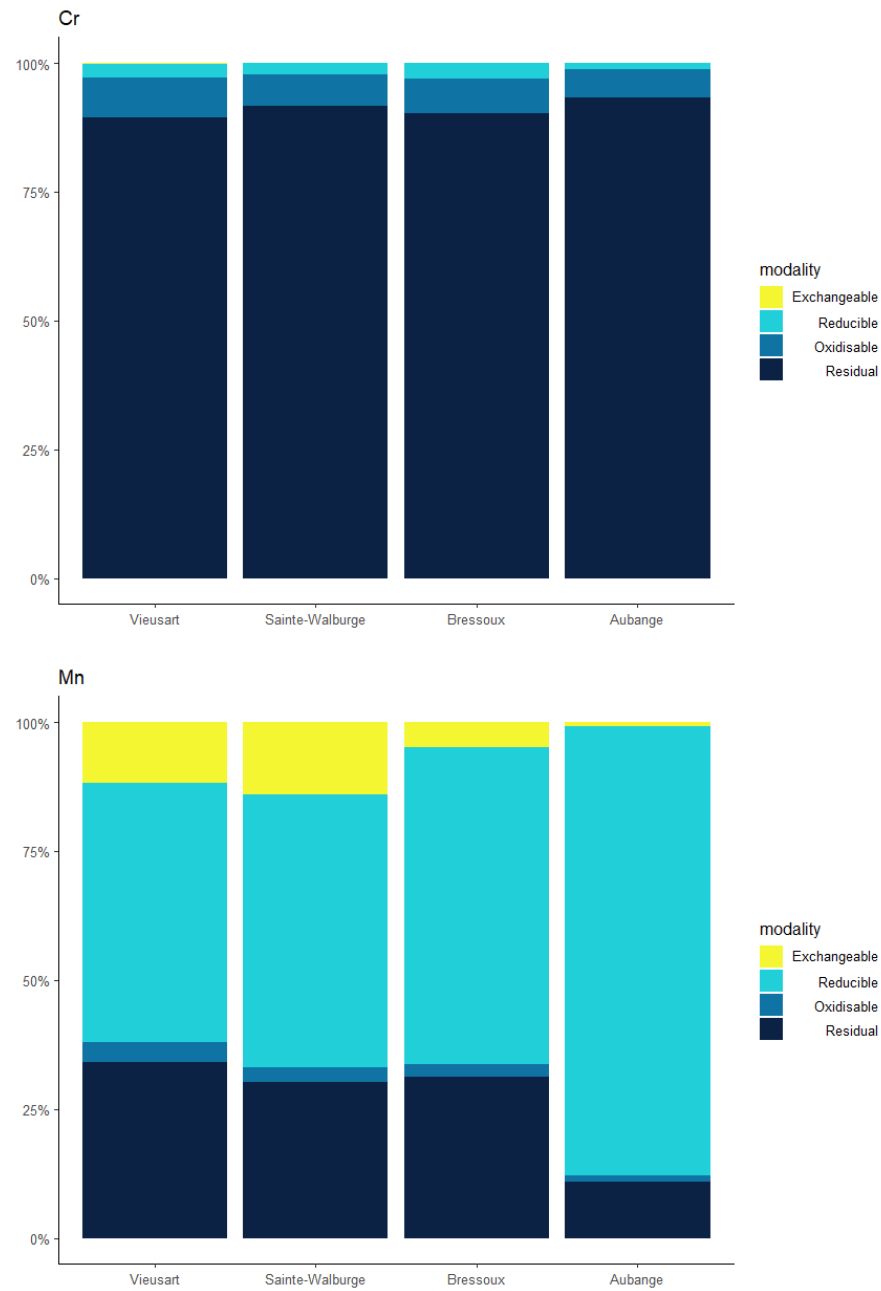
Element	R ²	Slope	Intercept	Mode
Soil				
Al	0,73	1,04	3640	Mining
Ca	1	0,88	324	Soil
Fe	0,95	0,81	6160	Mining
K	0,94	1,06	-228	Soil
Si	0,84	1,25	-37700	Mining
Vegetation/litter				
Al	0,72	0,70	169	Mining
Ca	0,91	0,25	813	Soil
Fe	0,96	0,43	-107	Soil
K	0,84	0,27	713	Soil
P	0,79	0,63	7	Mining
S	0,49	0,20	136	Soil
Si	0,79	0,63	102	Mining

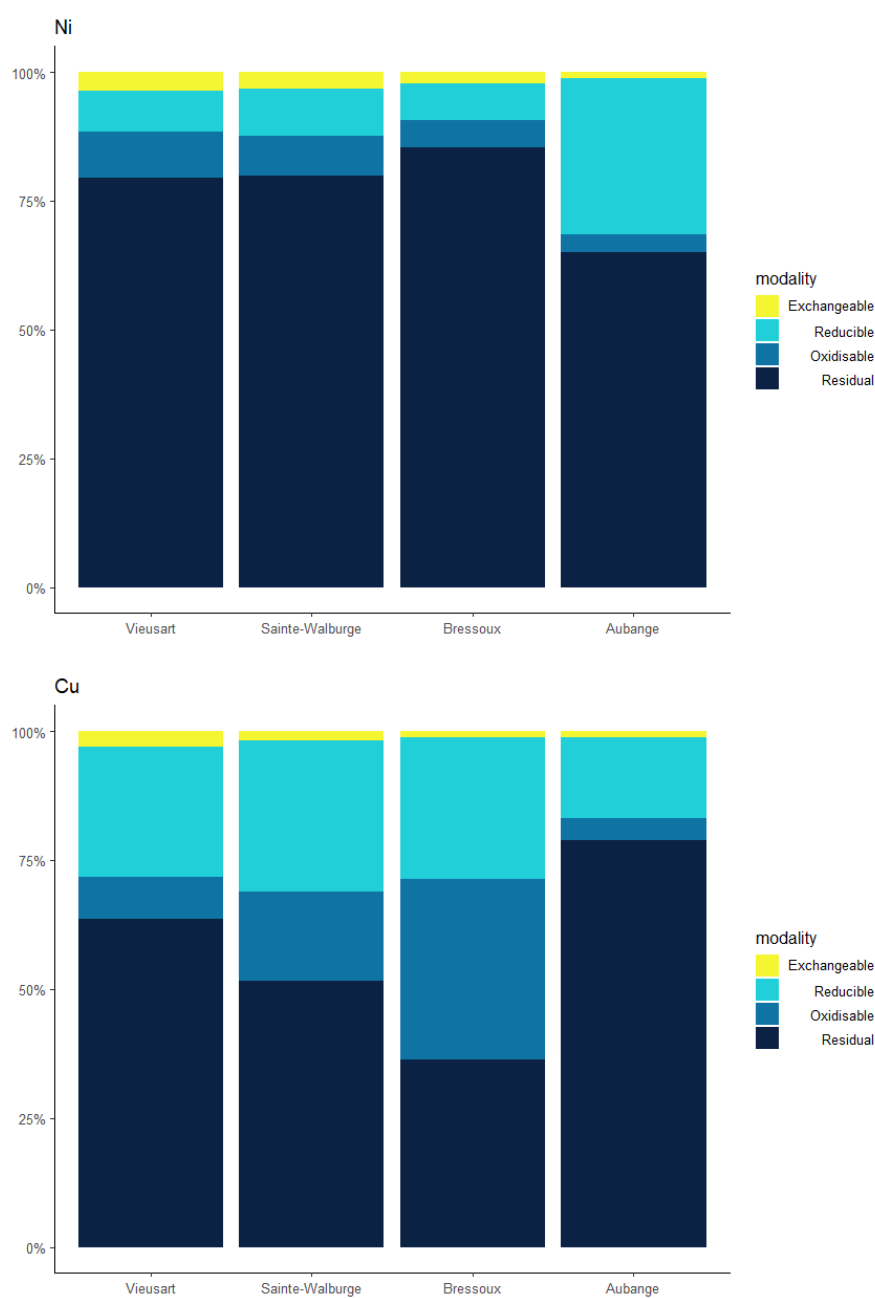
Table VI-2 - Reported pXRF content adjusted using the slope and intercept of the corresponding linear regression model (Table VI-1).

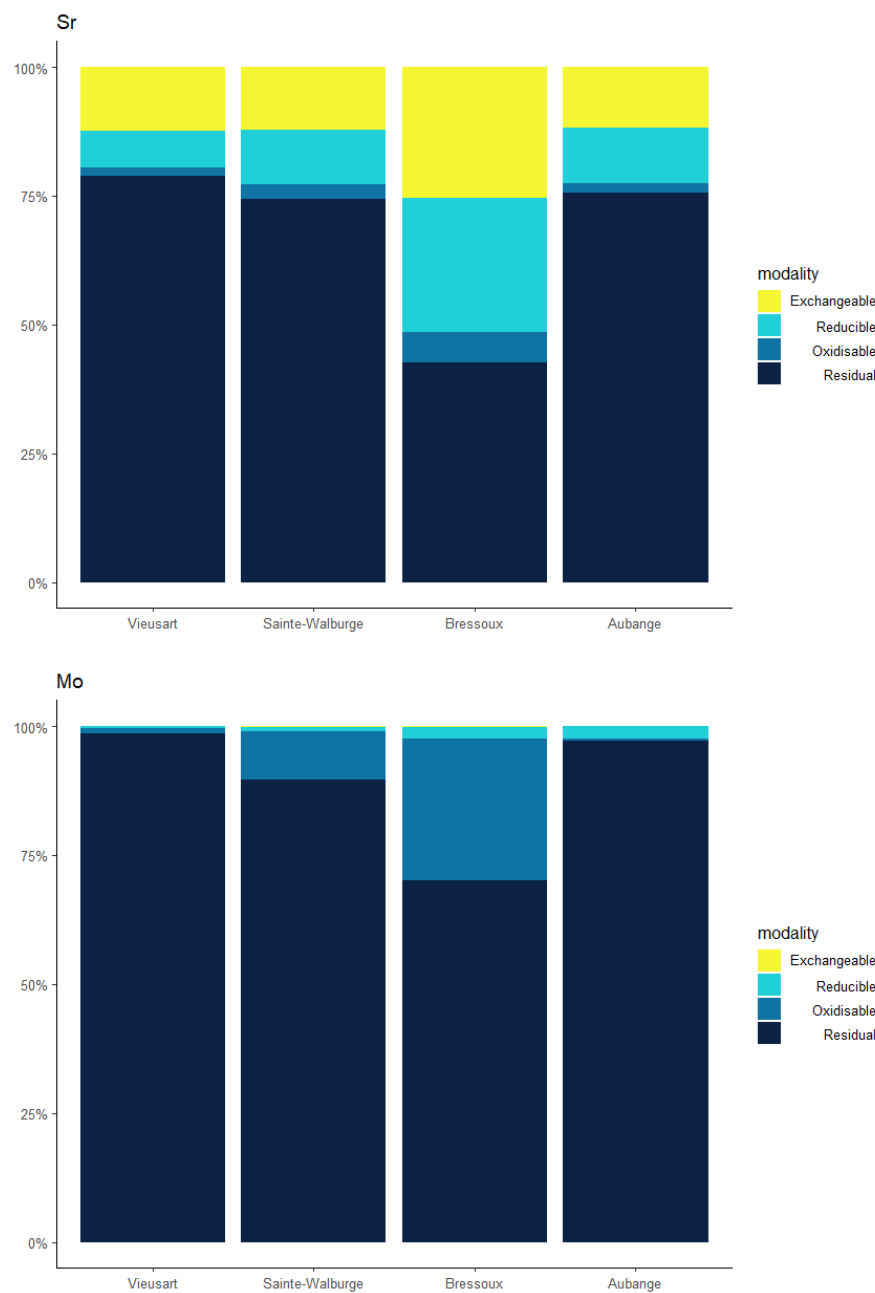
Soils							
(mg kg ⁻¹)	Al	Ca	Fe	K		Si	
Vieusart	52349	3864	39237	16806		301457	
Sainte-Walburge	59153	7526	30284	19156		263273	
Bressoux	56214	12245	39336	15878		186826	
Aubange	63415	4973	166332	12540		137933	
Organic matters							
(mg kg ⁻¹)	Al	Ca	Fe	K	P	S	Si
Fumier	3017	9231	2022	19386	7040	1843	39922
Compost	11765	14039	6372	8520	3978	1053	82758
Restitution	<LOD	11323	71	20990	8024	2231	5176

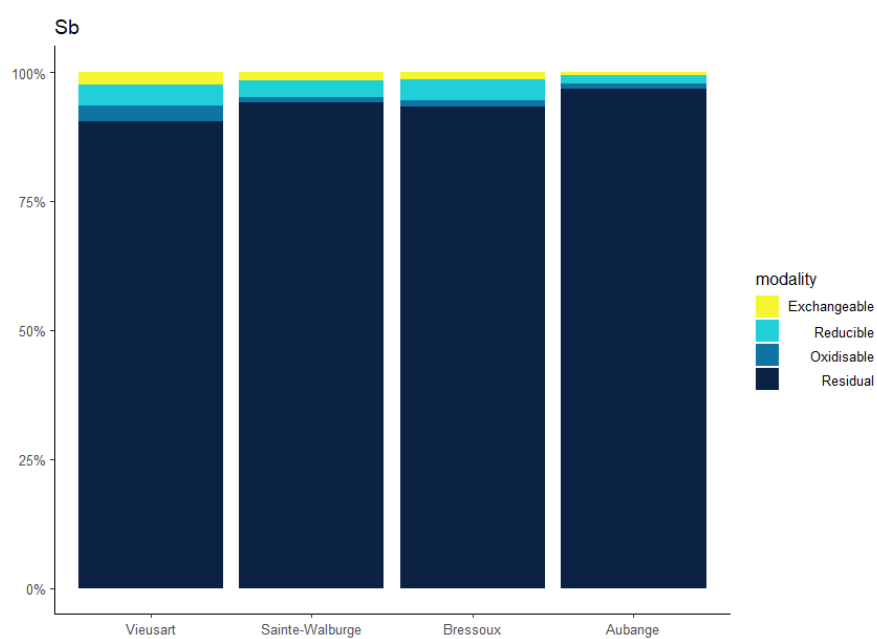
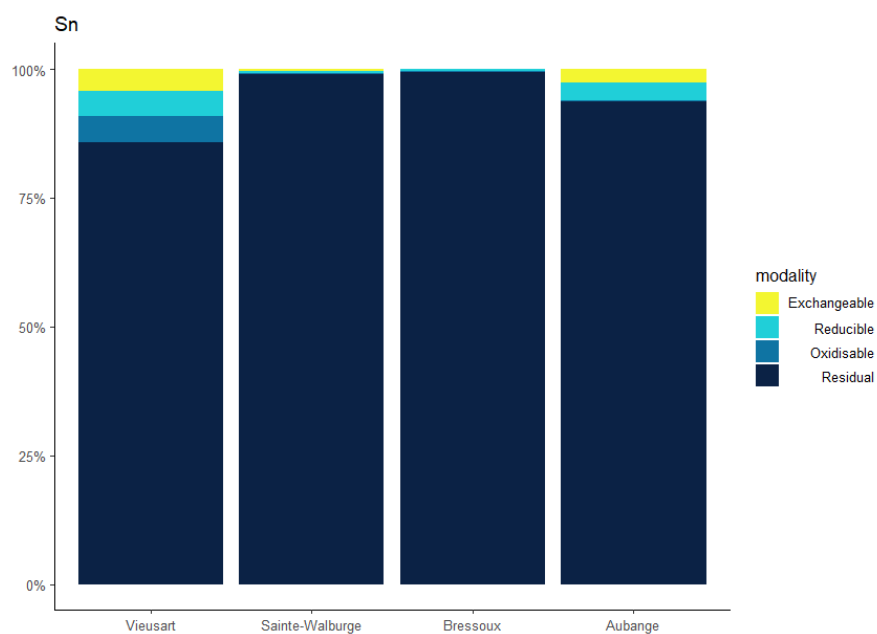
Modified BCR three-step sequential extraction

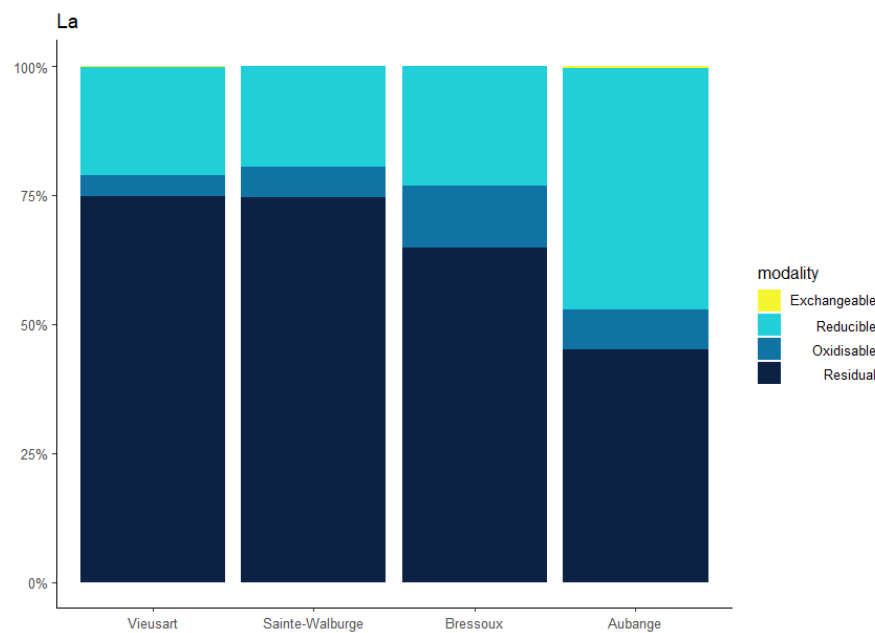
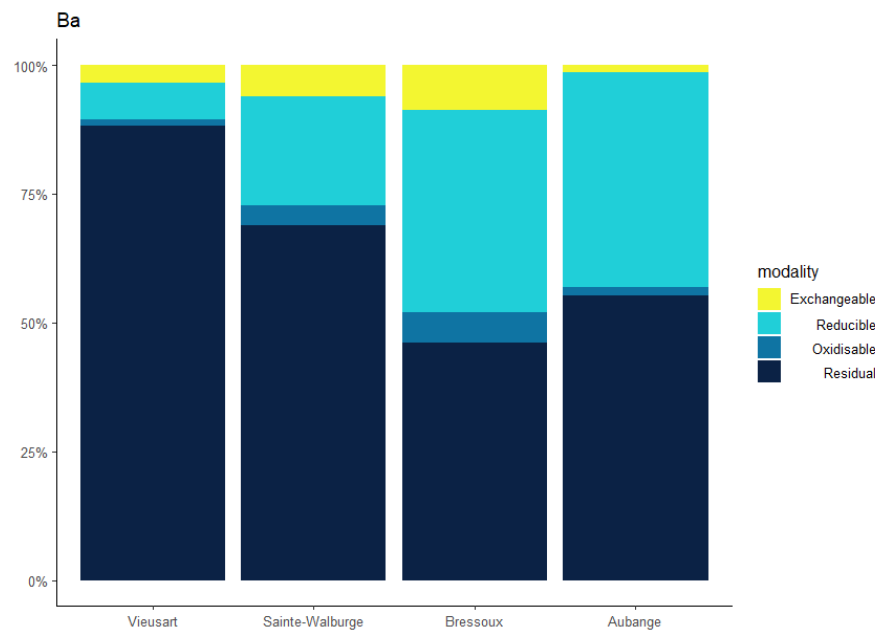


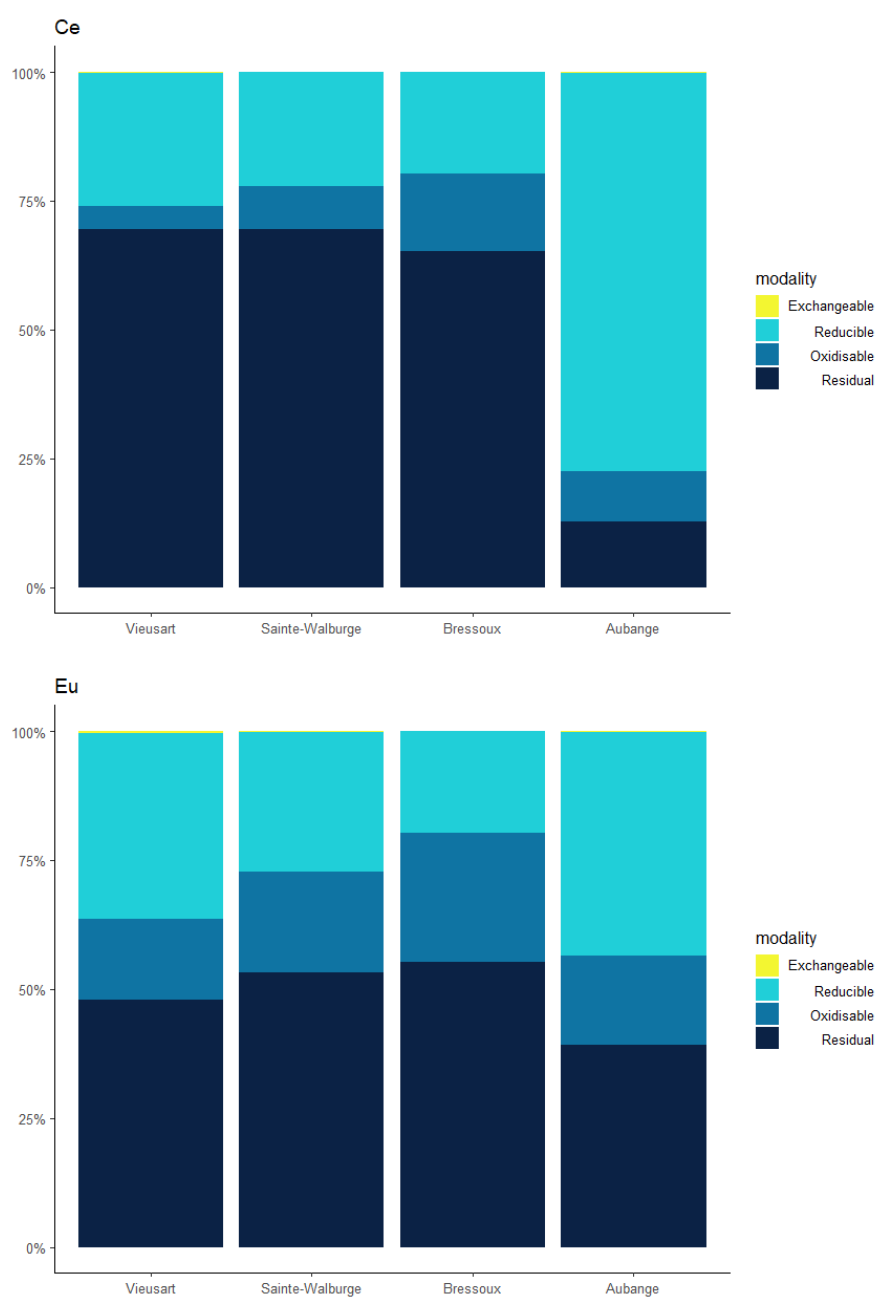


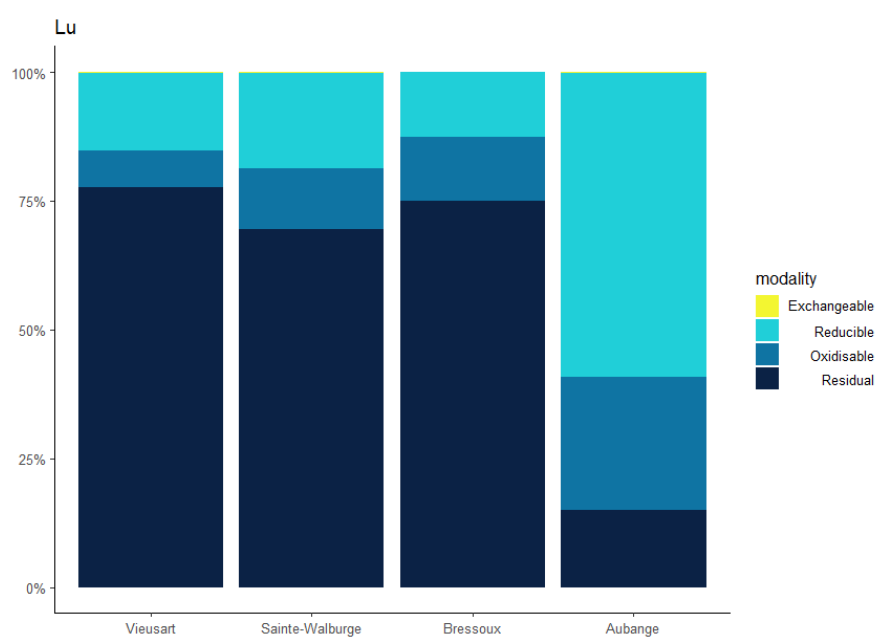












Trace element and rare earth element contents

Table VI-3 – Average trace element contents in soil and exogenous organic matter samples (n=2) and in plant parts and soil solution samples (n=3) for the greenhouse experiment.

Sample	Site	Modality	Date	Units	Sc	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	As	Se	Sr	Mo	Cd	Sn	Sb	Ba	Pb
Soil	Vieusart			mg kg ⁻¹	2,5E+00	1,7E+03	5,3E+01	4,9E+01	2,8E+02	7,8E+00	1,5E+01	1,2E+01	4,4E+01	7,6E+00	2,8E+00	3,6E+01	7,1E-01	2,7E-01	1,1E+00	6,3E-01	2,6E+02	2,0E+01
Soil	Sainte-Walburge			mg kg ⁻¹	7,3E+00	2,5E+03	8,3E+01	6,5E+01	4,6E+02	2,3E+01	4,1E+01	7,2E+01	3,5E+02	1,5E+01	4,4E+00	6,8E+01	2,1E+00	1,8E+00	1,3E+01	3,3E+00	3,4E+02	1,4E+02
Soil	Bressoux			mg kg ⁻¹	8,6E+00	9,4E+02	1,1E+02	7,5E+01	1,0E+03	4,0E+01	6,9E+01	2,5E+02	1,3E+03	3,4E+01	4,6E+00	7,0E+01	4,1E+00	6,5E+00	5,6E+01	1,2E+01	4,0E+02	5,9E+02
Soil	Aubange			mg kg ⁻¹	1,7E+01	2,5E+03	3,9E+02	1,3E+02	8,8E+03	6,2E+01	1,2E+02	1,5E+01	2,3E+02	1,4E+02	8,6E+00	5,0E+01	6,2E+00	4,2E-01	1,6E+00	9,9E-01	1,9E+02	6,6E+01
EOM		Cattle manure		mg kg ⁻¹	8,4E-01	3,7E+02	7,9E+00	2,6E+01	2,1E+02	1,2E+00	5,0E+00	1,8E+01	1,0E+02	1,4E+00	5,7E-01	5,5E+01	3,7E+00	3,1E-01	5,1E-01	2,0E-01	6,5E+01	3,7E+00
EOM		Green waste compost		mg kg ⁻¹	2,8E+00	1,0E+03	2,3E+01	2,5E+01	3,7E+02	1,1E+01	1,0E+01	2,8E+01	1,7E+02	4,1E+00	1,5E+00	8,7E+01	1,9E+00	6,2E-01	2,1E+00	7,6E-01	1,6E+02	3,6E+01
EOM		Cover crop restitution		mg kg ⁻¹	2,3E-02	7,3E+00	4,3E-01	1,2E+00	2,1E+01	7,1E-02	4,8E-01	2,8E+00	1,6E+01	8,3E-02	8,2E-02	2,4E+01	1,6E+00	1,4E-01	7,0E-02	3,1E-02	2,5E+01	3,0E-01
Roots	Vieusart	No application		mg kg ⁻¹	2,1E+00	7,8E+02	2,0E+01	1,9E+01	1,2E+02	3,0E+00	7,6E+00	2,1E+01	3,3E+01	4,5E+00	7,7E-01	3,3E+01	6,2E-01	1,1E+00	5,1E-01	3,3E-01	7,8E+01	7,0E+00
Roots	Vieusart	Cattle manure		mg kg ⁻¹	9,0E-01	3,2E+02	8,2E+00	7,1E+00	6,6E+01	1,7E+00	4,1E+00	1,8E+01	3,2E+01	1,5E+00	3,6E-01	2,3E+01	8,7E-01	6,4E-01	2,6E-01	1,6E-01	3,9E+01	3,2E+00
Roots	Vieusart	Green waste compost		mg kg ⁻¹	1,9E+00	7,7E+02	1,7E+01	1,5E+01	1,1E+02	2,5E+00	6,0E+00	1,8E+01	3,1E+01	3,0E+00	5,6E-01	3,4E+01	7,7E-01	7,1E-01	5,4E-01	2,8E-01	7,7E+01	6,9E+00
Roots	Vieusart	Cover crop restitution		mg kg ⁻¹	1,5E+00	5,6E+02	1,6E+01	1,3E+01	1,6E+02	3,0E+00	6,1E+00	1,8E+01	2,8E+01	4,2E+00	6,1E-01	2,9E+01	6,1E-01	9,9E-01	3,8E-01	2,5E-01	5,6E+01	5,4E+00
Roots	Sainte-Walburge	No application		mg kg ⁻¹	1,3E+00	3,0E+02	9,7E+00	7,9E+00	6,9E+01	4,8E+00	8,1E+00	3,5E+01	8,5E+01	3,4E+00	4,6E-01	2,7E+01	2,0E+00	2,1E+00	7,7E-01	3,8E-01	4,6E+01	1,1E+01
Roots	Sainte-Walburge	Cattle manure		mg kg ⁻¹	8,5E-01	2,0E+02	7,5E+00	5,2E+00	9,6E+01	6,6E+00	1,1E+01	3,9E+01	1,1E+02	6,3E+00	3,5E-01	4,5E+01	2,1E+00	5,0E+00	5,9E-01	3,5E-01	6,1E+01	8,0E+00
Roots	Sainte-Walburge	Green waste compost		mg kg ⁻¹	1,7E+00	3,3E+02	1,4E+01	9,3E+00	8,6E+01	6,4E+00	1,1E+01	4,2E+01	8,1E+01	3,4E+00	4,4E-01	4,2E+01	3,2E+00	3,1E+00	9,3E-01	5,8E-01	6,6E+01	1,3E+01
Roots	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	1,3E+00	2,3E+02	9,9E+00	7,2E+00	9,2E+01	7,0E+00	1,0E+01	5,0E+01	8,5E+01	5,2E+00	4,6E-01	4,4E+01	2,8E+00	3,8E+00	7,0E-01	5,1E-01	5,6E+01	1,1E+01
Roots	Bressoux	No application		mg kg ⁻¹	3,7E-01	3,9E+01	3,7E+00	1,6E+00	3,0E+01	1,5E+00	4,7E+00	7,9E+01	2,2E+02	4,8E+00	4,5E-01	2,1E+01	9,5E-01	3,4E+00	2,8E-01	6,7E-01	1,8E+01	1,7E+01
Roots	Bressoux	Cattle manure		mg kg ⁻¹	4,0E-01	4,7E+01	3,4E+00	1,9E+00	3,6E+01	1,4E+00	4,6E+00	6,2E+01	1,8E+02	3,5E+00	2,3E-01	2,5E+01	1,5E+00	3,8E+00	3,9E-01	5,3E-01	3,1E+01	1,6E+01
Roots	Bressoux	Green waste compost		mg kg ⁻¹	5,1E-01	5,7E+01	4,7E+00	2,5E+00	4,1E+01	1,4E+00	4,4E+00	7,5E+01	1,9E+02	3,0E+00	2,6E-01	2,1E+01	1,9E+00	3,7E+00	2,1E+00	6,9E-01	2,9E+01	2,2E+01
Roots	Bressoux	Cover crop restitution		mg kg ⁻¹	1,2E+00	1,5E+02	9,6E+00	5,5E+00	7,0E+01	2,7E+00	8,1E+00	1,1E+02	3,2E+02	4,5E+00	4,3E-01	2,9E+01	1,4E+00	6,9E+00	1,5E+00	1,4E+00	1,4E+02	4,1E+01
Roots	Aubange	No application		mg kg ⁻¹	1,2E+00	1,4E+02	2,1E+01	6,9E+00	4,5E+02	4,0E+00	9,9E+00	3,6E+00	2,3E+01	8,1E+00	3,5E-01	2,0E+01	6,5E-01	1,9E-01	2,1E-01	7,6E-02	1,3E+01	4,1E+00

Appendices

Roots	Aubange	Cattle manure	mg kg ⁻¹	1,0E+00	1,3E+02	1,7E+01	5,4E+00	3,2E+02	4,2E+00	1,0E+01	4,0E+00	2,2E+01	6,7E+00	1,8E-01	1,8E+01	4,9E-01	1,7E-01	1,0E-01	6,8E-02	1,1E+01	3,4E+00
Roots	Aubange	Green waste compost	mg kg ⁻¹	2,5E+00	3,1E+02	4,7E+01	1,3E+01	1,1E+03	7,8E+00	2,2E+01	5,7E+00	4,0E+01	2,1E+01	7,2E-01	1,9E+01	9,4E-01	2,6E-01	2,5E-01	1,5E-01	3,1E+01	8,2E+00
Roots	Aubange	Cover crop restitution	mg kg ⁻¹	1,9E+00	2,2E+02	3,1E+01	9,6E+00	5,7E+02	6,5E+00	1,6E+01	4,9E+00	3,3E+01	1,2E+01	4,5E-01	2,4E+01	6,0E-01	3,3E-01	2,5E-01	1,1E-01	1,6E+01	5,7E+00
Stems	Vieusart	No application	mg kg ⁻¹	2,0E+02	2,5E+00	5,7E-02	2,7E-01	1,5E+01	1,6E-02	1,4E-01	4,0E+00	2,6E+01	3,3E-02	1,9E-02	5,6E+00	9,7E-01	1,5E-01	3,9E-02	7,9E-03	1,5E+00	7,8E-02
Stems	Vieusart	Cattle manure	mg kg ⁻¹	1,0E-02	2,1E+00	5,1E-02	2,4E-01	1,4E+01	1,0E-02	1,4E-01	4,1E+00	2,8E+01	2,5E-02	2,8E-02	5,4E+00	3,2E+00	1,4E-01	2,9E-02	6,2E-03	3,5E+00	5,9E-02
Stems	Vieusart	Green waste compost	mg kg ⁻¹	9,9E-03	1,7E+00	4,4E-02	2,3E-01	1,8E+01	1,3E-02	2,2E-01	4,8E+00	3,9E+01	3,4E-02	3,3E-02	7,0E+00	3,6E+00	1,8E-01	2,4E-02	6,7E-03	2,6E+00	1,1E-01
Stems	Vieusart	Cover crop restitution	mg kg ⁻¹	2,4E-02	4,4E+00	9,2E-02	3,7E-01	2,5E+01	2,2E-02	2,8E-01	5,0E+00	2,9E+01	3,8E-02	2,8E-02	6,8E+00	1,4E+00	2,3E-01	4,1E-02	1,6E-02	2,6E+00	2,7E-01
Stems	Sainte-Walburge	No application	mg kg ⁻¹	2,6E-02	2,1E+00	5,4E-02	4,1E-01	2,2E+01	2,5E-02	2,8E-01	4,3E+00	1,2E+02	4,9E-01	2,0E-02	8,6E+00	5,3E+00	3,4E-01	1,1E-02	1,0E-02	4,3E+00	2,7E-01
Stems	Sainte-Walburge	Cattle manure	mg kg ⁻¹	3,1E-02	2,7E+00	6,9E-02	3,7E-01	2,9E+01	3,4E-02	4,1E-01	8,7E+00	3,0E+02	8,2E-01	1,9E-02	1,2E+01	9,2E+00	7,3E-01	1,6E-02	1,2E-02	1,1E+01	4,0E-01
Stems	Sainte-Walburge	Green waste compost	mg kg ⁻¹	3,6E-02	3,1E+00	7,5E-02	6,1E-01	2,7E+01	2,5E-02	5,5E-01	8,6E+00	2,9E+02	5,0E-01	3,0E-02	1,2E+01	1,2E+01	4,3E-01	1,4E-02	1,3E-02	7,2E+00	4,1E-01
Stems	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	3,8E-02	2,2E+00	6,0E-02	4,6E-01	3,2E+01	2,7E-02	3,0E-01	7,9E+00	2,8E+02	5,8E-01	1,9E-02	1,4E+01	1,1E+01	5,4E-01	2,4E-02	9,0E-03	7,9E+00	4,0E-01
Stems	Bressoux	No application	mg kg ⁻¹	2,9E-02	3,2E+00	1,0E-01	8,4E-01	2,1E+01	2,4E-02	4,5E-01	6,6E+00	7,8E+02	9,9E-01	2,0E-02	1,0E+01	1,2E+01	6,0E-01	3,6E-02	1,4E-02	4,7E+00	6,7E-01
Stems	Bressoux	Cattle manure	mg kg ⁻¹	2,4E-02	2,4E+00	4,2E-02	2,2E-01	1,2E+01	9,7E-03	2,8E-01	5,3E+00	4,1E+02	4,6E-01	2,0E-02	8,9E+00	1,0E+01	6,0E-01	3,4E-02	1,8E-02	7,4E+00	4,2E-01
Stems	Bressoux	Green waste compost	mg kg ⁻¹	2,8E-02	2,1E+00	4,1E-02	3,1E-01	1,0E+01	1,2E-02	2,2E-01	5,9E+00	5,1E+02	4,9E-01	4,1E-02	7,7E+00	7,7E+00	3,6E-01	1,4E-02	1,8E-02	4,4E+00	4,2E-01
Stems	Bressoux	Cover crop restitution	mg kg ⁻¹	2,6E-02	1,6E+00	3,9E-02	2,6E-01	1,1E+01	8,8E-03	1,9E-01	4,4E+00	5,3E+02	4,4E-01	2,8E-02	8,1E+00	6,8E+00	4,1E-01	1,1E-02	1,2E-02	4,5E+00	4,5E-01
Stems	Aubange	No application	mg kg ⁻¹	2,5E-02	2,9E+00	2,2E-01	3,1E-01	3,4E+01	3,1E-02	3,5E-01	4,7E+00	5,1E+01	8,7E-02	3,1E-02	5,2E+00	6,8E+00	1,3E-01	2,1E-02	7,2E-03	5,1E-01	2,3E-01
Stems	Aubange	Cattle manure	mg kg ⁻¹	2,1E-02	2,1E+00	1,5E-01	3,8E-01	2,8E+01	3,7E-02	2,6E-01	3,1E+00	2,7E+01	8,5E-02	3,9E-02	6,3E+00	1,1E+01	8,8E-02	2,1E-02	6,1E-03	6,0E-01	1,8E-01
Stems	Aubange	Green waste compost	mg kg ⁻¹	1,1E-02	1,2E+00	7,9E-02	2,7E-01	1,8E+01	1,6E-02	2,1E-01	2,2E+00	2,8E+01	4,8E-02	1,9E-02	3,8E+00	9,1E+00	5,3E-02	1,6E-02	3,8E-03	2,7E-01	1,3E-01
Stems	Aubange	Cover crop restitution	mg kg ⁻¹	2,1E-02	2,5E+00	1,8E-01	3,4E-01	3,3E+01	3,0E-02	3,0E-01	2,5E+00	3,1E+01	8,5E-02	3,2E-02	5,9E+00	8,3E+00	6,0E-02	1,4E-02	1,3E-02	5,2E-01	1,9E-01
Leaves	Vieusart	No application	mg kg ⁻¹	2,3E-02	5,7E+00	1,2E-01	8,0E-01	1,9E+02	5,8E-02	4,9E-01	3,0E+01	5,8E+01	2,0E-01	3,0E-02	1,7E+01	2,4E+00	2,1E-01	2,5E-01	6,3E-02	1,7E+00	1,1E+00
Leaves	Vieusart	Cattle manure	mg kg ⁻¹	2,8E-02	6,9E+00	1,4E-01	9,6E-01	1,0E+02	4,2E-02	7,5E-01	3,0E+01	5,8E+01	2,0E-01	5,6E-02	1,6E+01	5,7E+00	2,7E-01	2,4E-01	9,9E-02	3,2E+00	1,1E+00
Leaves	Vieusart	Green waste compost	mg kg ⁻¹	2,0E-02	6,7E+00	1,4E-01	1,2E+00	1,3E+02	4,6E-02	8,1E-01	2,6E+01	5,8E+01	1,6E-01	1,9E-02	1,5E+01	3,7E+00	2,4E-01	2,1E-01	7,5E-02	2,0E+00	9,8E-01
Leaves	Vieusart	Cover crop restitution	mg kg ⁻¹	3,2E-02	1,2E+01	1,9E-01	1,2E+00	2,2E+02	6,6E-02	6,2E-01	3,9E+01	6,5E+01	2,0E-01	8,4E-02	1,9E+01	3,7E+00	4,4E-01	2,6E-01	5,4E-02	2,9E+00	2,5E+00
Leaves	Sainte-Walburge	No application	mg kg ⁻¹	2,0E-02	4,0E+00	8,6E-02	6,4E-01	2,0E+02	6,0E-02	5,0E-01	2,0E+01	1,4E+02	7,7E-01	6,8E-02	1,8E+01	7,8E+00	5,7E-01	1,2E-01	3,3E-02	2,5E+00	1,1E+00
Leaves	Sainte-Walburge	Cattle manure	mg kg ⁻¹	1,9E-02	5,7E+00	1,2E-01	7,1E-01	2,7E+02	6,6E-02	6,1E-01	2,6E+01	1,7E+02	8,8E-01	4,5E-02	2,1E+01	7,9E+00	7,4E-01	1,9E-01	4,2E-02	4,7E+00	9,0E-01

Leaves	Sainte-Walburge	Green waste compost	mg kg ⁻¹	3,0E-02	5,5E+00	1,2E-01	6,5E-01	2,4E+02	4,8E-02	1,2E+00	3,6E+01	1,7E+02	7,5E-01	6,4E-02	2,3E+01	7,5E+00	5,5E-01	2,0E-01	6,6E-02	3,3E+00	1,0E+00
Leaves	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	2,6E-02	6,7E+00	1,3E-01	7,5E-01	2,8E+02	6,7E-02	8,1E-01	4,6E+01	1,8E+02	7,4E-01	6,5E-02	2,2E+01	6,6E+00	6,5E-01	2,5E-01	7,6E-02	3,2E+00	1,5E+00
Leaves	Bressoux	No application	mg kg ⁻¹	2,7E-02	8,4E+00	1,7E-01	9,3E-01	1,5E+02	4,4E-02	9,0E-01	6,3E+01	4,9E+02	1,1E+00	5,1E-02	2,4E+01	4,4E+00	8,0E-01	3,5E-01	8,4E-02	2,9E+00	2,2E+00
Leaves	Bressoux	Cattle manure	mg kg ⁻¹	2,0E-02	6,5E+00	1,3E-01	8,1E-01	1,4E+02	3,2E-02	6,5E-01	3,5E+01	4,9E+02	6,7E-01	1,9E-02	2,3E+01	5,1E+00	9,4E-01	2,5E-01	7,5E-02	4,5E+00	1,4E+00
Leaves	Bressoux	Green waste compost	mg kg ⁻¹	2,3E-02	9,5E+00	1,8E-01	8,5E-01	1,5E+02	3,9E-02	6,8E-01	3,5E+01	4,2E+02	9,1E-01	7,6E-02	2,3E+01	5,8E+00	6,6E-01	1,7E-01	7,5E-02	3,5E+00	1,3E+00
Leaves	Bressoux	Cover crop restitution	mg kg ⁻¹	2,2E-02	7,3E+00	1,4E-01	9,5E-01	1,5E+02	3,4E-02	4,7E-01	3,3E+01	5,9E+02	8,6E-01	3,4E-02	2,5E+01	4,8E+00	8,5E-01	1,9E-01	6,2E-02	3,0E+00	1,2E+00
Leaves	Aubange	No application	mg kg ⁻¹	1,8E-02	5,8E+00	1,1E-01	6,7E-01	3,3E+02	5,3E-02	9,9E-01	2,7E+01	5,8E+01	2,6E-01	3,9E-02	1,2E+01	2,0E+00	1,2E-01	1,7E-01	3,2E-02	8,2E-01	1,0E+00
Leaves	Aubange	Cattle manure	mg kg ⁻¹	3,7E-02	6,9E+00	1,8E-01	1,2E+00	3,5E+02	6,6E-02	1,2E+00	3,3E+01	5,6E+01	3,5E-01	6,9E-02	1,5E+01	2,0E+00	1,6E-01	2,0E-01	8,1E-02	9,5E-01	1,7E+00
Leaves	Aubange	Green waste compost	mg kg ⁻¹	2,8E-02	8,1E+00	1,7E-01	1,3E+00	2,9E+02	6,1E-02	1,4E+00	5,1E+01	6,9E+01	3,1E-01	3,9E-02	1,2E+01	2,5E+00	2,3E-01	2,8E-01	6,7E-02	1,0E+00	2,3E+00
Leaves	Aubange	Cover crop restitution	mg kg ⁻¹	2,6E-02	7,5E+00	2,4E-01	9,5E-01	4,2E+02	7,1E-02	1,2E+00	3,9E+01	5,9E+01	2,9E-01	3,4E-02	1,6E+01	1,9E+00	1,9E-01	2,3E-01	4,6E-02	1,0E+00	1,5E+00
Shoots	Vieusart	No application	mg kg ⁻¹	2,1E-02	3,5E+00	7,6E-02	4,5E-01	7,3E+01	3,0E-02	2,5E-01	1,2E+01	3,6E+01	8,6E-02	2,3E-02	9,1E+00	1,4E+00	1,7E-01	1,1E-01	2,6E-02	1,6E+00	4,1E-01
Shoots	Vieusart	Cattle manure	mg kg ⁻¹	1,6E-02	3,7E+00	8,1E-02	4,8E-01	4,3E+01	2,1E-02	3,5E-01	1,3E+01	3,8E+01	8,3E-02	3,7E-02	9,1E+00	4,1E+00	1,8E-01	1,0E-01	3,7E-02	3,4E+00	4,1E-01
Shoots	Vieusart	Green waste compost	mg kg ⁻¹	1,3E-02	3,4E+00	7,5E-02	5,5E-01	5,7E+01	2,4E-02	4,2E-01	1,2E+01	4,6E+01	7,6E-02	2,9E-02	9,8E+00	3,6E+00	2,0E-01	8,6E-02	3,0E-02	2,4E+00	4,0E-01
Shoots	Vieusart	Cover crop restitution	mg kg ⁻¹	2,6E-02	6,9E+00	1,2E-01	6,5E-01	9,1E+01	3,6E-02	3,9E-01	1,6E+01	4,1E+01	9,2E-02	4,6E-02	1,1E+01	2,1E+00	3,0E-01	1,1E-01	2,9E-02	2,7E+00	1,0E+00
Shoots	Sainte-Walburge	No application	mg kg ⁻¹	2,4E-02	2,8E+00	6,6E-02	5,0E-01	8,9E+01	3,8E-02	3,7E-01	1,0E+01	1,3E+02	5,9E-01	3,8E-02	1,2E+01	6,3E+00	4,2E-01	5,0E-02	1,9E-02	3,6E+00	5,6E-01
Shoots	Sainte-Walburge	Cattle manure	mg kg ⁻¹	2,6E-02	3,8E+00	8,9E-02	5,0E-01	1,2E+02	4,6E-02	4,9E-01	1,5E+01	2,5E+02	8,5E-01	2,9E-02	1,5E+01	8,7E+00	7,3E-01	8,4E-02	2,4E-02	8,5E+00	5,9E-01
Shoots	Sainte-Walburge	Green waste compost	mg kg ⁻¹	3,4E-02	4,0E+00	9,3E-02	6,2E-01	1,1E+02	3,4E-02	8,0E-01	1,9E+01	2,5E+02	6,0E-01	4,3E-02	1,6E+01	1,0E+01	4,8E-01	8,5E-02	3,3E-02	5,7E+00	6,3E-01
Shoots	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	3,3E-02	4,0E+00	8,7E-02	5,7E-01	1,3E+02	4,3E-02	5,1E-01	2,4E+01	2,4E+02	6,5E-01	3,7E-02	1,7E+01	9,4E+00	5,8E-01	1,2E-01	3,6E-02	6,0E+00	8,5E-01
Shoots	Bressoux	No application	mg kg ⁻¹	2,8E-02	5,5E+00	1,3E-01	8,8E-01	7,7E+01	3,3E-02	6,5E-01	3,1E+01	6,5E+02	1,0E+00	3,4E-02	1,6E+01	8,9E+00	6,8E-01	1,8E-01	4,5E-02	3,9E+00	1,3E+00
Shoots	Bressoux	Cattle manure	mg kg ⁻¹	2,2E-02	4,0E+00	7,4E-02	4,5E-01	6,0E+01	1,8E-02	4,2E-01	1,7E+01	4,4E+02	5,4E-01	1,9E-02	1,5E+01	8,3E+00	7,3E-01	1,2E-01	4,0E-02	6,3E+00	8,2E-01
Shoots	Bressoux	Green waste compost	mg kg ⁻¹	2,6E-02	5,1E+00	9,6E-02	5,4E-01	6,6E+01	2,3E-02	4,1E-01	1,8E+01	4,8E+02	6,6E-01	5,5E-02	1,4E+01	6,9E+00	4,8E-01	7,8E-02	4,1E-02	4,0E+00	7,9E-01
Shoots	Bressoux	Cover crop restitution	mg kg ⁻¹	2,4E-02	3,9E+00	8,2E-02	5,5E-01	7,1E+01	1,9E-02	3,1E-01	1,6E+01	5,5E+02	6,1E-01	3,0E-02	1,5E+01	5,9E+00	5,9E-01	8,7E-02	3,3E-02	3,9E+00	7,8E-01
Shoots	Aubange	No application	mg kg ⁻¹	2,2E-02	3,9E+00	1,8E-01	4,4E-01	1,4E+02	3,8E-02	5,7E-01	1,3E+01	5,4E+01	1,5E-01	3,3E-02	7,6E+00	5,2E+00	1,2E-01	7,4E-02	1,6E-02	6,2E-01	5,1E-01
Shoots	Aubange	Cattle manure	mg kg ⁻¹	2,7E-02	3,9E+00	1,6E-01	7,1E-01	1,5E+02	4,8E-02	6,0E-01	1,4E+01	3,8E+01	1,9E-01	5,1E-02	9,4E+00	7,4E+00	1,2E-01	8,9E-02	3,5E-02	7,3E-01	7,5E-01
Shoots	Aubange	Green waste compost	mg kg ⁻¹	1,7E-02	3,7E+00	1,1E-01	6,3E-01	1,2E+02	3,2E-02	6,3E-01	2,0E+01	4,3E+01	1,4E-01	2,7E-02	6,8E+00	6,7E+00	1,2E-01	1,1E-01	2,7E-02	5,4E-01	9,1E-01

Appendices

Shoots	Aubange	Cover crop restitution		mg kg ⁻¹	2,3E-02	4,5E+00	2,0E-01	5,8E-01	1,9E+02	4,6E-02	6,5E-01	1,7E+01	4,2E+01	1,7E-01	3,3E-02	9,7E+00	5,8E+00	1,1E-01	1,0E-01	2,6E-02	7,2E-01	7,2E-01
Plant	Vieusart	No application		mg kg ⁻¹	3,4E-01	1,3E+02	3,3E+00	3,5E+00	8,0E+01	5,0E-01	1,4E+00	1,4E+01	3,5E+01	8,1E-01	1,4E-01	1,3E+01	1,3E+00	3,1E-01	1,7E-01	7,3E-02	1,4E+01	1,5E+00
Plant	Vieusart	Cattle manure		mg kg ⁻¹	1,6E-01	5,4E+01	1,3E+00	1,5E+00	4,7E+01	2,9E-01	9,3E-01	1,4E+01	3,7E+01	3,0E-01	8,6E-02	1,1E+01	3,6E+00	2,5E-01	1,3E-01	5,7E-02	8,9E+00	8,3E-01
Plant	Vieusart	Green waste compost		mg kg ⁻¹	3,7E-01	1,5E+02	3,2E+00	3,3E+00	6,6E+01	4,9E-01	1,5E+00	1,3E+01	4,3E+01	6,4E-01	1,3E-01	1,4E+01	3,1E+00	3,0E-01	1,7E-01	7,6E-02	1,7E+01	1,6E+00
Plant	Vieusart	Cover crop restitution		mg kg ⁻¹	2,6E-01	9,3E+01	2,5E+00	2,6E+00	1,0E+02	4,8E-01	1,3E+00	1,7E+01	3,9E+01	7,0E-01	1,3E-01	1,4E+01	1,9E+00	4,0E-01	1,6E-01	6,3E-02	1,1E+01	1,7E+00
Plant	Sainte-Walburge	No application		mg kg ⁻¹	1,9E-01	4,1E+01	1,3E+00	1,4E+00	8,6E+01	6,5E-01	1,3E+00	1,3E+01	1,2E+02	9,5E-01	9,1E-02	1,4E+01	5,8E+00	6,4E-01	1,4E-01	6,4E-02	9,1E+00	1,8E+00
Plant	Sainte-Walburge	Cattle manure		mg kg ⁻¹	1,2E-01	2,6E+01	9,6E-01	1,0E+00	1,2E+02	8,2E-01	1,7E+00	1,8E+01	2,3E+02	1,5E+00	6,7E-02	1,9E+01	7,9E+00	1,2E+00	1,4E-01	6,2E-02	1,5E+01	1,5E+00
Plant	Sainte-Walburge	Green waste compost		mg kg ⁻¹	2,4E-01	4,5E+01	1,9E+00	1,7E+00	1,1E+02	8,2E-01	2,1E+00	2,2E+01	2,3E+02	9,5E-01	9,3E-02	1,9E+01	9,4E+00	7,9E-01	1,9E-01	1,0E-01	1,3E+01	2,1E+00
Plant	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	1,8E-01	2,9E+01	1,2E+00	1,3E+00	1,3E+02	8,2E-01	1,6E+00	2,6E+01	2,2E+02	1,2E+00	8,5E-02	2,0E+01	8,6E+00	9,4E-01	1,8E-01	9,0E-02	1,2E+01	2,0E+00
Plant	Bressoux	No application		mg kg ⁻¹	7,1E-02	9,7E+00	5,9E-01	9,7E-01	7,2E+01	2,2E-01	1,2E+00	3,7E+01	6,0E+02	1,6E+00	8,5E-02	1,7E+01	7,8E+00	1,1E+00	1,9E-01	1,3E-01	5,7E+00	3,4E+00
Plant	Bressoux	Cattle manure		mg kg ⁻¹	7,4E-02	9,8E+00	5,2E-01	6,4E-01	5,7E+01	2,1E-01	9,9E-01	2,3E+01	4,1E+02	9,3E-01	4,9E-02	1,6E+01	7,4E+00	1,1E+00	1,5E-01	1,1E-01	9,6E+00	2,9E+00
Plant	Bressoux	Green waste compost		mg kg ⁻¹	8,8E-02	1,2E+01	6,8E-01	7,8E-01	6,3E+01	2,0E-01	9,2E-01	2,5E+01	4,4E+02	9,5E-01	8,1E-02	1,5E+01	6,3E+00	8,9E-01	3,3E-01	1,2E-01	7,2E+00	3,5E+00
Plant	Bressoux	Cover crop restitution		mg kg ⁻¹	2,0E-01	2,5E+01	1,5E+00	1,3E+00	7,1E+01	4,2E-01	1,5E+00	3,0E+01	5,2E+02	1,2E+00	8,9E-02	1,7E+01	5,3E+00	1,5E+00	3,0E-01	2,3E-01	2,5E+01	6,7E+00
Plant	Aubange	No application		mg kg ⁻¹	2,1E-01	2,5E+01	3,5E+00	1,4E+00	1,9E+02	6,5E-01	2,0E+00	1,1E+01	4,9E+01	1,4E+00	8,4E-02	9,5E+00	4,4E+00	1,3E-01	9,6E-02	2,5E-02	2,6E+00	1,1E+00
Plant	Aubange	Cattle manure		mg kg ⁻¹	1,6E-01	2,0E+01	2,3E+00	1,3E+00	1,7E+02	5,8E-01	1,8E+00	1,3E+01	3,6E+01	1,0E+00	6,7E-02	1,0E+01	6,5E+00	1,2E-01	9,1E-02	3,9E-02	2,1E+00	1,1E+00
Plant	Aubange	Green waste compost		mg kg ⁻¹	3,8E-01	4,9E+01	7,1E+00	2,5E+00	2,7E+02	1,2E+00	3,8E+00	1,8E+01	4,3E+01	3,2E+00	1,3E-01	8,5E+00	5,8E+00	1,4E-01	1,3E-01	4,5E-02	5,1E+00	2,0E+00
Plant	Aubange	Cover crop restitution		mg kg ⁻¹	2,7E-01	3,3E+01	4,3E+00	1,8E+00	2,4E+02	9,2E-01	2,6E+00	1,5E+01	3,6E+01	1,7E+00	7,8E-02	1,1E+01	4,3E+00	1,3E-01	1,3E-01	3,9E-02	2,8E+00	1,3E+00
Solution	Vieusart	No application	05-05-21	µg L ⁻¹	3,7E-01	2,5E-01	1,8E+00	3,7E-01	1,7E+01	4,6E+00	2,1E+01	4,2E+00	6,4E+02	6,7E-01	4,2E-01	1,4E+03	1,9E-01	5,6E-01	2,5E-02	3,0E-01	3,4E+02	4,3E-02
Solution	Vieusart	Cattle manure	05-05-21	µg L ⁻¹	6,7E-01	6,6E-01	4,2E+00	6,9E-01	8,4E+01	9,5E+00	4,3E+01	1,9E+01	5,6E+02	2,3E+00	9,1E-01	1,9E+03	6,8E+00	8,6E-01	1,9E-01	4,7E-01	7,8E+02	3,6E-01
Solution	Vieusart	Green waste compost	05-05-21	µg L ⁻¹	8,6E-01	6,1E-01	4,0E+00	1,0E+00	1,8E+02	1,7E+01	5,6E+01	9,5E+00	3,2E+03	1,9E+00	8,7E-01	2,3E+03	3,4E+00	1,4E+00	7,4E-02	4,4E-01	5,0E+02	3,5E-01
Solution	Vieusart	Cover crop restitution	05-05-21	µg L ⁻¹	5,5E-01	3,7E-01	3,1E+00	5,6E-01	1,3E+02	1,4E+01	3,9E+01	8,3E+00	5,2E+02	1,6E+00	6,1E-01	1,9E+03	1,5E+00	1,2E+00	4,0E-02	3,3E-01	5,0E+02	1,4E-01
Solution	Vieusart	No plant	05-05-21	µg L ⁻¹	4,0E-01	2,6E-01	1,8E+00	4,6E-01	5,1E+01	5,3E+00	2,6E+01	5,7E+00	3,0E+02	8,1E-01	5,8E-01	1,5E+03	2,1E-01	8,0E-01	1,5E-02	2,8E-01	3,1E+02	7,9E-02
Solution	Sainte-Walburge	No application	05-05-21	µg L ⁻¹	7,7E-01	6,5E-01	7,8E+00	9,0E-01	2,8E+01	1,7E+01	5,1E+01	2,7E+01	6,3E+02	9,6E+00	1,2E+00	2,2E+03	3,6E+00	4,2E+00	4,9E-02	3,9E+00	5,0E+02	3,5E+00
Solution	Sainte-Walburge	Cattle manure	05-05-21	µg L ⁻¹	8,7E-01	1,2E+00	1,1E+01	1,0E+00	2,5E+02	1,5E+01	6,4E+01	7,5E+01	8,1E+02	1,4E+01	1,6E+00	2,1E+03	2,1E+01	5,2E+00	1,3E-01	4,4E+00	1,1E+03	4,3E+00
Solution	Sainte-Walburge	Green waste compost	05-05-21	µg L ⁻¹	7,0E-01	7,7E-01	8,6E+00	1,3E+00	3,6E+01	1,2E+01	4,2E+01	3,5E+01	8,3E+02	1,2E+01	1,4E+00	1,9E+03	1,2E+01	3,5E+00	8,9E-02	4,1E+00	7,3E+02	3,4E+00

Solution	Sainte-Walburge	Cover crop restitution	05-05-21	µg L ⁻¹	8,5E-01	6,5E-01	8,2E+00	7,6E-01	3,6E+01	1,1E+01	3,7E+01	2,8E+01	1,1E+03	9,5E+00	1,1E+00	2,3E+03	6,7E+00	3,7E+00	7,7E-02	3,8E+00	9,6E+02	2,7E+00
Solution	Sainte-Walburge	No plant	05-05-21	µg L ⁻¹	4,7E-01	3,2E-01	7,3E+00	5,9E-01	2,2E+00	4,6E+00	2,1E+01	2,1E+01	8,1E+02	7,4E+00	9,3E-01	1,5E+03	5,1E+00	2,1E+00	3,8E-02	3,9E+00	7,4E+02	1,9E+00
Solution	Bressoux	No application	05-05-21	µg L ⁻¹	3,8E-01	4,8E-01	8,2E+00	3,7E-01	9,8E+00	2,2E+00	3,3E+01	3,3E+01	2,3E+03	1,1E+01	7,4E-01	1,8E+03	3,0E+00	9,9E+00	3,9E-02	1,2E+01	6,7E+02	4,0E+00
Solution	Bressoux	Cattle manure	05-05-21	µg L ⁻¹	5,3E-01	1,1E+00	1,3E+01	6,8E-01	4,2E+01	3,3E+00	5,4E+01	1,3E+02	1,7E+03	1,8E+01	1,1E+00	2,1E+03	3,4E+01	1,2E+01	1,2E-01	1,4E+01	1,3E+03	5,7E+00
Solution	Bressoux	Green waste compost	05-05-21	µg L ⁻¹	5,8E-01	9,2E-01	9,1E+00	9,8E-01	6,2E+01	3,6E+00	5,1E+01	5,7E+01	3,6E+03	1,2E+01	9,6E-01	2,3E+03	1,5E+01	1,2E+01	7,2E-02	1,2E+01	6,1E+02	6,5E+00
Solution	Bressoux	Cover crop restitution	05-05-21	µg L ⁻¹	4,8E-01	7,4E-01	8,1E+00	3,7E-01	3,5E+01	2,5E+00	3,5E+01	4,0E+01	2,7E+03	1,2E+01	1,0E+00	2,2E+03	8,6E+00	1,4E+01	4,5E-02	1,1E+01	9,9E+02	4,2E+00
Solution	Bressoux	No plant	05-05-21	µg L ⁻¹	3,7E-01	4,9E-01	7,6E+00	4,8E-01	5,5E+01	3,5E+00	3,8E+01	3,3E+01	2,8E+03	1,4E+01	9,1E-01	1,8E+03	7,4E+00	1,0E+01	3,9E-02	1,1E+01	6,8E+02	4,3E+00
Solution	Aubange	No application	05-05-21	µg L ⁻¹	5,1E-01	1,7E-01	1,7E+00	3,4E-01	4,0E+01	1,1E+01	3,1E+01	2,2E+00	3,7E+02	1,9E+00	4,2E-01	1,1E+03	4,1E+00	6,1E-02	2,0E-02	9,7E-02	5,3E+01	4,3E-02
Solution	Aubange	Cattle manure	05-05-21	µg L ⁻¹	6,4E-01	3,3E-01	2,2E+00	3,9E-01	3,1E+01	3,1E+00	1,5E+01	6,1E+00	5,4E+02	2,0E+00	5,5E-01	1,5E+03	1,1E+01	4,9E-02	9,4E-02	1,2E-01	7,2E+01	2,9E-02
Solution	Aubange	Green waste compost	05-05-21	µg L ⁻¹	6,1E-01	2,5E-01	1,7E+00	4,6E-01	2,7E+01	7,7E+00	2,6E+01	2,8E+00	7,3E+02	1,1E+00	5,5E-01	1,3E+03	1,1E+01	5,1E-02	4,0E-02	9,1E-02	6,2E+01	2,4E-02
Solution	Aubange	Cover crop restitution	05-05-21	µg L ⁻¹	6,4E-01	2,3E-01	1,4E+00	4,0E-01	2,0E+02	1,6E+01	3,3E+01	2,5E+00	3,6E+02	1,4E+00	4,1E-01	1,4E+03	6,3E+00	8,4E-02	3,4E-02	8,6E-02	7,7E+01	1,7E-02
Solution	Aubange	No plant	05-05-21	µg L ⁻¹	6,2E-01	2,1E-01	9,9E-01	3,3E-01	2,6E+01	1,3E+01	3,7E+01	1,7E+00	2,9E+02	7,5E-01	6,0E-01	1,4E+03	7,6E+00	5,0E-02	2,1E-02	8,4E-02	9,3E+01	2,1E-02
Solution	Vieusart	No application	22-06-21	µg L ⁻¹	1,3E-01	1,6E-01	1,7E+00	4,1E-01	8,3E-01	6,7E+00	2,3E+01	6,9E+00	8,2E+02	8,1E-01	5,8E-01	4,8E+02	2,6E+00	1,9E-01	3,9E-02	4,6E-01	7,4E+01	1,7E-01
Solution	Vieusart	Cattle manure	22-06-21	µg L ⁻¹	9,1E-02	4,4E-01	5,0E+00	5,1E-01	4,6E-01	1,5E+00	1,1E+01	1,7E+01	4,2E+02	3,7E+00	8,6E-01	2,6E+02	9,7E+00	2,8E-01	1,4E-01	7,4E-01	9,3E+01	2,4E-01
Solution	Vieusart	Green waste compost	22-06-21	µg L ⁻¹	1,4E-01	2,4E-01	2,5E+00	5,0E-01	9,9E+00	4,6E+00	2,1E+01	1,0E+01	5,0E+02	1,4E+00	7,7E-01	4,5E+02	3,5E+00	4,1E-01	6,7E-02	5,5E-01	9,2E+01	4,5E-01
Solution	Vieusart	Cover crop restitution	22-06-21	µg L ⁻¹	6,0E-02	1,9E-01	2,1E+00	3,6E-01	8,1E-01	4,3E+00	1,1E+01	7,9E+00	5,4E+02	1,0E+00	6,8E-01	2,9E+02	1,9E+00	1,5E-01	4,6E-02	4,5E-01	5,5E+01	1,5E-01
Solution	Vieusart	No plant	22-06-21	µg L ⁻¹	1,5E-01	1,4E-01	2,0E+00	2,8E-01	1,9E+02	3,4E+00	1,2E+01	5,3E+00	5,2E+02	8,2E-01	3,2E-01	6,3E+02	1,1E+00	2,9E-01	9,9E-03	3,2E-01	1,5E+02	9,6E-02
Solution	Sainte-Walburge	No application	22-06-21	µg L ⁻¹	2,4E-01	3,8E-01	1,1E+01	1,3E+00	5,6E-01	2,9E+01	6,7E+01	2,8E+01	7,0E+02	9,4E+00	2,0E+00	8,4E+02	1,5E+01	2,7E+00	8,0E-02	4,9E+00	1,6E+02	4,3E+00
Solution	Sainte-Walburge	Cattle manure	22-06-21	µg L ⁻¹	3,5E-01	1,3E+00	1,4E+01	9,4E-01	5,7E+00	9,4E+00	5,7E+01	5,7E+01	2,2E+03	1,9E+01	1,6E+00	1,7E+03	3,0E+01	3,6E+00	6,2E-01	5,3E+00	6,7E+02	5,2E+00
Solution	Sainte-Walburge	Green waste compost	22-06-21	µg L ⁻¹	3,8E-01	5,4E-01	1,1E+01	1,3E+00	1,1E+00	1,2E+01	7,8E+01	3,7E+01	1,4E+03	1,1E+01	2,1E+00	1,4E+03	2,4E+01	4,4E+00	2,9E-01	4,9E+00	3,1E+02	5,1E+00
Solution	Sainte-Walburge	Cover crop restitution	22-06-21	µg L ⁻¹	2,8E-01	2,9E-01	8,7E+00	1,0E+00	1,9E+00	2,4E+01	3,7E+01	2,1E+01	4,6E+02	8,6E+00	1,3E+00	1,2E+03	1,9E+01	2,0E+00	8,9E-02	4,2E+00	4,3E+02	2,6E+00
Solution	Sainte-Walburge	No plant	22-06-21	µg L ⁻¹	1,3E-01	2,8E-01	1,1E+01	4,8E-01	2,4E+01	5,4E+00	1,3E+01	1,5E+01	8,4E+02	1,1E+01	8,7E-01	6,2E+02	1,5E+01	5,9E-01	4,2E-02	4,1E+00	4,1E+02	6,9E-01
Solution	Bressoux	No application	22-06-21	µg L ⁻¹	3,8E-01	5,7E-01	1,0E+01	8,3E-01	5,9E+00	8,2E+00	1,1E+02	5,9E+01	2,6E+03	9,2E+00	1,3E+00	1,9E+03	5,4E+00	1,0E+01	1,4E-01	1,5E+01	1,9E+02	1,2E+01
Solution	Bressoux	Cattle manure	22-06-21	µg L ⁻¹	4,5E-01	1,3E+00	1,4E+01	7,5E-01	3,6E+01	2,7E+00	6,9E+01	1,1E+02	2,9E+03	1,6E+01	1,4E+00	2,2E+03	2,3E+01	9,0E+00	7,6E-01	1,5E+01	5,6E+02	7,5E+00
Solution	Bressoux	Green waste compost	22-06-21	µg L ⁻¹	4,2E-01	1,0E+00	1,1E+01	1,6E+00	8,1E+00	4,1E+00	1,4E+02	8,1E+01	2,5E+03	1,2E+01	1,9E+00	1,9E+03	1,1E+01	8,8E+00	2,9E-01	1,5E+01	2,1E+02	1,7E+01

Appendices

Solution	Bressoux	Cover crop restitution	22-06-21	µg L ⁻¹	3,1E-01	6,7E-01	1,0E+01	7,2E-01	1,4E+01	6,8E+00	8,9E+01	5,9E+01	2,5E+03	9,3E+00	1,4E+00	1,8E+03	7,9E+00	9,8E+00	1,9E-01	1,6E+01	2,1E+02	9,6E+00
Solution	Bressoux	No plant	22-06-21	µg L ⁻¹	1,8E-01	4,0E-01	1,0E+01	4,2E-01	4,3E+02	2,8E+00	2,7E+01	3,2E+01	1,3E+03	1,5E+01	9,1E-01	1,1E+03	7,2E+00	5,5E+00	5,3E-02	1,4E+01	5,3E+02	3,0E+00
Solution	Aubange	No application	22-06-21	µg L ⁻¹	1,7E-01	7,3E-01	1,8E+00	3,6E-01	2,4E+01	7,5E+00	2,1E+01	4,1E+00	2,2E+03	7,4E-01	2,8E-01	5,6E+02	3,4E-01	1,9E-02	4,7E-02	8,8E-02	2,6E+01	1,8E-01
Solution	Aubange	Cattle manure	22-06-21	µg L ⁻¹	5,2E-01	4,6E-01	2,9E+00	4,4E-01	2,0E+01	4,3E+00	2,8E+01	9,1E+00	2,2E+03	1,8E+00	4,1E-01	1,6E+03	1,5E+00	4,1E-02	1,7E-01	1,5E-01	5,5E+01	9,8E-02
Solution	Aubange	Green waste compost	22-06-21	µg L ⁻¹	2,2E-01	2,6E-01	2,2E+00	4,5E-01	3,2E+01	5,6E+00	3,1E+01	5,0E+00	1,4E+03	1,1E+00	4,6E-01	7,5E+02	8,9E-01	3,7E-02	1,3E-01	1,1E-01	2,8E+01	7,1E-02
Solution	Aubange	Cover crop restitution	22-06-21	µg L ⁻¹	5,9E-01	4,6E-01	3,3E+00	4,1E-01	6,6E+01	1,5E+01	3,0E+01	5,9E+00	1,9E+03	1,1E+00	7,1E-01	1,9E+03	5,8E-01	4,8E-02	9,3E-02	1,4E-01	6,2E+01	8,3E-02
Solution	Aubange	No plant	22-06-21	µg L ⁻¹	2,6E-01	9,8E-02	1,1E+00	2,4E-01	1,8E+00	4,0E+00	9,5E+00	1,9E+00	5,4E+02	7,8E-01	2,8E-01	8,9E+02	2,0E-01	1,8E-02	1,3E-02	8,3E-02	2,4E+01	6,3E-03
Tap water			19-05-21	µg L ⁻¹	5,6E-02	5,7E-02	8,4E-02	1,0E-01	1,0E+00	5,2E-01	5,0E+01	2,7E+02	9,8E+02	1,1E-01	6,9E-01	2,7E+02	1,9E-01	1,5E-01	8,3E-02	2,4E-01	5,4E+01	1,8E+01

Table VI-4 – Standard deviations of trace element contents in soil and exogenous organic matter samples (n=2) and in plant parts and soil solution samples (n=3) for the greenhouse experiment.

Sample	Site	Modality	Date	Units	Sc	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	As	Se	Sr	Mo	Cd	Sn	Sb	Ba	Pb
Soil	Vieusart			mg kg ⁻¹	2,2E-01	1,2E+02	2,8E+00	2,8E+00	4,0E+00	4,9E-01	6,9E-01	1,9E-01	6,0E-03	4,6E-03	2,6E-01	1,2E+00	1,8E-02	9,8E-03	7,9E-02	3,5E-02	6,4E+00	1,3E-01
Soil	Sainte-Walburge			mg kg ⁻¹	5,7E+00	4,7E+02	6,2E+00	3,0E+00	5,7E+01	8,5E-01	1,7E+00	5,0E+00	3,6E+00	4,7E+00	1,0E+00	2,5E+01	6,5E-02	2,2E-01	3,7E+00	5,6E-01	3,3E+01	5,2E+01
Soil	Bressoux			mg kg ⁻¹	3,7E+00	1,3E+02	2,4E+00	2,0E+00	6,1E+01	8,9E-01	2,4E+00	6,2E+00	5,4E+01	1,3E+00	1,3E+00	1,3E+01	2,6E-01	4,1E-01	5,5E+00	1,1E+00	4,2E+01	1,1E+01
Soil	Aubange			mg kg ⁻¹	2,7E+00	1,7E+01	1,2E+01	6,8E+00	2,3E+02	4,2E+00	4,6E-01	7,2E-02	4,6E-01	5,4E+00	1,4E+00	3,8E+00	3,9E-01	4,3E-03	1,0E-01	7,7E-02	1,2E+01	1,1E+00
EOM		Cattle manure		mg kg ⁻¹	4,7E-02	6,4E+00	2,7E-01	6,7E-01	3,6E+00	5,3E-02	6,6E-02	3,2E-01	4,1E-01	1,1E-01	1,7E-01	8,8E-02	6,5E-02	1,3E-03	6,5E-02	1,3E-02	1,4E+00	1,4E-02
EOM		Green waste compost		mg kg ⁻¹	7,0E-02	1,2E+01	6,7E-02	3,7E-01	4,7E+00	9,1E-02	1,5E-02	3,0E-01	2,4E+00	1,1E-01	2,3E-02	3,8E-01	5,2E-02	6,0E-03	6,1E-02	3,2E-02	2,1E+00	7,7E-01
EOM		Cover crop restitution		mg kg ⁻¹	6,6E-03	3,4E+00	6,4E-02	3,9E-01	6,2E+00	1,3E-02	1,8E-01	7,2E-01	4,1E+00	1,5E-02	4,2E-03	6,5E+00	3,8E-01	3,2E-02	8,2E-03	7,2E-03	6,9E+00	1,0E-01
Roots	Vieusart	No application		mg kg ⁻¹	4,4E-01	1,4E+02	6,0E+00	7,3E+00	2,2E+01	3,9E-01	1,8E+00	3,2E+00	8,9E+00	2,1E+00	3,1E-01	3,9E+00	9,2E-02	2,2E-01	7,0E-02	6,7E-02	1,2E+01	1,3E+00
Roots	Vieusart	Cattle manure		mg kg ⁻¹	6,7E-02	3,3E+01	4,4E-01	8,6E-01	1,5E+01	2,3E-01	6,6E-01	3,1E+00	3,7E+00	7,3E-02	9,1E-02	3,7E+00	3,3E-02	1,6E-01	3,9E-02	1,2E-02	5,8E+00	2,8E-01
Roots	Vieusart	Green waste compost		mg kg ⁻¹	3,2E-01	8,0E+01	2,2E+00	2,1E+00	1,2E+01	2,4E-01	7,2E-01	3,2E+00	2,5E+00	5,1E-01	1,4E-01	1,4E+00	7,0E-02	9,8E-02	4,0E-02	4,0E-02	9,2E+00	1,0E+00
Roots	Vieusart	Cover crop restitution		mg kg ⁻¹	8,4E-01	3,3E+02	8,2E+00	6,9E+00	4,1E+01	9,3E-01	1,9E+00	1,2E+00	5,4E+00	2,4E+00	2,1E-01	3,4E+00	1,2E-01	4,3E-02	2,0E-01	1,0E-01	3,0E+01	3,0E+00
Roots	Sainte-Walburge	No application		mg kg ⁻¹	2,3E-01	7,6E+01	1,7E+00	1,3E+00	2,4E+01	8,8E-01	7,7E-01	1,4E+00	2,0E+01	1,2E+00	1,1E-01	5,6E+00	1,4E-01	1,3E-01	2,0E-01	5,6E-02	1,4E+01	2,1E+00
Roots	Sainte-Walburge	Cattle manure		mg kg ⁻¹	2,1E-01	7,8E+01	2,2E+00	1,5E+00	1,8E+01	3,2E+00	3,3E+00	1,2E+01	6,2E+01	6,3E+00	2,1E-01	5,9E+00	7,1E-01	2,9E+00	3,4E-02	7,3E-02	9,8E+00	2,1E+00
Roots	Sainte-Walburge	Green waste compost		mg kg ⁻¹	9,5E-01	1,5E+02	9,7E+00	4,3E+00	4,5E+01	1,2E+00	3,3E+00	4,3E+00	5,5E+00	9,6E-01	1,5E-01	3,8E+00	2,4E-01	2,2E-01	3,7E-01	2,0E-01	1,1E+01	2,9E+00
Roots	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	2,2E-01	4,7E+01	2,6E+00	2,0E+00	5,6E+01	1,6E+00	2,1E+00	8,0E+00	1,2E+01	4,3E+00	6,5E-02	3,6E+00	3,5E-01	5,4E-01	1,3E-01	1,6E-01	5,2E+00	1,4E+00
Roots	Bressoux	No application		mg kg ⁻¹	1,2E-01	7,6E+00	5,7E-01	4,9E-01	7,2E+00	1,2E-01	5,0E-01	1,2E+01	2,7E+01	2,1E+00	1,5E-01	2,0E+00	1,9E-01	9,0E-01	2,0E-02	8,0E-02	5,5E+00	4,3E+00
Roots	Bressoux	Cattle manure		mg kg ⁻¹	1,8E-01	2,3E+01	1,4E+00	1,0E+00	1,0E+01	4,9E-01	1,4E+00	1,3E+01	3,0E+01	7,7E-01	1,6E-01	1,3E+00	9,4E-02	7,5E-01	2,5E-01	1,3E-01	8,0E+00	6,4E+00
Roots	Bressoux	Green waste compost		mg kg ⁻¹	2,3E-01	2,5E+01	1,9E+00	6,8E-01	1,1E+01	3,2E-01	7,8E-01	1,1E+01	4,0E+01	7,6E-01	1,3E-01	2,7E+00	2,9E-01	8,6E-01	3,0E+00	2,0E-01	1,0E+01	4,8E+00
Roots	Bressoux	Cover crop restitution		mg kg ⁻¹	5,7E-01	7,1E+01	5,3E+00	3,2E+00	2,3E+01	1,2E+00	3,2E+00	2,6E+01	5,4E+01	1,1E+00	1,3E-01	8,3E+00	6,2E-02	1,5E+00	6,5E-01	7,1E-01	1,8E+02	1,7E+01
Roots	Aubange	No application		mg kg ⁻¹	4,3E-01	4,2E+01	7,9E+00	9,3E-01	1,4E+02	9,5E-01	3,2E+00	3,4E-01	4,1E+00	3,0E+00	1,0E-01	2,4E+00	1,2E-01	4,1E-02	1,6E-01	2,4E-02	2,1E+00	1,1E+00
Roots	Aubange	Cattle manure		mg kg ⁻¹	4,0E-01	5,5E+01	6,9E+00	2,0E+00	1,5E+02	8,0E-01	1,1E+00	6,2E-01	5,2E+00	2,8E+00	5,7E-02	2,8E+00	1,3E-01	5,4E-02	3,3E-02	2,1E-02	4,4E+00	1,4E+00
Roots	Aubange	Green waste compost		mg kg ⁻¹	1,1E+00	1,2E+02	1,8E+01	4,8E+00	8,9E+02	2,9E+00	1,2E+01	1,5E+00	1,4E+01	6,8E+00	1,8E-01	8,2E+00	3,0E-01	1,8E-01	1,0E-01	5,5E-02	2,0E+01	3,1E+00

Appendices

Roots	Aubange	Cover crop restitution		mg kg ⁻¹	1,0E-01	2,8E+01	2,1E+00	9,5E-01	8,3E+01	9,0E-01	3,5E+00	6,0E-01	2,8E+00	1,1E+00	7,0E-02	4,3E+00	2,6E-02	1,1E-02	7,4E-02	5,9E-03	2,1E+00	6,1E-01
Stems	Vieusart	No application		mg kg ⁻¹	7,2E-03	6,3E-01	7,1E-03	1,2E-01	4,6E+00	3,4E-03	3,2E-02	1,1E+00	1,2E+01	2,9E-03	7,5E-04	1,2E+00	2,3E-01	4,1E-02	4,2E-02	3,0E-03	2,4E-01	1,7E-02
Stems	Vieusart	Cattle manure		mg kg ⁻¹	1,0E-03	1,0E+00	2,7E-02	1,1E-01	2,5E+00	2,5E-03	4,0E-02	1,6E+00	2,9E+00	1,3E-02	1,5E-02	1,7E+00	2,5E-01	5,8E-02	2,6E-02	2,6E-03	1,5E+00	1,8E-02
Stems	Vieusart	Green waste compost		mg kg ⁻¹	3,2E-03	2,1E-01	9,9E-03	3,6E-02	2,3E+00	3,0E-03	9,8E-02	3,1E-01	2,3E+00	4,3E-03	1,3E-02	8,4E-01	3,8E-01	2,5E-02	1,1E-02	1,9E-04	3,0E-01	2,0E-02
Stems	Vieusart	Cover crop restitution		mg kg ⁻¹	3,3E-03	3,2E+00	6,5E-02	1,8E-01	7,5E+00	1,1E-02	1,1E-01	2,0E+00	1,7E+01	1,2E-02	1,2E-02	7,1E-01	5,7E-01	5,9E-02	3,2E-02	6,2E-03	3,0E-01	6,6E-02
Stems	Sainte-Walburge	No application		mg kg ⁻¹	4,0E-03	1,7E+00	3,6E-02	2,1E-01	1,2E+01	9,3E-03	1,8E-01	1,8E-01	2,8E+01	2,6E-01	3,0E-04	7,5E-01	1,5E+00	1,1E-01	6,9E-03	1,4E-03	3,8E-01	7,5E-02
Stems	Sainte-Walburge	Cattle manure		mg kg ⁻¹	1,1E-02	5,1E-01	1,7E-02	1,2E-01	3,2E+00	1,0E-02	9,2E-02	1,5E+00	8,3E+01	5,9E-01	1,5E-03	6,7E-01	1,3E+00	4,7E-01	5,4E-03	3,8E-03	5,3E-01	6,1E-02
Stems	Sainte-Walburge	Green waste compost		mg kg ⁻¹	9,9E-03	6,6E-01	1,2E-02	1,9E-01	3,5E+00	5,0E-03	4,1E-01	2,9E+00	6,8E+01	2,1E-01	1,8E-02	1,6E+00	3,2E+00	5,1E-02	1,1E-03	2,2E-03	1,4E+00	8,0E-02
Stems	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	4,3E-03	7,0E-01	1,5E-02	5,5E-02	9,7E-01	2,7E-03	2,9E-02	3,2E+00	9,8E+01	1,0E-01	1,3E-03	1,1E+00	1,5E+00	5,7E-02	1,2E-02	1,2E-03	4,3E-01	6,9E-02
Stems	Bressoux	No application		mg kg ⁻¹	8,9E-03	1,1E+00	4,7E-02	8,0E-01	1,3E+01	5,6E-03	2,3E-01	1,1E+00	1,6E+02	2,7E-01	5,1E-04	1,0E+00	1,2E+00	2,3E-01	1,8E-02	3,0E-03	1,2E+00	1,7E-01
Stems	Bressoux	Cattle manure		mg kg ⁻¹	1,8E-02	7,2E-01	1,4E-02	9,7E-02	4,6E+00	2,4E-03	6,6E-02	1,8E+00	2,0E+02	7,4E-02	1,3E-03	8,8E-01	4,8E+00	8,0E-02	3,6E-02	1,5E-02	4,7E-01	5,2E-02
Stems	Bressoux	Green waste compost		mg kg ⁻¹	8,6E-03	6,6E-01	1,5E-02	7,6E-02	1,7E+00	5,5E-03	7,3E-02	2,4E+00	1,9E+02	9,9E-02	2,0E-02	1,7E+00	2,6E-01	1,0E-01	7,5E-03	6,7E-03	1,3E+00	7,4E-02
Stems	Bressoux	Cover crop restitution		mg kg ⁻¹	1,1E-02	9,0E-01	2,5E-02	6,6E-02	8,6E-01	3,5E-03	2,4E-02	9,6E-01	1,3E+02	1,3E-01	1,4E-02	1,0E+00	2,8E-01	4,2E-02	6,5E-03	6,2E-03	9,2E-01	1,9E-01
Stems	Aubange	No application		mg kg ⁻¹	1,2E-02	2,2E+00	2,0E-01	1,4E-01	7,7E+00	2,2E-02	9,6E-02	2,1E+00	1,5E+01	5,9E-02	2,1E-02	1,2E+00	2,0E+00	2,2E-02	9,6E-03	1,4E-03	2,1E-01	1,4E-01
Stems	Aubange	Cattle manure		mg kg ⁻¹	9,7E-03	1,1E+00	1,2E-01	1,4E-01	8,8E+00	1,8E-02	6,1E-02	2,5E-01	8,8E+00	4,3E-02	1,8E-02	1,7E+00	9,7E-01	2,9E-02	1,5E-02	8,6E-04	1,5E-01	3,5E-02
Stems	Aubange	Green waste compost		mg kg ⁻¹	5,4E-03	8,2E-01	8,2E-02	1,2E-01	4,4E+00	5,4E-03	1,1E-01	2,6E-01	1,6E+01	2,8E-02	2,3E-04	9,6E-01	2,6E+00	3,1E-03	5,4E-03	1,5E-03	1,8E-02	1,3E-02
Stems	Aubange	Cover crop restitution		mg kg ⁻¹	1,0E-02	1,1E+00	1,5E-01	7,4E-02	9,8E+00	1,1E-02	5,2E-02	9,3E-01	2,1E+01	5,8E-02	2,1E-02	1,7E+00	2,6E+00	2,0E-02	4,3E-03	1,4E-02	2,1E-01	8,5E-02
Leaves	Vieusart	No application		mg kg ⁻¹	3,7E-03	2,1E+00	3,2E-02	8,5E-02	3,3E+01	9,3E-03	1,2E-01	3,2E+00	9,1E+00	4,2E-02	1,6E-02	1,2E+00	4,1E-01	2,6E-02	5,9E-02	1,2E-02	1,8E-01	3,5E-02
Leaves	Vieusart	Cattle manure		mg kg ⁻¹	7,1E-03	2,0E+00	5,1E-02	1,6E-01	5,2E+00	1,1E-02	2,3E-01	4,6E+00	6,4E+00	4,1E-02	3,2E-02	1,1E+00	4,2E-01	1,2E-01	9,2E-02	7,6E-02	3,3E-01	2,9E-01
Leaves	Vieusart	Green waste compost		mg kg ⁻¹	5,7E-03	3,0E+00	8,8E-02	8,8E-01	2,9E+01	1,5E-02	7,7E-01	4,3E+00	1,1E+01	3,7E-02	7,3E-04	2,3E+00	7,5E-01	1,1E-01	8,1E-02	3,2E-02	4,7E-01	6,9E-02
Leaves	Vieusart	Cover crop restitution		mg kg ⁻¹	3,8E-03	2,5E+00	1,2E-02	4,3E-01	2,1E+01	8,5E-03	4,0E-02	5,4E+00	2,0E+00	1,1E-02	2,2E-02	1,9E+00	1,4E-01	1,2E-01	5,4E-02	5,0E-03	4,8E-01	1,5E+00
Leaves	Sainte-Walburge	No application		mg kg ⁻¹	5,5E-04	8,3E-01	1,2E-02	8,5E-02	5,2E+00	9,1E-03	2,6E-02	1,1E+00	2,6E+01	2,0E-01	2,7E-02	2,8E+00	7,3E-01	1,8E-01	2,0E-02	1,0E-02	4,1E-01	7,3E-01
Leaves	Sainte-Walburge	Cattle manure		mg kg ⁻¹	3,6E-03	1,5E+00	2,5E-02	1,9E-01	7,4E+01	1,6E-02	1,2E-01	7,6E+00	5,7E+01	2,6E-01	2,6E-02	5,2E+00	3,1E+00	2,8E-02	6,0E-02	1,1E-02	1,3E+00	3,6E-01
Leaves	Sainte-Walburge	Green waste compost		mg kg ⁻¹	1,5E-02	4,8E-01	1,0E-02	1,0E-01	3,8E+01	3,0E-03	5,2E-01	7,8E+00	3,3E+01	9,3E-02	4,5E-02	4,5E+00	5,2E-01	6,3E-02	5,7E-02	2,8E-02	5,5E-01	3,2E-01
Leaves	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	1,9E-03	9,1E-01	1,0E-02	1,0E-01	2,3E+01	3,8E-03	1,4E-01	6,5E+00	1,7E+01	3,0E-02	5,4E-02	2,1E+00	4,0E-01	6,0E-02	5,8E-02	2,9E-02	1,4E-01	3,0E-01

Leaves	Bressoux	No application	mg kg ⁻¹	2,0E-03	8,5E-01	1,3E-02	7,7E-02	2,2E+01	2,3E-03	2,0E-01	1,3E+01	6,7E+01	1,7E-01	3,0E-02	5,6E+00	7,2E-01	2,4E-01	8,1E-02	5,3E-03	6,1E-01	4,7E-01
Leaves	Bressoux	Cattle manure	mg kg ⁻¹	8,5E-04	4,2E-01	1,9E-03	2,9E-01	1,4E+01	1,6E-03	1,4E-01	9,3E+00	4,1E+01	7,6E-02	1,5E-04	2,6E+00	2,6E-01	1,1E-01	7,7E-02	9,9E-03	7,8E-01	2,7E-01
Leaves	Bressoux	Green waste compost	mg kg ⁻¹	1,8E-03	3,2E+00	2,6E-02	4,2E-01	4,8E+01	3,7E-03	2,1E-01	1,3E+01	2,8E+01	1,4E-01	2,9E-02	7,9E-01	7,8E-01	7,3E-02	7,0E-02	2,5E-02	3,6E-01	2,7E-01
Leaves	Bressoux	Cover crop restitution	mg kg ⁻¹	7,2E-03	2,5E+00	3,7E-02	1,6E-01	1,1E+01	4,0E-03	4,5E-02	2,1E+00	7,5E+01	5,6E-02	2,6E-02	1,1E+00	3,7E-01	1,4E-01	6,7E-02	7,4E-03	1,9E-01	2,1E-01
Leaves	Aubange	No application	mg kg ⁻¹	4,3E-03	1,1E+00	2,4E-02	1,5E-01	1,3E+01	6,4E-03	2,7E-01	8,6E+00	6,0E+00	4,3E-02	3,4E-02	3,4E-01	1,3E-01	7,2E-03	2,8E-02	9,9E-03	1,7E-01	5,1E-01
Leaves	Aubange	Cattle manure	mg kg ⁻¹	5,9E-03	7,8E-01	7,7E-02	5,9E-01	3,0E+01	1,0E-02	8,6E-02	4,7E+00	4,1E+00	7,3E-02	1,8E-02	1,8E+00	3,6E-01	1,9E-02	4,5E-02	2,0E-02	4,9E-02	5,9E-01
Leaves	Aubange	Green waste compost	mg kg ⁻¹	7,0E-03	1,8E+00	2,2E-02	3,5E-01	3,7E+01	8,7E-03	2,9E-01	1,1E+01	4,7E+00	5,5E-02	3,4E-02	1,5E+00	2,2E-01	9,1E-02	4,0E-02	1,7E-02	4,7E-02	5,6E-01
Leaves	Aubange	Cover crop restitution	mg kg ⁻¹	4,1E-03	4,9E-01	6,5E-02	1,5E-01	6,3E+01	2,0E-02	3,8E-01	1,5E+00	2,2E+00	4,9E-02	2,5E-02	3,5E-01	1,3E-01	5,2E-02	2,9E-02	3,0E-03	4,9E-02	3,4E-01
Shoots	Vieusart	No application	mg kg ⁻¹	4,3E-03	6,4E-01	1,3E-02	7,9E-02	1,2E+01	5,2E-03	1,8E-02	1,5E+00	1,1E+01	1,2E-02	4,9E-03	1,0E+00	2,9E-01	3,5E-02	4,0E-02	4,4E-03	1,4E-01	1,2E-02
Shoots	Vieusart	Cattle manure	mg kg ⁻¹	3,0E-03	8,5E-01	2,8E-02	3,0E-02	4,0E+00	2,8E-03	1,2E-01	2,9E+00	4,1E+00	8,9E-03	3,4E-03	1,3E+00	2,3E-01	4,4E-02	3,0E-02	2,4E-02	8,7E-01	1,1E-01
Shoots	Vieusart	Green waste compost	mg kg ⁻¹	3,9E-03	1,1E+00	3,0E-02	3,1E-01	1,3E+01	4,3E-03	2,4E-01	1,5E+00	2,4E+00	1,6E-02	8,5E-03	1,4E+00	4,8E-01	4,8E-02	2,0E-02	1,0E-02	3,2E-01	4,2E-02
Shoots	Vieusart	Cover crop restitution	mg kg ⁻¹	1,1E-03	2,8E+00	4,0E-02	2,5E-01	1,1E+01	1,0E-02	6,7E-02	1,1E+00	1,0E+01	1,1E-02	2,1E-03	9,0E-01	3,9E-01	7,4E-02	3,2E-02	5,2E-03	3,2E-01	5,9E-01
Shoots	Sainte-Walburge	No application	mg kg ⁻¹	2,3E-03	1,4E+00	2,5E-02	1,5E-01	2,4E-01	4,8E-03	1,1E-01	7,0E-01	1,0E+01	2,3E-01	9,9E-03	1,7E+00	7,7E-01	1,3E-01	1,1E-02	3,8E-03	3,4E-01	2,7E-01
Shoots	Sainte-Walburge	Cattle manure	mg kg ⁻¹	7,6E-03	8,1E-01	1,2E-03	8,5E-03	3,1E+01	1,0E-02	2,2E-02	3,2E+00	5,6E+01	4,6E-01	1,1E-02	2,1E+00	1,4E+00	3,0E-01	2,5E-02	2,7E-03	4,7E-01	1,7E-01
Shoots	Sainte-Walburge	Green waste compost	mg kg ⁻¹	1,1E-02	2,9E-01	6,9E-03	8,9E-02	1,9E+01	2,6E-03	1,0E-01	4,0E+00	4,8E+01	1,3E-01	2,8E-02	2,5E+00	1,8E+00	5,4E-02	2,3E-02	1,0E-02	1,0E+00	8,4E-02
Shoots	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	2,0E-03	4,4E-01	6,5E-03	2,0E-02	1,0E+01	2,1E-03	5,9E-02	9,6E-01	5,1E+01	6,3E-02	2,0E-02	1,5E+00	1,0E+00	5,4E-02	2,6E-02	1,2E-02	3,4E-01	1,5E-01
Shoots	Bressoux	No application	mg kg ⁻¹	5,9E-03	1,0E+00	3,2E-02	4,5E-01	1,5E+01	2,2E-03	2,0E-01	5,6E+00	7,1E+01	2,2E-01	1,3E-02	3,1E+00	5,0E-01	2,3E-01	4,3E-02	1,6E-03	9,2E-01	2,9E-01
Shoots	Bressoux	Cattle manure	mg kg ⁻¹	1,1E-02	2,6E-01	1,0E-02	1,2E-01	9,5E+00	1,3E-03	1,5E-02	4,5E+00	1,2E+02	7,2E-02	8,8E-04	3,0E-01	2,9E+00	6,1E-02	7,5E-03	1,3E-02	1,2E-01	1,1E-01
Shoots	Bressoux	Green waste compost	mg kg ⁻¹	5,7E-03	1,6E+00	7,4E-03	1,6E-01	2,2E+01	4,3E-03	7,8E-02	4,3E+00	1,1E+02	9,9E-02	2,7E-03	1,5E+00	2,5E-01	8,7E-02	2,6E-02	8,3E-03	8,9E-01	8,5E-02
Shoots	Bressoux	Cover crop restitution	mg kg ⁻¹	8,2E-03	1,5E+00	2,0E-02	6,5E-02	6,0E+00	2,5E-03	2,1E-02	1,7E+00	5,2E+01	1,1E-01	9,1E-03	4,4E-01	1,1E-01	2,4E-02	3,7E-02	3,6E-03	6,1E-01	1,9E-01
Shoots	Aubange	No application	mg kg ⁻¹	9,0E-03	1,5E+00	1,4E-01	9,1E-02	5,2E+00	1,6E-02	2,1E-02	4,3E+00	8,3E+00	3,9E-02	1,2E-02	1,0E+00	1,3E+00	1,6E-02	1,2E-02	4,0E-03	1,9E-01	2,5E-01
Shoots	Aubange	Cattle manure	mg kg ⁻¹	4,5E-03	9,8E-01	1,0E-01	2,6E-01	1,7E+01	1,4E-02	5,0E-02	2,2E+00	6,0E+00	5,4E-02	1,8E-02	1,8E+00	5,4E-01	2,6E-02	2,1E-02	7,8E-03	8,2E-02	1,9E-01
Shoots	Aubange	Green waste compost	mg kg ⁻¹	6,0E-03	5,0E-01	5,0E-02	1,2E-01	1,4E+01	3,9E-03	1,1E-01	4,2E+00	8,1E+00	3,9E-02	1,3E-02	8,7E-01	1,6E+00	3,0E-02	2,0E-02	7,5E-03	1,4E-02	2,0E-01
Shoots	Aubange	Cover crop restitution	mg kg ⁻¹	6,8E-03	8,7E-01	1,1E-01	9,8E-02	1,7E+01	4,9E-03	1,5E-01	7,6E-01	1,3E+01	2,7E-02	2,2E-02	9,8E-01	1,6E+00	2,2E-02	1,3E-02	8,0E-03	1,4E-01	1,1E-01
Plant	Vieusart	No application	mg kg ⁻¹	1,2E-01	4,0E+01	1,4E+00	1,7E+00	1,3E+01	1,3E-01	4,4E-01	1,9E+00	1,0E+01	4,5E-01	6,6E-02	1,6E+00	2,5E-01	6,2E-02	5,4E-02	2,0E-02	3,8E+00	3,7E-01

Appendices

Plant	Vieusart	Cattle manure		mg kg ⁻¹	2,3E-02	8,8E+00	1,8E-01	2,1E-01	4,7E+00	5,2E-02	1,7E-01	2,6E+00	4,0E+00	3,7E-02	1,5E-02	1,5E+00	2,3E-01	5,8E-02	2,2E-02	2,3E-02	1,3E+00	1,6E-01
Plant	Vieusart	Green waste compost		mg kg ⁻¹	7,8E-02	2,2E+01	5,7E-01	7,5E-01	1,3E+01	7,0E-02	3,6E-01	1,3E+00	1,8E+00	1,3E-01	3,3E-02	1,6E+00	3,6E-01	6,0E-02	2,6E-02	1,9E-03	2,6E+00	2,7E-01
Plant	Vieusart	Cover crop restitution		mg kg ⁻¹	1,6E-01	6,5E+01	1,6E+00	1,2E+00	1,4E+01	2,1E-01	3,8E-01	1,0E+00	8,1E+00	3,5E-01	4,2E-02	8,3E-01	3,4E-01	6,9E-02	3,2E-02	2,4E-02	6,0E+00	1,0E+00
Plant	Sainte-Walburge	No application		mg kg ⁻¹	4,1E-02	1,2E+01	3,0E-01	2,7E-01	2,6E+00	1,6E-01	2,2E-01	6,2E-01	1,1E+01	3,4E-01	1,6E-02	1,9E+00	7,2E-01	1,0E-01	2,3E-02	1,3E-02	1,8E+00	4,4E-01
Plant	Sainte-Walburge	Cattle manure		mg kg ⁻¹	1,7E-02	7,8E+00	2,3E-01	1,5E-01	2,6E+01	3,6E-01	3,7E-01	1,9E+00	4,8E+01	1,1E+00	1,9E-02	2,1E+00	1,3E+00	6,0E-01	2,1E-02	4,2E-03	4,7E-01	6,8E-02
Plant	Sainte-Walburge	Green waste compost		mg kg ⁻¹	1,3E-01	2,2E+01	1,4E+00	6,8E-01	1,4E+01	2,3E-01	4,5E-01	3,9E+00	4,0E+01	1,4E-01	4,1E-02	2,0E+00	1,7E+00	3,3E-02	3,3E-02	2,9E-02	1,2E+00	5,6E-01
Plant	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	3,8E-02	3,9E+00	3,1E-01	2,1E-01	9,6E+00	1,5E-01	1,8E-01	6,4E-01	4,8E+01	5,0E-01	2,4E-02	1,9E+00	7,9E-01	9,8E-02	2,5E-02	1,8E-02	8,1E-01	2,6E-01
Plant	Bressoux	No application		mg kg ⁻¹	1,6E-02	1,2E+00	1,2E-01	4,5E-01	1,5E+01	5,4E-02	2,1E-01	3,3E+00	5,6E+01	6,2E-01	1,1E-02	2,6E+00	2,8E-01	4,0E-01	3,6E-02	2,3E-02	1,0E+00	3,2E-01
Plant	Bressoux	Cattle manure		mg kg ⁻¹	3,3E-02	3,2E+00	2,0E-01	2,4E-01	7,3E+00	6,9E-02	2,0E-01	5,5E+00	1,0E+02	7,6E-02	2,3E-02	3,6E-01	2,5E+00	1,4E-01	4,2E-02	3,0E-02	1,2E+00	1,0E+00
Plant	Bressoux	Green waste compost		mg kg ⁻¹	3,1E-02	3,6E+00	2,4E-01	1,7E-01	2,0E+01	4,4E-02	1,9E-01	5,1E+00	9,6E+01	1,6E-01	1,9E-02	1,6E+00	3,3E-01	1,3E-01	3,9E-01	3,7E-02	1,4E+00	6,9E-01
Plant	Bressoux	Cover crop restitution		mg kg ⁻¹	1,1E-01	1,4E+01	9,6E-01	5,4E-01	4,7E+00	2,3E-01	6,0E-01	6,2E+00	4,8E+01	2,7E-01	2,6E-02	1,8E+00	1,5E-01	2,9E-01	1,2E-01	1,3E-01	3,0E+01	3,3E+00
Plant	Aubange	No application		mg kg ⁻¹	9,1E-02	8,8E+00	1,6E+00	2,0E-01	2,9E+01	2,3E-01	6,9E-01	3,5E+00	6,8E+00	6,1E-01	1,7E-02	7,1E-01	1,0E+00	1,4E-02	3,4E-02	1,8E-03	5,1E-01	4,6E-01
Plant	Aubange	Cattle manure		mg kg ⁻¹	6,1E-02	8,2E+00	1,0E+00	1,5E-01	2,5E+01	1,4E-01	1,7E-01	2,1E+00	5,3E+00	4,0E-01	2,2E-02	1,8E+00	5,2E-01	2,9E-02	2,3E-02	7,6E-03	6,2E-01	3,7E-01
Plant	Aubange	Green waste compost		mg kg ⁻¹	1,4E-01	1,6E+01	2,5E+00	5,8E-01	1,3E+02	3,9E-01	1,6E+00	3,3E+00	8,6E+00	1,1E+00	2,0E-02	1,8E+00	1,4E+00	4,5E-02	4,6E-03	6,7E-03	2,7E+00	3,6E-01
Plant	Aubange	Cover crop restitution		mg kg ⁻¹	5,5E-03	1,5E+00	1,4E-03	1,7E-01	2,5E+01	7,4E-02	3,7E-01	3,9E-01	1,1E+01	5,4E-02	1,3E-02	4,2E-01	7,2E-01	2,8E-03	2,0E-03	7,4E-03	4,2E-02	1,7E-02
Solution	Vieusart	No application	05-05-21	µg L ⁻¹	1,6E-01	9,1E-02	1,8E-01	5,9E-02	1,4E+01	1,1E+00	7,3E+00	6,6E-02	5,4E+02	3,7E-02	1,6E-01	4,8E+02	4,5E-02	2,7E-01	7,0E-03	1,5E-02	7,5E+01	1,5E-02
Solution	Vieusart	Cattle manure	05-05-21	µg L ⁻¹	3,0E-01	3,8E-02	6,1E-01	9,2E-02	6,0E+01	4,0E+00	1,5E+01	4,3E+00	3,2E+02	5,3E-01	1,2E-01	7,0E+02	1,2E+00	1,3E-01	6,0E-02	1,3E-02	2,7E+02	2,5E-02
Solution	Vieusart	Green waste compost	05-05-21	µg L ⁻¹	8,0E-01	3,3E-01	1,2E+00	6,6E-01	2,6E+02	1,3E+01	4,4E+01	2,0E+00	4,0E+03	1,2E+00	7,6E-01	9,9E+02	3,5E+00	1,2E+00	2,6E-02	4,5E-02	1,6E+02	2,5E-01
Solution	Vieusart	Cover crop restitution	05-05-21	µg L ⁻¹	1,4E-01	1,3E-01	2,1E+00	3,8E-01	1,4E+02	1,4E+01	2,9E+01	2,1E+00	9,8E+01	1,3E+00	1,6E-01	3,0E+02	1,3E+00	5,7E-01	4,0E-02	3,2E-02	1,8E+01	1,4E-01
Solution	Vieusart	No plant	05-05-21	µg L ⁻¹	2,7E-01	9,5E-02	2,8E-01	2,6E-01	7,4E+01	3,0E+00	2,0E+01	2,8E+00	3,5E+02	1,9E-01	2,4E-01	7,0E+02	3,7E-02	6,3E-01	1,6E-02	1,7E-02	3,4E+01	4,2E-02
Solution	Sainte-Walburge	No application	05-05-21	µg L ⁻¹	2,6E-01	4,0E-01	1,3E+00	1,6E-01	3,4E+01	8,5E+00	8,3E+00	1,6E+00	6,6E+01	5,2E+00	2,3E-01	5,6E+02	5,0E-01	3,6E-01	6,1E-03	1,1E-01	1,9E+02	1,9E-01
Solution	Sainte-Walburge	Cattle manure	05-05-21	µg L ⁻¹	2,9E-01	3,4E-01	1,4E+00	1,9E-01	3,8E+02	1,1E+01	2,7E+01	1,5E+01	3,7E+02	3,7E+00	2,9E-01	3,6E+02	2,5E+00	2,1E+00	4,6E-03	2,4E-01	5,3E+01	2,2E+00
Solution	Sainte-Walburge	Green waste compost	05-05-21	µg L ⁻¹	1,5E-01	1,2E-01	1,1E+00	1,3E-01	4,3E+01	9,0E+00	1,7E+01	5,1E+00	7,1E+02	4,8E+00	5,7E-02	1,5E+02	2,5E+00	1,3E+00	9,8E-03	2,1E-01	2,0E+02	1,5E+00
Solution	Sainte-Walburge	Cover crop restitution	05-05-21	µg L ⁻¹	3,5E-01	2,9E-01	9,3E-01	9,8E-02	4,3E+01	6,3E+00	1,6E+01	5,1E+00	5,6E+02	1,7E+00	1,3E-01	5,8E+02	1,3E+00	1,5E+00	3,9E-02	7,0E-02	2,6E+02	1,2E+00
Solution	Sainte-Walburge	No plant	05-05-21	µg L ⁻¹	1,5E-01	4,0E-02	6,2E-01	9,6E-03	1,3E+00	2,5E+00	4,9E+00	2,2E+00	3,4E+02	6,1E-01	2,7E-02	4,6E+02	1,6E-01	4,4E-01	1,6E-02	6,0E-02	1,5E+02	7,5E-01

Solution	Bressoux	No application	05-05-21	µg L ⁻¹	9,3E-02	2,0E-02	3,3E-01	4,8E-02	2,2E+00	6,3E-01	2,0E+00	1,6E+00	3,1E+02	1,1E+00	4,8E-03	3,2E+02	3,2E-01	9,1E-01	3,0E-02	2,6E-01	1,1E+02	5,5E-01
Solution	Bressoux	Cattle manure	05-05-21	µg L ⁻¹	7,5E-02	1,4E-01	3,2E-01	1,3E-01	4,4E+01	2,1E+00	1,5E+01	6,0E+00	2,9E+02	1,0E+00	6,9E-02	3,2E+02	8,8E+00	2,7E+00	3,4E-02	9,4E-01	4,6E+02	2,1E+00
Solution	Bressoux	Green waste compost	05-05-21	µg L ⁻¹	8,8E-02	2,7E-01	2,3E-01	1,6E-01	7,0E+01	7,2E-01	1,3E+01	3,1E+00	1,8E+03	1,8E+00	1,6E-02	3,1E+02	4,9E+00	2,7E+00	4,1E-02	2,4E-01	1,7E+02	2,3E+00
Solution	Bressoux	Cover crop restitution	05-05-21	µg L ⁻¹	2,3E-01	3,5E-01	3,1E-01	4,6E-02	3,4E+01	7,5E-01	1,4E+01	5,0E+00	9,3E+02	1,4E+00	9,2E-02	7,2E+02	3,4E+00	3,9E+00	1,2E-02	4,9E-01	2,7E+02	2,2E+00
Solution	Bressoux	No plant	05-05-21	µg L ⁻¹	4,5E-02	2,0E-01	6,1E-01	1,4E-01	4,5E+01	1,9E+00	8,0E+00	2,0E+00	5,1E+02	1,5E+00	2,5E-01	1,3E+02	5,9E-01	1,8E+00	2,1E-02	5,2E-01	5,4E+01	1,2E+00
Solution	Aubange	No application	05-05-21	µg L ⁻¹	1,5E-01	7,9E-02	1,1E+00	1,4E-01	4,9E+01	1,0E+01	2,6E+01	8,3E-01	2,4E+02	2,3E+00	2,1E-01	2,6E+02	1,6E+00	4,3E-02	2,7E-02	2,5E-02	2,4E+01	5,8E-02
Solution	Aubange	Cattle manure	05-05-21	µg L ⁻¹	9,9E-02	5,9E-02	4,0E-01	3,0E-02	2,7E+01	1,7E+00	8,0E+00	4,3E-01	3,9E+02	5,9E-01	2,5E-01	1,6E+02	3,5E+00	1,1E-02	3,1E-02	3,3E-03	2,4E+00	2,6E-02
Solution	Aubange	Green waste compost	05-05-21	µg L ⁻¹	3,9E-01	3,9E-02	1,1E+00	1,3E-01	4,2E+01	9,3E+00	2,7E+01	3,1E-01	4,8E+02	4,9E-01	4,4E-01	5,7E+02	1,0E+01	4,7E-02	1,6E-02	9,2E-03	5,0E+01	3,8E-02
Solution	Aubange	Cover crop restitution	05-05-21	µg L ⁻¹	1,6E-01	6,7E-02	5,5E-01	2,3E-01	3,3E+02	1,9E+01	3,6E+01	7,3E-01	7,9E+01	1,3E+00	2,1E-01	1,7E+02	1,4E+00	8,9E-02	1,5E-02	1,5E-02	5,0E+01	2,6E-02
Solution	Aubange	No plant	05-05-21	µg L ⁻¹	3,0E-01	1,7E-01	2,5E-01	1,2E-01	2,3E+01	1,1E+01	3,2E+01	8,2E-01	2,1E+02	2,7E-01	4,0E-01	6,7E+02	3,8E+00	3,5E-02	1,6E-02	1,2E-02	2,5E+01	1,9E-02
Solution	Vieusart	No application	22-06-21	µg L ⁻¹	2,4E-02	2,7E-02	3,1E-02	2,5E-02	2,4E-01	1,1E+00	2,5E+00	2,8E-01	5,6E+01	7,4E-02	1,1E-01	1,2E+02	3,5E-01	4,3E-02	2,1E-03	2,1E-02	1,8E+01	6,0E-03
Solution	Vieusart	Cattle manure	22-06-21	µg L ⁻¹	1,4E-02	5,4E-02	3,9E-01	3,4E-02	1,1E-01	5,5E-01	1,8E+00	1,7E+00	3,1E+02	9,7E-01	1,1E-01	9,5E+00	1,8E+00	6,6E-02	6,2E-02	5,4E-02	9,3E+00	6,7E-02
Solution	Vieusart	Green waste compost	22-06-21	µg L ⁻¹	3,3E-02	4,8E-02	1,7E-01	5,8E-02	1,4E+01	1,6E+00	9,8E+00	1,7E+00	1,8E+02	3,8E-02	1,7E-01	1,4E+02	5,1E-01	1,4E-01	5,3E-03	4,8E-02	2,6E+01	1,4E-01
Solution	Vieusart	Cover crop restitution	22-06-21	µg L ⁻¹	8,4E-03	4,3E-02	2,6E-01	1,6E-02	7,3E-01	7,2E-01	2,9E+00	2,8E-01	1,2E+02	1,1E-01	1,0E-02	2,7E+00	2,9E-01	2,9E-02	2,0E-02	3,8E-02	8,8E+00	7,9E-02
Solution	Vieusart	No plant	22-06-21	µg L ⁻¹	2,8E-02	4,0E-02	2,4E-01	7,6E-02	2,4E+02	5,6E-01	3,7E+00	6,1E-01	5,4E+02	5,5E-02	5,3E-02	8,6E+01	2,6E-02	2,2E-01	7,3E-03	1,2E-02	5,8E+01	2,0E-02
Solution	Sainte-Walburge	No application	22-06-21	µg L ⁻¹	1,4E-01	1,3E-01	1,6E+00	1,8E-01	3,1E-01	1,8E+01	4,6E+01	1,1E+01	4,5E+02	1,2E+00	8,8E-01	4,4E+02	2,9E+00	1,9E+00	2,1E-02	1,9E-01	5,8E+01	2,9E+00
Solution	Sainte-Walburge	Cattle manure	22-06-21	µg L ⁻¹	2,1E-01	1,0E+00	2,3E+00	4,1E-01	3,8E+00	6,8E+00	3,1E+01	2,3E+01	2,7E+03	7,1E+00	7,7E-01	1,4E+03	1,0E+01	3,6E+00	6,0E-01	9,7E-01	3,1E+02	3,5E+00
Solution	Sainte-Walburge	Green waste compost	22-06-21	µg L ⁻¹	2,0E-01	1,5E-01	5,0E-01	1,9E-01	4,1E-01	3,5E+00	3,5E+01	7,0E+00	4,7E+02	8,2E-01	7,3E-01	6,1E+02	7,0E+00	2,6E+00	2,5E-01	3,3E-01	1,2E+02	3,1E+00
Solution	Sainte-Walburge	Cover crop restitution	22-06-21	µg L ⁻¹	4,6E-02	7,0E-02	1,0E+00	1,3E-01	1,9E+00	1,2E+01	1,0E+01	2,0E+00	1,7E+02	1,9E+00	2,2E-01	3,0E+02	6,0E+00	4,3E-01	3,5E-02	2,3E-01	1,9E+02	7,2E-01
Solution	Sainte-Walburge	No plant	22-06-21	µg L ⁻¹	1,5E-02	4,1E-02	1,9E-01	4,6E-02	6,7E+00	2,4E+00	2,4E+00	6,0E-01	7,1E+02	2,5E-01	6,5E-02	5,2E+01	2,3E+00	2,2E-01	2,8E-02	7,5E-02	5,0E+01	1,2E-01
Solution	Bressoux	No application	22-06-21	µg L ⁻¹	1,6E-01	1,5E-01	1,0E+00	2,9E-01	3,0E+00	2,7E+00	6,0E+01	9,5E+00	9,9E+02	1,8E+00	3,9E-01	5,4E+02	6,2E-01	3,4E+00	9,6E-02	9,5E-01	6,3E+01	5,1E+00
Solution	Bressoux	Cattle manure	22-06-21	µg L ⁻¹	1,3E-01	1,6E-01	1,2E+00	1,2E-01	4,4E+00	4,1E-01	1,4E+01	1,3E+01	1,7E+03	2,4E+00	4,0E-02	5,9E+02	1,7E+00	2,4E+00	6,1E-01	5,2E-01	1,7E+02	1,1E+00
Solution	Bressoux	Green waste compost	22-06-21	µg L ⁻¹	1,1E-01	9,5E-02	1,3E+00	1,8E-01	2,5E+00	5,6E-01	2,4E+01	7,0E+00	4,2E+02	7,1E-01	1,8E-01	4,3E+02	1,8E+00	2,4E+00	1,7E-01	9,7E-01	6,7E+01	3,9E+00
Solution	Bressoux	Cover crop restitution	22-06-21	µg L ⁻¹	1,5E-01	1,1E-01	1,1E+00	1,1E-01	7,4E+00	5,5E-01	2,6E+01	5,7E+00	9,4E+02	1,8E+00	1,9E-01	6,9E+02	1,2E+00	3,1E+00	2,4E-02	1,3E+00	1,1E+02	3,1E+00
Solution	Bressoux	No plant	22-06-21	µg L ⁻¹	3,0E-02	1,6E-01	9,3E-01	8,7E-02	2,4E+02	3,3E-01	7,6E+00	3,4E+00	1,9E+02	2,0E+00	1,5E-01	2,4E+02	5,5E-01	1,4E+00	3,1E-03	7,1E-01	3,0E+01	5,5E-01

Appendices

Solution	Aubange	No application	22-06-21	µg L ⁻¹	1,3E-01	9,9E-01	1,7E+00	3,5E-01	3,6E+01	6,3E+00	1,8E+01	2,2E+00	1,8E+03	6,0E-01	2,4E-01	3,8E+02	1,4E-01	1,1E-02	2,1E-02	2,6E-02	2,6E+01	2,5E-01
Solution	Aubange	Cattle manure	22-06-21	µg L ⁻¹	4,2E-01	2,2E-01	1,0E+00	5,5E-02	1,5E+01	1,3E+00	1,0E+01	1,4E+00	2,2E+03	3,2E-01	8,4E-02	1,1E+03	5,6E-01	1,4E-02	6,2E-02	3,8E-02	4,0E+01	7,2E-02
Solution	Aubange	Green waste compost	22-06-21	µg L ⁻¹	6,6E-02	2,2E-01	8,8E-01	1,1E-02	4,4E+01	2,9E+00	1,3E+01	4,3E-01	1,0E+03	2,0E-01	2,9E-01	2,6E+02	1,4E-01	2,8E-02	5,4E-02	3,7E-03	2,8E+01	1,0E-01
Solution	Aubange	Cover crop restitution	22-06-21	µg L ⁻¹	5,1E-02	3,4E-01	2,8E+00	1,1E-01	8,9E+01	1,2E+01	1,7E+01	2,2E+00	6,9E+02	4,6E-01	2,2E-01	3,2E+02	2,8E-01	1,8E-02	2,6E-02	5,1E-02	3,9E+01	5,2E-02
Solution	Aubange	No plant	22-06-21	µg L ⁻¹	1,3E-01	1,3E-02	1,1E-01	3,9E-03	7,7E-01	2,2E+00	2,6E+00	4,8E-01	1,2E+02	1,1E-01	6,2E-02	4,0E+02	1,5E-02	6,2E-03	5,7E-03	3,5E-03	7,7E+00	7,5E-03
Tap water			19-05-21	µg L ⁻¹	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table VI-5 - Average rare earth element contents in soil and exogenous organic matter samples (n=2) and in plant parts and soil solution samples (n=3) for the greenhouse experiment.

Sample	Site	Modality	Date	Units	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Soil	Vieusart			mg kg ⁻¹	2,3E+01	5,0E+01	5,8E+00	2,3E+01	4,2E+00	7,4E-01	3,6E+00	4,4E-01	2,5E+00	4,6E-01	1,3E+00	1,9E-01	1,2E+00	1,7E-01
Soil	Sainte-Walburge			mg kg ⁻¹	3,0E+01	5,8E+01	7,8E+00	3,1E+01	5,9E+00	1,1E+00	5,3E+00	6,5E-01	3,6E+00	6,9E-01	1,9E+00	2,6E-01	1,7E+00	2,5E-01
Soil	Bressoux			mg kg ⁻¹	2,1E+01	4,9E+01	6,1E+00	2,5E+01	5,3E+00	1,1E+00	4,8E+00	5,9E-01	3,3E+00	6,1E-01	1,6E+00	2,3E-01	1,4E+00	2,1E-01
Soil	Aubange			mg kg ⁻¹	3,1E+01	1,0E+02	9,4E+00	3,9E+01	8,5E+00	2,0E+00	8,8E+00	1,3E+00	7,7E+00	1,5E+00	4,0E+00	6,2E-01	3,8E+00	5,3E-01
EOM		Cattle manure		mg kg ⁻¹	3,1E+00	5,8E+00	7,2E-01	2,8E+00	5,3E-01	9,9E-02	5,1E-01	6,7E-02	4,0E-01	8,1E-02	2,2E-01	3,3E-02	2,2E-01	3,3E-02
EOM		Green waste compost		mg kg ⁻¹	8,4E+00	1,5E+01	2,0E+00	7,6E+00	1,5E+00	3,1E-01	1,4E+00	1,9E-01	1,1E+00	2,2E-01	6,4E-01	9,6E-02	6,1E-01	9,6E-02
EOM		Cover crop restitution		mg kg ⁻¹	1,0E-01	2,0E-01	2,2E-02	8,4E-02	1,7E-02	2,7E-03	1,5E-02	1,7E-03	1,0E-02	2,2E-03	5,6E-03	8,2E-04	5,4E-03	8,3E-04
Roots	Vieusart	No application		mg kg ⁻¹	7,9E+00	1,6E+01	2,0E+00	7,8E+00	1,6E+00	3,1E-01	1,4E+00	1,9E-01	1,1E+00	2,1E-01	5,9E-01	8,9E-02	5,6E-01	8,4E-02
Roots	Vieusart	Cattle manure		mg kg ⁻¹	3,7E+00	7,3E+00	8,6E-01	3,3E+00	6,3E-01	1,2E-01	5,8E-01	7,5E-02	4,4E-01	8,6E-02	2,4E-01	3,5E-02	2,3E-01	3,4E-02
Roots	Vieusart	Green waste compost		mg kg ⁻¹	7,1E+00	1,4E+01	1,7E+00	6,5E+00	1,3E+00	2,4E-01	1,1E+00	1,5E-01	8,8E-01	1,7E-01	4,9E-01	7,2E-02	4,6E-01	7,1E-02
Roots	Vieusart	Cover crop restitution		mg kg ⁻¹	6,4E+00	1,2E+01	1,6E+00	6,1E+00	1,2E+00	2,2E-01	1,1E+00	1,4E-01	8,1E-01	1,5E-01	4,3E-01	6,4E-02	4,1E-01	6,2E-02
Roots	Sainte-Walburge	No application		mg kg ⁻¹	3,7E+00	7,5E+00	8,9E-01	3,5E+00	7,1E-01	1,4E-01	6,5E-01	8,4E-02	5,0E-01	9,6E-02	2,7E-01	4,0E-02	2,5E-01	3,8E-02
Roots	Sainte-Walburge	Cattle manure		mg kg ⁻¹	2,5E+00	5,0E+00	6,0E-01	2,3E+00	4,7E-01	9,3E-02	4,6E-01	5,9E-02	3,5E-01	6,8E-02	1,9E-01	2,8E-02	1,7E-01	2,6E-02
Roots	Sainte-Walburge	Green waste compost		mg kg ⁻¹	3,9E+00	8,0E+00	9,4E-01	3,7E+00	7,6E-01	1,6E-01	7,5E-01	1,0E-01	6,1E-01	1,2E-01	3,3E-01	4,8E-02	3,0E-01	4,7E-02
Roots	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	3,7E+00	7,4E+00	8,8E-01	3,5E+00	6,8E-01	1,4E-01	6,4E-01	8,1E-02	4,8E-01	1,2E-01	2,6E-01	3,7E-02	2,4E-01	3,6E-02
Roots	Bressoux	No application		mg kg ⁻¹	7,5E-01	1,5E+00	1,8E-01	7,0E-01	1,5E-01	3,3E-02	1,6E-01	2,0E-02	1,2E-01	2,2E-02	6,1E-02	8,8E-03	5,4E-02	7,6E-03
Roots	Bressoux	Cattle manure		mg kg ⁻¹	8,8E-01	1,8E+00	2,1E-01	8,4E-01	1,7E-01	3,8E-02	1,8E-01	2,4E-02	1,4E-01	2,5E-02	6,9E-02	9,5E-03	6,0E-02	8,7E-03
Roots	Bressoux	Green waste compost		mg kg ⁻¹	1,1E+00	2,3E+00	2,7E-01	1,1E+00	2,1E-01	4,6E-02	2,1E-01	2,7E-02	1,6E-01	3,0E-02	8,4E-02	1,2E-02	7,4E-02	1,1E-02
Roots	Bressoux	Cover crop restitution		mg kg ⁻¹	2,7E+00	5,3E+00	6,3E-01	2,5E+00	5,1E-01	1,0E-01	5,0E-01	6,2E-02	3,4E-01	6,5E-02	1,8E-01	2,5E-02	1,6E-01	2,4E-02
Roots	Aubange	No application		mg kg ⁻¹	2,3E+00	6,5E+00	6,7E-01	2,7E+00	6,0E-01	1,4E-01	5,9E-01	8,4E-02	5,1E-01	9,5E-02	2,7E-01	3,8E-02	2,5E-01	3,7E-02
Roots	Aubange	Cattle manure		mg kg ⁻¹	1,8E+00	4,3E+00	5,2E-01	2,1E+00	4,8E-01	1,1E-01	4,8E-01	6,9E-02	4,2E-01	7,9E-02	2,2E-01	3,2E-02	2,0E-01	3,0E-02
Roots	Aubange	Green waste compost		mg kg ⁻¹	4,8E+00	1,5E+01	1,4E+00	5,6E+00	1,3E+00	2,9E-01	1,3E+00	1,9E-01	1,1E+00	2,1E-01	5,8E-01	8,4E-02	5,4E-01	7,7E-02

Appendices

Roots	Aubange	Cover crop restitution	mg kg ⁻¹	3,2E+00	7,6E+00	9,2E-01	3,8E+00	8,4E-01	1,9E-01	8,6E-01	1,2E-01	7,4E-01	1,4E-01	3,9E-01	5,8E-02	3,6E-01	5,3E-02
Stems	Vieusart	No application	mg kg ⁻¹	2,0E-02	3,6E-02	4,3E-03	1,5E-02	2,4E-03	5,6E-04	2,6E-03	3,3E-04	1,8E-03	3,9E-04	9,3E-04	1,2E-04	1,1E-03	1,7E-04
Stems	Vieusart	Cattle manure	mg kg ⁻¹	7,4E-03	1,3E-02	1,6E-03	6,1E-03	9,3E-04	2,1E-04	9,2E-04	1,9E-04	1,0E-03	1,5E-04	6,2E-04	7,6E-05	5,8E-04	1,1E-04
Stems	Vieusart	Green waste compost	mg kg ⁻¹	1,0E-02	1,8E-02	2,2E-03	8,1E-03	1,3E-03	4,1E-04	1,5E-03	1,7E-04	1,1E-03	1,9E-04	5,2E-04	6,7E-05	6,2E-04	6,4E-05
Stems	Vieusart	Cover crop restitution	mg kg ⁻¹	1,6E-02	3,0E-02	3,7E-03	1,4E-02	2,7E-03	6,3E-04	2,9E-03	4,4E-04	2,9E-03	6,0E-04	1,7E-03	2,5E-04	1,5E-03	2,4E-04
Stems	Sainte-Walburge	No application	mg kg ⁻¹	1,0E-02	2,1E-02	2,5E-03	1,1E-02	1,6E-03	4,2E-04	1,8E-03	2,4E-04	1,4E-03	2,7E-04	7,6E-04	1,2E-04	7,1E-04	1,5E-04
Stems	Sainte-Walburge	Cattle manure	mg kg ⁻¹	8,9E-03	1,7E-02	1,8E-03	7,2E-03	1,4E-03	3,8E-04	2,0E-03	2,6E-04	1,6E-03	2,9E-04	1,1E-03	1,0E-04	7,8E-04	1,4E-04
Stems	Sainte-Walburge	Green waste compost	mg kg ⁻¹	1,6E-02	3,0E-02	3,5E-03	1,4E-02	2,8E-03	9,4E-04	2,9E-03	4,1E-04	2,0E-03	4,0E-04	1,2E-03	1,7E-04	1,1E-03	1,3E-04
Stems	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	8,5E-03	1,6E-02	2,0E-03	7,6E-03	1,0E-03	6,7E-04	1,9E-03	2,4E-04	1,1E-03	2,4E-04	6,4E-04	1,1E-04	6,6E-04	1,4E-04
Stems	Bressoux	No application	mg kg ⁻¹	1,8E-02	3,6E-02	4,7E-03	1,7E-02	3,1E-03	1,2E-03	3,4E-03	3,6E-04	2,2E-03	4,2E-04	1,4E-03	1,9E-04	1,0E-03	1,7E-04
Stems	Bressoux	Cattle manure	mg kg ⁻¹	7,9E-03	1,5E-02	2,0E-03	7,4E-03	1,3E-03	6,7E-04	1,4E-03	1,8E-04	9,5E-04	1,6E-04	4,7E-04	4,9E-05	3,9E-04	7,8E-05
Stems	Bressoux	Green waste compost	mg kg ⁻¹	6,6E-03	1,2E-02	1,5E-03	5,4E-03	7,2E-04	5,6E-04	1,3E-03	1,3E-04	7,2E-04	1,3E-04	5,0E-04	6,8E-05	4,3E-04	7,4E-05
Stems	Bressoux	Cover crop restitution	mg kg ⁻¹	1,1E-02	2,3E-02	2,9E-03	1,1E-02	1,7E-03	5,6E-04	2,2E-03	2,7E-04	1,4E-03	2,3E-04	6,3E-04	8,5E-05	6,0E-04	9,5E-05
Stems	Aubange	No application	mg kg ⁻¹	1,8E-02	4,1E-02	4,8E-03	1,9E-02	4,0E-03	1,4E-03	4,3E-03	6,9E-04	3,7E-03	8,3E-04	1,9E-03	3,2E-04	2,0E-03	3,0E-04
Stems	Aubange	Cattle manure	mg kg ⁻¹	1,3E-02	3,2E-02	3,6E-03	1,4E-02	2,8E-03	1,4E-03	3,6E-03	4,3E-04	3,0E-03	6,1E-04	1,5E-03	2,5E-04	1,5E-03	2,5E-04
Stems	Aubange	Green waste compost	mg kg ⁻¹	8,3E-03	1,4E-02	2,2E-03	8,5E-03	1,3E-03	9,1E-04	2,1E-03	2,5E-04	1,7E-03	3,1E-04	8,3E-04	1,3E-04	8,4E-04	1,4E-04
Stems	Aubange	Cover crop restitution	mg kg ⁻¹	1,9E-02	4,0E-02	4,8E-03	1,9E-02	3,5E-03	1,4E-03	4,6E-03	6,1E-04	3,3E-03	7,2E-04	1,8E-03	2,6E-04	1,6E-03	2,6E-04
Leaves	Vieusart	No application	mg kg ⁻¹	6,3E-02	8,2E-02	1,1E-02	3,9E-02	6,6E-03	1,5E-03	7,2E-03	9,1E-04	4,9E-03	9,1E-04	2,9E-03	3,5E-04	2,4E-03	3,8E-04
Leaves	Vieusart	Cattle manure	mg kg ⁻¹	4,3E-02	7,3E-02	7,7E-03	2,9E-02	5,4E-03	1,2E-03	6,1E-03	6,8E-04	4,4E-03	8,2E-04	2,4E-03	3,8E-04	2,7E-03	4,0E-04
Leaves	Vieusart	Green waste compost	mg kg ⁻¹	4,6E-02	7,4E-02	8,8E-03	3,3E-02	5,3E-03	1,3E-03	5,7E-03	7,7E-04	4,5E-03	9,6E-04	2,7E-03	4,0E-04	2,7E-03	4,2E-04
Leaves	Vieusart	Cover crop restitution	mg kg ⁻¹	9,3E-02	1,4E-01	1,7E-02	6,7E-02	1,2E-02	2,2E-03	1,2E-02	1,3E-03	8,0E-03	1,5E-03	4,1E-03	5,7E-04	3,8E-03	5,8E-04
Leaves	Sainte-Walburge	No application	mg kg ⁻¹	4,4E-02	8,1E-02	8,9E-03	3,5E-02	6,6E-03	8,4E-04	5,8E-03	7,0E-04	4,0E-03	7,1E-04	1,6E-03	2,2E-04	1,3E-03	2,4E-04
Leaves	Sainte-Walburge	Cattle manure	mg kg ⁻¹	2,2E-02	4,1E-02	4,9E-03	1,8E-02	3,4E-03	9,0E-04	3,7E-03	5,3E-04	3,0E-03	5,4E-04	2,0E-03	3,1E-04	1,9E-03	3,2E-04
Leaves	Sainte-Walburge	Green waste compost	mg kg ⁻¹	2,5E-02	4,4E-02	5,0E-03	1,8E-02	3,5E-03	9,1E-04	4,0E-03	5,7E-04	3,4E-03	7,1E-04	1,8E-03	3,1E-04	1,8E-03	3,0E-04
Leaves	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	3,1E-02	5,7E-02	6,9E-03	2,6E-02	4,7E-03	1,2E-03	5,1E-03	7,8E-04	3,5E-03	9,0E-04	2,1E-03	3,8E-04	2,1E-03	4,8E-04

Leaves	Bressoux	No application	mg kg ⁻¹	4,0E-02	7,5E-02	8,6E-03	3,3E-02	5,9E-03	1,4E-03	6,5E-03	8,4E-04	4,9E-03	9,6E-04	2,8E-03	4,5E-04	2,8E-03	4,7E-04
Leaves	Bressoux	Cattle manure	mg kg ⁻¹	2,9E-02	5,2E-02	6,0E-03	2,3E-02	3,7E-03	7,2E-04	4,3E-03	5,7E-04	2,9E-03	5,7E-04	1,8E-03	3,0E-04	1,7E-03	2,5E-04
Leaves	Bressoux	Green waste compost	mg kg ⁻¹	5,4E-02	1,1E-01	1,2E-02	4,6E-02	9,2E-03	1,4E-03	8,2E-03	1,2E-03	5,5E-03	9,7E-04	2,5E-03	3,7E-04	2,5E-03	3,6E-04
Leaves	Bressoux	Cover crop restitution	mg kg ⁻¹	2,6E-02	5,0E-02	5,6E-03	2,2E-02	4,3E-03	9,4E-04	4,5E-03	5,3E-04	3,3E-03	7,0E-04	1,7E-03	2,8E-04	2,0E-03	2,7E-04
Leaves	Aubange	No application	mg kg ⁻¹	4,2E-02	6,9E-02	7,7E-03	3,0E-02	5,0E-03	1,1E-03	5,3E-03	5,9E-04	3,3E-03	6,0E-04	1,9E-03	2,4E-04	1,7E-03	2,4E-04
Leaves	Aubange	Cattle manure	mg kg ⁻¹	3,6E-02	6,4E-02	7,9E-03	3,1E-02	5,2E-03	1,3E-03	6,3E-03	7,9E-04	4,9E-03	9,8E-04	2,8E-03	4,1E-04	2,5E-03	3,8E-04
Leaves	Aubange	Green waste compost	mg kg ⁻¹	3,6E-02	6,1E-02	7,4E-03	2,9E-02	5,2E-03	1,3E-03	5,7E-03	7,5E-04	4,1E-03	8,1E-04	2,4E-03	3,4E-04	2,5E-03	3,6E-04
Leaves	Aubange	Cover crop restitution	mg kg ⁻¹	5,3E-02	8,7E-02	1,1E-02	4,3E-02	8,2E-03	1,9E-03	8,3E-03	8,8E-04	5,4E-03	9,9E-04	3,0E-03	3,9E-04	2,6E-03	3,7E-04
Shoots	Vieusart	No application	mg kg ⁻¹	3,4E-02	5,1E-02	6,3E-03	2,3E-02	3,7E-03	8,8E-04	4,1E-03	5,2E-04	2,8E-03	5,6E-04	1,6E-03	2,0E-04	1,5E-03	2,4E-04
Shoots	Vieusart	Cattle manure	mg kg ⁻¹	1,9E-02	3,3E-02	3,7E-03	1,4E-02	2,4E-03	5,5E-04	2,7E-03	3,5E-04	2,1E-03	3,8E-04	1,2E-03	1,8E-04	1,3E-03	2,0E-04
Shoots	Vieusart	Green waste compost	mg kg ⁻¹	2,2E-02	3,7E-02	4,4E-03	1,6E-02	2,7E-03	7,2E-04	2,9E-03	3,7E-04	2,2E-03	4,5E-04	1,2E-03	1,8E-04	1,3E-03	1,8E-04
Shoots	Vieusart	Cover crop restitution	mg kg ⁻¹	4,1E-02	6,7E-02	8,2E-03	3,1E-02	5,7E-03	1,2E-03	5,9E-03	7,1E-04	4,6E-03	8,7E-04	2,5E-03	3,5E-04	2,2E-03	3,5E-04
Shoots	Sainte-Walburge	No application	mg kg ⁻¹	2,3E-02	4,3E-02	4,8E-03	2,0E-02	3,5E-03	5,8E-04	3,3E-03	4,1E-04	2,3E-03	4,3E-04	1,1E-03	1,6E-04	9,4E-04	1,8E-04
Shoots	Sainte-Walburge	Cattle manure	mg kg ⁻¹	1,4E-02	2,6E-02	3,0E-03	1,1E-02	2,2E-03	5,8E-04	2,7E-03	3,6E-04	2,1E-03	3,9E-04	1,4E-03	1,8E-04	1,2E-03	2,1E-04
Shoots	Sainte-Walburge	Green waste compost	mg kg ⁻¹	1,9E-02	3,5E-02	4,0E-03	1,6E-02	3,1E-03	9,2E-04	3,3E-03	4,7E-04	2,5E-03	5,2E-04	1,4E-03	2,3E-04	1,4E-03	1,9E-04
Shoots	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	1,8E-02	3,3E-02	4,0E-03	1,5E-02	2,5E-03	9,1E-04	3,2E-03	4,6E-04	2,1E-03	5,1E-04	1,3E-03	2,2E-04	1,2E-03	2,8E-04
Shoots	Bressoux	No application	mg kg ⁻¹	2,8E-02	5,4E-02	6,4E-03	2,4E-02	4,3E-03	1,3E-03	4,7E-03	5,7E-04	3,4E-03	6,6E-04	2,0E-03	3,0E-04	1,8E-03	3,1E-04
Shoots	Bressoux	Cattle manure	mg kg ⁻¹	1,6E-02	3,0E-02	3,5E-03	1,3E-02	2,2E-03	6,9E-04	2,5E-03	3,3E-04	1,7E-03	3,2E-04	9,8E-04	1,4E-04	8,9E-04	1,5E-04
Shoots	Bressoux	Green waste compost	mg kg ⁻¹	2,6E-02	5,2E-02	5,9E-03	2,2E-02	4,3E-03	9,0E-04	4,2E-03	5,8E-04	2,7E-03	4,7E-04	1,3E-03	1,9E-04	1,2E-03	1,9E-04
Shoots	Bressoux	Cover crop restitution	mg kg ⁻¹	1,7E-02	3,4E-02	4,0E-03	1,5E-02	2,8E-03	7,2E-04	3,2E-03	3,8E-04	2,2E-03	4,3E-04	1,1E-03	1,7E-04	1,2E-03	1,7E-04
Shoots	Aubange	No application	mg kg ⁻¹	2,6E-02	5,0E-02	5,8E-03	2,3E-02	4,3E-03	1,3E-03	4,6E-03	6,5E-04	3,6E-03	7,5E-04	1,9E-03	2,9E-04	1,9E-03	2,8E-04
Shoots	Aubange	Cattle manure	mg kg ⁻¹	2,2E-02	4,5E-02	5,2E-03	2,1E-02	3,7E-03	1,4E-03	4,6E-03	5,7E-04	3,8E-03	7,5E-04	2,0E-03	3,1E-04	1,9E-03	3,0E-04
Shoots	Aubange	Green waste compost	mg kg ⁻¹	1,8E-02	3,1E-02	4,1E-03	1,6E-02	2,7E-03	1,0E-03	3,4E-03	4,3E-04	2,5E-03	4,9E-04	1,4E-03	2,0E-04	1,4E-03	2,2E-04
Shoots	Aubange	Cover crop restitution	mg kg ⁻¹	3,2E-02	5,9E-02	7,2E-03	2,8E-02	5,3E-03	1,6E-03	6,1E-03	7,2E-04	4,1E-03	8,2E-04	2,3E-03	3,2E-04	2,0E-03	3,1E-04
Plant	Vieusart	No application	mg kg ⁻¹	1,3E+00	2,6E+00	3,3E-01	1,3E+00	2,6E-01	5,0E-02	2,4E-01	3,1E-02	1,8E-01	3,4E-02	9,6E-02	1,4E-02	9,1E-02	1,4E-02

Appendices

Plant	Vieusart	Cattle manure		mg kg ⁻¹	6,0E-01	1,2E+00	1,4E-01	5,3E-01	1,0E-01	1,9E-02	9,3E-02	1,2E-02	7,1E-02	1,4E-02	3,9E-02	5,7E-03	3,7E-02	5,5E-03
Plant	Vieusart	Green waste compost		mg kg ⁻¹	1,4E+00	2,7E+00	3,2E-01	1,2E+00	2,4E-01	4,6E-02	2,2E-01	2,8E-02	1,7E-01	3,3E-02	9,3E-02	1,4E-02	8,9E-02	1,4E-02
Plant	Vieusart	Cover crop restitution		mg kg ⁻¹	1,0E+00	2,0E+00	2,5E-01	9,6E-01	1,9E-01	3,5E-02	1,7E-01	2,2E-02	1,3E-01	2,4E-02	6,9E-02	1,0E-02	6,5E-02	9,8E-03
Plant	Sainte-Walburge	No application		mg kg ⁻¹	4,9E-01	9,9E-01	1,2E-01	4,6E-01	9,3E-02	1,8E-02	8,6E-02	1,1E-02	6,6E-02	1,3E-02	3,5E-02	5,3E-03	3,3E-02	5,0E-03
Plant	Sainte-Walburge	Cattle manure		mg kg ⁻¹	3,1E-01	6,1E-01	7,2E-02	2,9E-01	5,7E-02	1,1E-02	5,6E-02	7,2E-03	4,3E-02	8,3E-03	2,3E-02	3,4E-03	2,1E-02	3,2E-03
Plant	Sainte-Walburge	Green waste compost		mg kg ⁻¹	5,0E-01	1,0E+00	1,2E-01	4,8E-01	9,8E-02	2,1E-02	9,8E-02	1,3E-02	7,9E-02	1,5E-02	4,3E-02	6,3E-03	4,0E-02	6,1E-03
Plant	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	4,4E-01	8,7E-01	1,0E-01	4,1E-01	8,0E-02	1,6E-02	7,7E-02	9,7E-03	5,7E-02	1,4E-02	3,0E-02	4,5E-03	2,9E-02	4,4E-03
Plant	Bressoux	No application		mg kg ⁻¹	1,2E-01	2,4E-01	2,8E-02	1,1E-01	2,3E-02	5,4E-03	2,5E-02	3,1E-03	1,8E-02	3,4E-03	9,5E-03	1,4E-03	8,4E-03	1,2E-03
Plant	Bressoux	Cattle manure		mg kg ⁻¹	1,3E-01	2,7E-01	3,2E-02	1,2E-01	2,5E-02	5,8E-03	2,7E-02	3,5E-03	2,0E-02	3,6E-03	1,0E-02	1,4E-03	8,8E-03	1,3E-03
Plant	Bressoux	Green waste compost		mg kg ⁻¹	1,7E-01	3,3E-01	3,9E-02	1,5E-01	3,1E-02	6,6E-03	3,1E-02	4,0E-03	2,2E-02	4,2E-03	1,2E-02	1,7E-03	1,0E-02	1,6E-03
Plant	Bressoux	Cover crop restitution		mg kg ⁻¹	4,1E-01	8,2E-01	9,8E-02	3,8E-01	7,8E-02	1,6E-02	7,7E-02	9,5E-03	5,3E-02	1,0E-02	2,8E-02	3,9E-03	2,5E-02	3,7E-03
Plant	Aubange	No application		mg kg ⁻¹	3,8E-01	1,1E+00	1,1E-01	4,4E-01	9,7E-02	2,2E-02	9,7E-02	1,4E-02	8,3E-02	1,6E-02	4,4E-02	6,4E-03	4,1E-02	6,0E-03
Plant	Aubange	Cattle manure		mg kg ⁻¹	2,5E-01	6,0E-01	7,2E-02	3,0E-01	6,5E-02	1,5E-02	6,6E-02	9,4E-03	5,8E-02	1,1E-02	3,0E-02	4,5E-03	2,8E-02	4,1E-03
Plant	Aubange	Green waste compost		mg kg ⁻¹	7,2E-01	2,2E+00	2,1E-01	8,5E-01	1,9E-01	4,3E-02	1,9E-01	2,8E-02	1,7E-01	3,1E-02	8,7E-02	1,3E-02	8,1E-02	1,2E-02
Plant	Aubange	Cover crop restitution		mg kg ⁻¹	4,6E-01	1,1E+00	1,3E-01	5,3E-01	1,2E-01	2,7E-02	1,2E-01	1,7E-02	1,0E-01	1,9E-02	5,4E-02	8,0E-03	5,0E-02	7,3E-03
Solution	Vieusart	No application	05-05-21	µg L ⁻¹	6,6E-01	3,7E-01	8,2E-02	3,6E-01	5,9E-02	1,7E-02	7,3E-02	8,1E-03	6,1E-02	1,8E-02	6,8E-02	1,2E-02	9,7E-02	2,0E-02
Solution	Vieusart	Cattle manure	05-05-21	µg L ⁻¹	4,1E-01	2,6E-01	8,1E-02	4,5E-01	1,1E-01	3,7E-02	1,5E-01	2,5E-02	2,6E-01	8,5E-02	3,5E-01	6,1E-02	4,6E-01	8,7E-02
Solution	Vieusart	Green waste compost	05-05-21	µg L ⁻¹	1,8E+00	1,1E+00	2,5E-01	1,1E+00	2,0E-01	4,4E-02	2,4E-01	3,0E-02	2,6E-01	8,1E-02	3,8E-01	7,8E-02	6,7E-01	1,4E-01
Solution	Vieusart	Cover crop restitution	05-05-21	µg L ⁻¹	9,1E-01	5,4E-01	1,1E-01	4,8E-01	8,2E-02	2,3E-02	1,1E-01	1,4E-02	1,3E-01	4,5E-02	2,1E-01	4,1E-02	3,4E-01	6,7E-02
Solution	Vieusart	No plant	05-05-21	µg L ⁻¹	1,7E+00	1,1E+00	2,2E-01	8,8E-01	1,4E-01	3,3E-02	1,7E-01	1,8E-02	1,2E-01	2,8E-02	9,4E-02	1,5E-02	1,2E-01	2,5E-02
Solution	Sainte-Walburge	No application	05-05-21	µg L ⁻¹	1,8E-01	1,1E-01	2,7E-02	1,4E-01	3,9E-02	1,8E-02	6,4E-02	1,2E-02	1,3E-01	4,7E-02	2,2E-01	4,2E-02	3,4E-01	6,5E-02
Solution	Sainte-Walburge	Cattle manure	05-05-21	µg L ⁻¹	1,8E-01	1,4E-01	3,5E-02	1,9E-01	6,2E-02	2,7E-02	9,4E-02	1,2E-02	1,2E-01	4,0E-02	1,9E-01	3,7E-02	2,9E-01	5,7E-02
Solution	Sainte-Walburge	Green waste compost	05-05-21	µg L ⁻¹	1,5E-01	9,6E-02	2,9E-02	1,6E-01	4,6E-02	2,2E-02	7,0E-02	9,8E-03	9,4E-02	3,3E-02	1,6E-01	3,1E-02	2,5E-01	4,9E-02
Solution	Sainte-Walburge	Cover crop restitution	05-05-21	µg L ⁻¹	1,2E-01	7,7E-02	1,7E-02	9,4E-02	3,1E-02	2,5E-02	5,1E-02	7,2E-03	7,9E-02	3,0E-02	1,5E-01	3,0E-02	2,4E-01	4,8E-02
Solution	Sainte-Walburge	No plant	05-05-21	µg L ⁻¹	9,1E-02	3,9E-02	1,3E-02	7,2E-02	2,6E-02	1,7E-02	4,1E-02	5,3E-03	5,6E-02	2,0E-02	9,1E-02	1,7E-02	1,4E-01	2,7E-02

Solution	Bressoux	No application	05-05-21	µg L ⁻¹	9,8E-02	5,7E-02	1,3E-02	6,3E-02	1,9E-02	1,6E-02	2,7E-02	1,9E-03	1,3E-02	3,0E-03	1,2E-02	2,1E-03	1,9E-02	4,3E-03
Solution	Bressoux	Cattle manure	05-05-21	µg L ⁻¹	1,4E-01	9,4E-02	2,4E-02	1,3E-01	4,1E-02	2,8E-02	5,5E-02	4,0E-03	2,4E-02	5,7E-03	2,0E-02	3,4E-03	2,5E-02	5,4E-03
Solution	Bressoux	Green waste compost	05-05-21	µg L ⁻¹	1,7E-01	1,3E-01	2,8E-02	1,4E-01	3,7E-02	1,7E-02	4,9E-02	4,3E-03	2,8E-02	6,7E-03	2,5E-02	4,2E-03	3,6E-02	7,5E-03
Solution	Bressoux	Cover crop restitution	05-05-21	µg L ⁻¹	1,2E-01	8,4E-02	1,5E-02	7,2E-02	2,5E-02	2,1E-02	3,3E-02	2,3E-03	1,4E-02	3,4E-03	1,2E-02	2,2E-03	1,7E-02	3,7E-03
Solution	Bressoux	No plant	05-05-21	µg L ⁻¹	1,2E-01	7,4E-02	1,6E-02	7,7E-02	2,3E-02	1,3E-02	3,1E-02	2,5E-03	1,6E-02	4,0E-03	1,4E-02	2,5E-03	2,0E-02	4,5E-03
Solution	Aubange	No application	05-05-21	µg L ⁻¹	2,8E-01	9,3E-02	3,3E-02	1,6E-01	3,0E-02	7,6E-03	4,8E-02	9,8E-03	1,1E-01	3,8E-02	1,6E-01	3,0E-02	2,4E-01	4,5E-02
Solution	Aubange	Cattle manure	05-05-21	µg L ⁻¹	2,3E-01	1,2E-01	3,9E-02	1,9E-01	3,7E-02	8,5E-03	4,4E-02	5,7E-03	4,2E-02	1,1E-02	3,9E-02	6,4E-03	4,7E-02	9,2E-03
Solution	Aubange	Green waste compost	05-05-21	µg L ⁻¹	3,2E-01	1,5E-01	5,1E-02	2,6E-01	5,9E-02	1,5E-02	8,7E-02	1,8E-02	1,8E-01	5,5E-02	2,2E-01	3,9E-02	2,9E-01	5,6E-02
Solution	Aubange	Cover crop restitution	05-05-21	µg L ⁻¹	5,1E-01	2,9E-01	6,3E-02	2,8E-01	4,8E-02	1,2E-02	6,9E-02	1,2E-02	1,3E-01	4,9E-02	2,3E-01	4,5E-02	3,5E-01	6,5E-02
Solution	Aubange	No plant	05-05-21	µg L ⁻¹	6,3E-01	2,4E-01	6,9E-02	2,9E-01	4,9E-02	1,1E-02	7,1E-02	1,2E-02	1,2E-01	3,9E-02	1,6E-01	2,9E-02	2,2E-01	4,2E-02
Solution	Vieusart	No application	22-06-21	µg L ⁻¹	1,5E-01	7,5E-02	3,4E-02	1,8E-01	4,3E-02	1,1E-02	6,3E-02	1,5E-02	1,5E-01	5,1E-02	2,2E-01	3,9E-02	3,0E-01	5,9E-02
Solution	Vieusart	Cattle manure	22-06-21	µg L ⁻¹	8,4E-02	5,6E-02	2,9E-02	1,7E-01	4,3E-02	1,1E-02	6,7E-02	1,4E-02	1,6E-01	5,7E-02	2,6E-01	4,8E-02	3,7E-01	7,0E-02
Solution	Vieusart	Green waste compost	22-06-21	µg L ⁻¹	1,4E-01	8,5E-02	4,3E-02	2,5E-01	6,7E-02	1,8E-02	1,1E-01	2,5E-02	2,8E-01	9,7E-02	4,2E-01	7,5E-02	5,9E-01	1,1E-01
Solution	Vieusart	Cover crop restitution	22-06-21	µg L ⁻¹	1,1E-01	7,1E-02	2,9E-02	1,6E-01	3,8E-02	8,5E-03	5,3E-02	1,1E-02	1,1E-01	3,8E-02	1,6E-01	2,9E-02	2,3E-01	4,3E-02
Solution	Vieusart	No plant	22-06-21	µg L ⁻¹	3,8E-01	3,0E-01	6,7E-02	3,1E-01	5,8E-02	1,3E-02	7,3E-02	1,1E-02	9,9E-02	3,0E-02	1,3E-01	2,3E-02	1,8E-01	3,5E-02
Solution	Sainte-Walburge	No application	22-06-21	µg L ⁻¹	7,3E-02	2,8E-02	1,6E-02	9,3E-02	2,8E-02	5,8E-03	5,1E-02	1,2E-02	1,5E-01	5,9E-02	3,0E-01	6,1E-02	5,4E-01	1,2E-01
Solution	Sainte-Walburge	Cattle manure	22-06-21	µg L ⁻¹	1,3E-01	1,6E-01	2,9E-02	1,5E-01	4,3E-02	6,8E-03	6,7E-02	1,1E-02	1,2E-01	4,5E-02	2,1E-01	4,3E-02	3,7E-01	7,6E-02
Solution	Sainte-Walburge	Green waste compost	22-06-21	µg L ⁻¹	8,3E-02	3,8E-02	1,9E-02	1,1E-01	3,6E-02	7,6E-03	6,4E-02	1,3E-02	1,5E-01	5,8E-02	2,9E-01	5,7E-02	4,9E-01	1,0E-01
Solution	Sainte-Walburge	Cover crop restitution	22-06-21	µg L ⁻¹	6,3E-02	2,7E-02	1,2E-02	6,7E-02	2,3E-02	6,9E-03	3,9E-02	7,5E-03	8,3E-02	3,1E-02	1,5E-01	2,8E-02	2,3E-01	4,7E-02
Solution	Sainte-Walburge	No plant	22-06-21	µg L ⁻¹	4,6E-02	2,4E-02	9,0E-03	4,8E-02	1,4E-02	1,2E-04	2,0E-02	2,6E-03	2,2E-02	7,1E-03	3,2E-02	6,3E-03	5,7E-02	1,3E-02
Solution	Bressoux	No application	22-06-21	µg L ⁻¹	1,3E-01	7,8E-02	1,8E-02	8,7E-02	2,1E-02	2,5E-03	2,7E-02	3,3E-03	2,9E-02	9,2E-03	4,4E-02	9,3E-03	8,8E-02	2,0E-02
Solution	Bressoux	Cattle manure	22-06-21	µg L ⁻¹	8,9E-02	7,2E-02	1,7E-02	9,0E-02	2,6E-02	7,1E-03	3,4E-02	3,3E-03	2,2E-02	6,2E-03	2,7E-02	5,2E-03	4,5E-02	1,0E-02
Solution	Bressoux	Green waste compost	22-06-21	µg L ⁻¹	1,3E-01	1,0E-01	2,5E-02	1,3E-01	3,1E-02	4,4E-03	4,2E-02	5,6E-03	4,3E-02	1,4E-02	6,5E-02	1,3E-02	1,2E-01	2,7E-02
Solution	Bressoux	Cover crop restitution	22-06-21	µg L ⁻¹	8,7E-02	6,7E-02	1,4E-02	7,0E-02	1,7E-02	9,7E-04	2,3E-02	3,2E-03	2,5E-02	8,4E-03	3,9E-02	8,0E-03	7,4E-02	1,7E-02
Solution	Bressoux	No plant	22-06-21	µg L ⁻¹	6,3E-02	3,6E-02	8,9E-03	4,4E-02	1,4E-02	5,5E-03	1,9E-02	1,5E-03	9,5E-03	2,2E-03	9,2E-03	1,7E-03	1,4E-02	3,2E-03

Appendices

Solution	Aubange	No application	22-06-21	$\mu\text{g L}^{-1}$	2,0E-01	2,6E-01	3,7E-02	1,6E-01	3,1E-02	6,8E-03	3,6E-02	5,0E-03	3,4E-02	8,2E-03	2,8E-02	5,0E-03	3,9E-02	7,6E-03
Solution	Aubange	Cattle manure	22-06-21	$\mu\text{g L}^{-1}$	1,6E-01	8,7E-02	2,7E-02	1,2E-01	2,3E-02	5,1E-03	3,0E-02	4,2E-03	3,6E-02	1,1E-02	4,6E-02	8,9E-03	7,1E-02	1,5E-02
Solution	Aubange	Green waste compost	22-06-21	$\mu\text{g L}^{-1}$	1,9E-01	1,8E-01	3,3E-02	1,5E-01	3,0E-02	6,7E-03	4,0E-02	6,5E-03	6,4E-02	2,0E-02	8,1E-02	1,6E-02	1,3E-01	2,7E-02
Solution	Aubange	Cover crop restitution	22-06-21	$\mu\text{g L}^{-1}$	5,1E-01	3,1E-01	5,7E-02	2,4E-01	3,7E-02	8,6E-03	4,6E-02	6,1E-03	4,8E-02	1,5E-02	6,0E-02	1,2E-02	1,0E-01	2,2E-02
Solution	Aubange	No plant	22-06-21	$\mu\text{g L}^{-1}$	1,6E-01	4,0E-02	2,2E-02	9,5E-02	1,4E-02	3,3E-03	1,6E-02	2,0E-03	1,4E-02	4,0E-03	1,5E-02	2,7E-03	2,2E-02	4,7E-03
Tap water			19-05-21	$\mu\text{g L}^{-1}$	8,5E-03	3,7E-03	1,4E-03	6,6E-03	1,7E-03	3,5E-04	2,9E-03	3,1E-04	2,9E-03	7,7E-04	2,3E-03	4,5E-04	2,5E-03	3,3E-04

Table VI-6 - Standard deviations of rare earth element contents in soil and exogenous organic matter samples (n=2) and in plant parts and soil solution samples (n=3) for the greenhouse experiment.

Sample	Site	Modality	Date	Units	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Soil	Vieusart			mg kg ⁻¹	2,0E-01	4,7E-01	2,9E-03	1,2E-01	1,2E-02	2,9E-02	1,7E-01	1,5E-02	8,7E-02	2,7E-02	1,1E-01	1,8E-02	1,2E-01	1,5E-02
Soil	Sainte-Walburge			mg kg ⁻¹	8,2E+00	1,0E+01	1,4E+00	4,9E+00	1,1E+00	2,6E-01	1,3E+00	1,7E-01	9,4E-01	1,7E-01	6,0E-01	8,7E-02	6,3E-01	1,0E-01
Soil	Bressoux			mg kg ⁻¹	2,7E+00	6,0E+00	7,4E-01	3,1E+00	8,2E-01	1,9E-01	9,3E-01	1,3E-01	6,4E-01	1,3E-01	3,4E-01	6,4E-02	3,6E-01	5,4E-02
Soil	Aubange			mg kg ⁻¹	2,9E+00	9,8E+00	7,1E-01	2,9E+00	7,2E-01	1,5E-01	6,9E-01	9,6E-02	6,1E-01	1,1E-01	3,2E-01	8,1E-02	3,9E-01	4,1E-02
EOM		Cattle manure		mg kg ⁻¹	2,8E-01	9,5E-01	5,4E-02	2,3E-01	4,1E-02	9,2E-04	2,6E-02	3,2E-03	2,2E-02	9,2E-03	6,7E-03	1,4E-04	1,3E-03	2,3E-04
EOM		Green waste compost		mg kg ⁻¹	2,4E-01	3,5E-01	6,6E-02	1,8E-01	3,3E-02	8,8E-03	3,7E-02	4,7E-03	4,1E-02	4,9E-03	1,6E-02	2,9E-03	1,3E-02	4,9E-03
EOM		Cover crop restitution		mg kg ⁻¹	6,5E-02	1,2E-01	1,4E-02	5,2E-02	9,0E-03	1,1E-03	7,1E-03	6,9E-04	3,9E-03	6,7E-04	1,5E-03	1,0E-04	9,9E-04	1,5E-04
Roots	Vieusart	No application		mg kg ⁻¹	1,5E+00	3,4E+00	5,2E-01	2,1E+00	4,9E-01	1,1E-01	4,5E-01	6,3E-02	3,6E-01	6,2E-02	1,7E-01	2,6E-02	1,5E-01	2,1E-02
Roots	Vieusart	Cattle manure		mg kg ⁻¹	5,6E-01	1,1E+00	1,4E-01	5,5E-01	1,1E-01	1,7E-02	9,2E-02	1,1E-02	5,7E-02	9,9E-03	2,4E-02	3,5E-03	2,5E-02	3,5E-03
Roots	Vieusart	Green waste compost		mg kg ⁻¹	5,2E-01	1,1E+00	1,3E-01	5,4E-01	1,1E-01	3,0E-02	1,0E-01	1,6E-02	1,1E-01	2,3E-02	6,3E-02	8,5E-03	6,1E-02	1,0E-02
Roots	Vieusart	Cover crop restitution		mg kg ⁻¹	3,6E+00	7,1E+00	8,7E-01	3,4E+00	6,3E-01	1,1E-01	5,7E-01	7,1E-02	4,2E-01	7,8E-02	2,3E-01	3,3E-02	2,2E-01	3,5E-02
Roots	Sainte-Walburge	No application		mg kg ⁻¹	7,4E-01	1,5E+00	1,8E-01	6,8E-01	1,5E-01	2,6E-02	1,3E-01	1,8E-02	8,9E-02	1,8E-02	4,9E-02	8,6E-03	4,4E-02	7,1E-03
Roots	Sainte-Walburge	Cattle manure		mg kg ⁻¹	9,4E-01	1,8E+00	2,2E-01	8,6E-01	1,6E-01	2,9E-02	1,4E-01	2,0E-02	1,1E-01	2,3E-02	6,1E-02	9,4E-03	6,2E-02	9,0E-03
Roots	Sainte-Walburge	Green waste compost		mg kg ⁻¹	1,4E+00	3,0E+00	3,3E-01	1,3E+00	2,8E-01	6,7E-02	3,1E-01	4,4E-02	2,8E-01	5,7E-02	1,6E-01	2,4E-02	1,4E-01	2,2E-02
Roots	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	3,4E-01	6,2E-01	6,3E-02	2,5E-01	3,6E-02	1,5E-02	4,6E-02	5,3E-03	4,9E-02	5,4E-02	2,3E-02	3,9E-03	3,7E-02	4,3E-03
Roots	Bressoux	No application		mg kg ⁻¹	2,0E-01	4,3E-01	4,9E-02	1,8E-01	3,7E-02	8,1E-03	3,7E-02	5,3E-03	3,0E-02	5,5E-03	1,8E-02	2,5E-03	1,6E-02	2,4E-03
Roots	Bressoux	Cattle manure		mg kg ⁻¹	5,1E-01	1,0E+00	1,2E-01	4,6E-01	9,0E-02	1,5E-02	8,6E-02	1,1E-02	6,1E-02	1,1E-02	3,1E-02	4,0E-03	2,8E-02	3,9E-03
Roots	Bressoux	Green waste compost		mg kg ⁻¹	4,8E-01	9,6E-01	1,1E-01	4,4E-01	8,6E-02	1,7E-02	8,0E-02	9,5E-03	5,1E-02	9,4E-03	2,6E-02	4,4E-03	2,7E-02	4,2E-03
Roots	Bressoux	Cover crop restitution		mg kg ⁻¹	1,5E+00	2,9E+00	3,5E-01	1,4E+00	2,7E-01	5,3E-02	2,7E-01	3,2E-02	1,8E-01	3,3E-02	9,4E-02	1,3E-02	8,4E-02	1,2E-02
Roots	Aubange	No application		mg kg ⁻¹	3,0E-01	1,2E+00	9,1E-02	3,7E-01	9,6E-02	2,8E-02	1,3E-01	2,3E-02	1,5E-01	3,0E-02	8,9E-02	1,4E-02	8,6E-02	1,3E-02
Roots	Aubange	Cattle manure		mg kg ⁻¹	6,6E-01	2,0E+00	2,0E-01	7,8E-01	1,8E-01	4,4E-02	1,8E-01	2,7E-02	1,7E-01	3,0E-02	8,7E-02	1,3E-02	8,2E-02	1,3E-02
Roots	Aubange	Green waste compost		mg kg ⁻¹	2,3E+00	9,6E+00	6,8E-01	2,7E+00	6,2E-01	1,4E-01	6,5E-01	9,2E-02	5,5E-01	1,0E-01	2,9E-01	4,3E-02	2,7E-01	3,7E-02

Appendices

Roots	Aubange	Cover crop restitution	mg kg ⁻¹	3,8E-01	1,0E+00	1,1E-01	4,5E-01	1,1E-01	2,5E-02	1,1E-01	1,4E-02	8,5E-02	1,9E-02	4,9E-02	7,6E-03	5,4E-02	7,9E-03
Stems	Vieusart	No application	mg kg ⁻¹	1,5E-02	2,7E-02	3,0E-03	1,0E-02	8,1E-04	3,2E-04	1,7E-03	6,5E-05	4,4E-04	8,3E-05	1,0E-04	1,2E-05	2,8E-04	6,3E-05
Stems	Vieusart	Cattle manure	mg kg ⁻¹	4,8E-03	8,4E-03	1,1E-03	4,2E-03	5,7E-04	1,7E-04	4,4E-04	2,9E-05	5,4E-04	1,0E-04	4,1E-04	6,3E-05	3,8E-04	7,4E-05
Stems	Vieusart	Green waste compost	mg kg ⁻¹	3,0E-03	5,8E-03	7,5E-04	2,5E-03	5,7E-04	1,1E-04	3,1E-04	2,7E-05	1,5E-04	2,9E-05	1,4E-04	2,3E-05	1,5E-04	1,1E-05
Stems	Vieusart	Cover crop restitution	mg kg ⁻¹	1,0E-02	2,0E-02	2,6E-03	1,0E-02	1,9E-03	3,9E-04	2,1E-03	4,2E-04	2,7E-03	6,2E-04	1,7E-03	2,3E-04	1,5E-03	2,3E-04
Stems	Sainte-Walburge	No application	mg kg ⁻¹	9,0E-03	1,9E-02	2,3E-03	1,0E-02	1,8E-03	3,9E-04	1,3E-03	2,6E-04	1,5E-03	2,7E-04	7,8E-04	1,4E-04	9,3E-04	1,7E-04
Stems	Sainte-Walburge	Cattle manure	mg kg ⁻¹	3,8E-03	7,3E-03	1,0E-03	3,6E-03	1,1E-03	3,5E-04	1,0E-03	2,0E-04	9,1E-04	1,3E-04	6,4E-04	8,0E-05	4,3E-04	7,6E-05
Stems	Sainte-Walburge	Green waste compost	mg kg ⁻¹	3,2E-03	6,3E-03	7,7E-04	3,1E-03	8,1E-04	1,9E-04	4,7E-04	6,8E-05	5,2E-04	9,4E-05	2,6E-04	4,2E-05	3,8E-04	3,9E-05
Stems	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	3,2E-03	7,2E-03	8,1E-04	3,4E-03	8,4E-04	1,1E-04	4,0E-04	6,8E-05	3,8E-04	1,2E-04	2,2E-04	3,4E-05	1,7E-04	5,9E-05
Stems	Bressoux	No application	mg kg ⁻¹	8,6E-03	1,6E-02	1,8E-03	6,3E-03	1,3E-03	2,3E-04	1,7E-03	1,8E-04	1,5E-03	2,7E-04	8,0E-04	6,2E-05	5,4E-04	9,3E-05
Stems	Bressoux	Cattle manure	mg kg ⁻¹	5,5E-03	1,1E-02	1,4E-03	5,5E-03	1,2E-03	2,5E-04	8,3E-04	1,0E-04	6,7E-04	7,1E-05	2,3E-04	3,5E-05	2,7E-04	4,5E-05
Stems	Bressoux	Green waste compost	mg kg ⁻¹	3,1E-03	5,5E-03	6,7E-04	2,5E-03	3,1E-04	1,7E-04	6,7E-04	8,2E-05	3,4E-04	8,7E-05	2,8E-04	2,1E-05	1,7E-04	4,5E-05
Stems	Bressoux	Cover crop restitution	mg kg ⁻¹	1,4E-02	3,0E-02	3,8E-03	1,4E-02	2,6E-03	3,0E-04	2,5E-03	3,1E-04	1,6E-03	2,3E-04	5,8E-04	8,1E-05	5,8E-04	8,8E-05
Stems	Aubange	No application	mg kg ⁻¹	1,5E-02	3,9E-02	4,2E-03	1,6E-02	4,0E-03	8,4E-04	3,8E-03	5,8E-04	3,7E-03	7,3E-04	1,9E-03	3,1E-04	1,9E-03	2,8E-04
Stems	Aubange	Cattle manure	mg kg ⁻¹	9,4E-03	2,4E-02	3,0E-03	1,2E-02	2,9E-03	7,1E-04	2,7E-03	3,2E-04	2,3E-03	4,3E-04	1,1E-03	1,5E-04	1,1E-03	1,9E-04
Stems	Aubange	Green waste compost	mg kg ⁻¹	8,9E-03	1,6E-02	2,4E-03	1,0E-02	1,9E-03	3,0E-04	2,7E-03	3,1E-04	1,9E-03	3,9E-04	1,1E-03	1,6E-04	1,0E-03	1,6E-04
Stems	Aubange	Cover crop restitution	mg kg ⁻¹	1,3E-02	2,9E-02	3,5E-03	1,3E-02	3,2E-03	9,4E-04	3,3E-03	4,7E-04	2,7E-03	5,7E-04	1,5E-03	2,1E-04	1,3E-03	2,1E-04
Leaves	Vieusart	No application	mg kg ⁻¹	9,1E-03	1,7E-02	1,9E-03	8,3E-03	1,4E-03	4,7E-04	1,3E-03	2,9E-04	1,3E-03	3,0E-04	8,9E-04	1,1E-04	9,6E-04	1,8E-04
Leaves	Vieusart	Cattle manure	mg kg ⁻¹	1,4E-02	3,0E-02	2,7E-03	1,0E-02	2,9E-03	4,6E-04	2,5E-03	2,6E-04	1,7E-03	2,4E-04	7,9E-04	1,4E-04	6,0E-04	6,9E-05
Leaves	Vieusart	Green waste compost	mg kg ⁻¹	1,8E-02	3,6E-02	4,4E-03	1,5E-02	2,9E-03	5,1E-04	2,4E-03	2,9E-04	1,4E-03	3,3E-04	7,9E-04	1,5E-04	7,4E-04	1,3E-04
Leaves	Vieusart	Cover crop restitution	mg kg ⁻¹	2,8E-02	5,5E-02	6,1E-03	2,5E-02	3,4E-03	4,8E-04	3,0E-03	3,5E-04	1,8E-03	3,0E-04	6,9E-04	6,3E-05	9,0E-04	6,8E-05
Leaves	Sainte-Walburge	No application	mg kg ⁻¹	2,2E-02	4,9E-02	6,1E-03	2,5E-02	5,7E-03	5,6E-05	4,1E-03	3,5E-04	2,1E-03	2,3E-04	5,3E-04	8,4E-05	4,2E-04	4,9E-05
Leaves	Sainte-Walburge	Cattle manure	mg kg ⁻¹	6,6E-03	1,2E-02	1,6E-03	5,2E-03	8,4E-04	3,8E-04	1,5E-03	1,8E-04	1,3E-03	2,8E-04	6,7E-04	1,4E-04	6,5E-04	7,1E-05
Leaves	Sainte-Walburge	Green waste compost	mg kg ⁻¹	3,7E-03	4,4E-03	3,4E-04	1,7E-03	1,9E-04	1,6E-04	6,8E-04	6,1E-05	2,2E-04	4,3E-05	5,7E-05	9,9E-05	2,2E-04	2,1E-05
Leaves	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	5,2E-03	1,0E-02	1,3E-03	3,7E-03	5,1E-04	1,4E-04	8,7E-04	9,9E-05	5,5E-04	1,6E-04	1,8E-04	1,5E-04	1,9E-04	1,2E-04

Leaves	Bressoux	No application	mg kg ⁻¹	8,4E-03	1,8E-02	1,4E-03	4,3E-03	4,2E-04	7,8E-05	9,7E-04	1,3E-04	2,6E-04	1,2E-04	2,1E-04	3,0E-05	3,5E-04	1,1E-04
Leaves	Bressoux	Cattle manure	mg kg ⁻¹	2,4E-03	3,8E-03	4,5E-04	2,3E-03	1,8E-04	1,2E-04	2,2E-04	5,3E-05	2,4E-04	6,5E-05	1,4E-04	3,3E-05	2,2E-04	2,2E-05
Leaves	Bressoux	Green waste compost	mg kg ⁻¹	3,6E-02	7,8E-02	1,1E-02	3,9E-02	8,8E-03	7,0E-04	7,0E-03	5,6E-04	2,7E-03	3,3E-04	7,8E-04	1,1E-04	5,7E-04	6,8E-05
Leaves	Bressoux	Cover crop restitution	mg kg ⁻¹	5,1E-03	1,0E-02	1,3E-03	4,3E-03	1,1E-03	1,6E-04	7,5E-04	1,1E-04	1,1E-03	2,1E-04	7,7E-04	1,3E-04	5,7E-04	7,1E-05
Leaves	Aubange	No application	mg kg ⁻¹	1,5E-02	2,7E-02	2,8E-03	1,2E-02	1,8E-03	3,9E-04	1,3E-03	2,1E-04	1,1E-03	1,8E-04	6,5E-04	1,0E-04	5,7E-04	7,6E-05
Leaves	Aubange	Cattle manure	mg kg ⁻¹	6,2E-03	1,3E-02	1,4E-03	6,3E-03	1,9E-03	3,4E-04	1,8E-03	3,0E-04	1,8E-03	4,1E-04	9,6E-04	1,3E-04	7,8E-04	7,1E-05
Leaves	Aubange	Green waste compost	mg kg ⁻¹	1,1E-03	7,6E-04	2,2E-04	1,0E-03	3,5E-04	6,5E-05	2,4E-04	7,7E-05	3,3E-04	5,4E-05	3,9E-05	4,5E-05	1,1E-04	5,2E-05
Leaves	Aubange	Cover crop restitution	mg kg ⁻¹	1,1E-02	2,8E-02	3,1E-03	1,4E-02	3,1E-03	6,6E-04	2,8E-03	2,2E-04	1,4E-03	2,9E-04	6,5E-04	1,1E-04	4,0E-04	7,2E-05
Shoots	Vieusart	No application	mg kg ⁻¹	8,6E-03	1,6E-02	1,9E-03	6,9E-03	3,0E-04	1,9E-04	1,1E-03	6,6E-05	7,0E-04	1,4E-04	3,6E-04	3,3E-05	4,8E-04	9,7E-05
Shoots	Vieusart	Cattle manure	mg kg ⁻¹	5,2E-03	1,1E-02	1,1E-03	4,0E-03	9,6E-04	2,4E-04	7,6E-04	8,4E-05	7,1E-04	9,7E-05	3,3E-04	7,9E-05	3,8E-04	5,3E-05
Shoots	Vieusart	Green waste compost	mg kg ⁻¹	8,1E-03	1,6E-02	1,9E-03	6,7E-03	1,3E-03	2,4E-04	1,0E-03	1,1E-04	5,2E-04	9,7E-05	2,4E-04	4,9E-05	1,3E-04	4,0E-05
Shoots	Vieusart	Cover crop restitution	mg kg ⁻¹	8,6E-03	1,8E-02	2,0E-03	8,5E-03	1,5E-03	1,5E-04	1,2E-03	2,5E-04	1,3E-03	3,2E-04	9,3E-04	1,4E-04	7,4E-04	1,3E-04
Shoots	Sainte-Walburge	No application	mg kg ⁻¹	1,4E-02	3,0E-02	3,7E-03	1,6E-02	3,2E-03	2,2E-04	2,2E-03	2,9E-04	1,7E-03	2,5E-04	6,5E-04	9,6E-05	7,1E-04	9,2E-05
Shoots	Sainte-Walburge	Cattle manure	mg kg ⁻¹	3,0E-03	5,8E-03	7,8E-04	2,6E-03	8,4E-04	2,2E-04	5,5E-04	1,0E-04	6,2E-04	9,7E-05	4,0E-04	4,0E-05	2,7E-04	3,0E-05
Shoots	Sainte-Walburge	Green waste compost	mg kg ⁻¹	2,8E-03	4,3E-03	4,2E-04	1,7E-03	4,7E-04	1,8E-04	1,3E-04	6,7E-05	2,6E-04	8,0E-05	1,7E-04	6,0E-05	1,8E-04	2,8E-05
Shoots	Sainte-Walburge	Cover crop restitution	mg kg ⁻¹	1,3E-03	2,2E-03	3,7E-04	6,6E-04	3,7E-04	4,2E-05	4,6E-04	4,7E-05	2,7E-04	9,7E-05	1,8E-04	7,6E-05	1,1E-04	7,4E-05
Shoots	Bressoux	No application	mg kg ⁻¹	7,4E-03	1,4E-02	1,3E-03	4,8E-03	8,5E-04	1,6E-04	1,3E-03	1,5E-04	9,6E-04	2,0E-04	5,5E-04	4,9E-05	4,2E-04	1,0E-04
Shoots	Bressoux	Cattle manure	mg kg ⁻¹	4,6E-03	8,5E-03	1,1E-03	4,4E-03	7,8E-04	1,4E-04	6,2E-04	8,8E-05	3,8E-04	2,5E-05	1,4E-04	2,1E-05	1,1E-04	3,7E-05
Shoots	Bressoux	Green waste compost	mg kg ⁻¹	1,7E-02	3,7E-02	4,9E-03	1,8E-02	3,9E-03	3,3E-04	3,1E-03	3,0E-04	1,3E-03	1,7E-04	4,7E-04	6,4E-05	3,3E-04	3,7E-05
Shoots	Bressoux	Cover crop restitution	mg kg ⁻¹	9,5E-03	2,0E-02	2,6E-03	9,1E-03	1,9E-03	2,4E-04	1,7E-03	2,1E-04	1,2E-03	2,0E-04	5,3E-04	8,9E-05	5,2E-04	7,4E-05
Shoots	Aubange	No application	mg kg ⁻¹	1,5E-02	3,4E-02	3,7E-03	1,4E-02	3,2E-03	6,1E-04	2,8E-03	4,5E-04	2,7E-03	5,3E-04	1,4E-03	2,3E-04	1,4E-03	2,1E-04
Shoots	Aubange	Cattle manure	mg kg ⁻¹	7,9E-03	1,8E-02	2,3E-03	9,2E-03	2,4E-03	5,6E-04	2,3E-03	3,0E-04	2,0E-03	4,1E-04	9,6E-04	1,4E-04	9,6E-04	1,4E-04
Shoots	Aubange	Green waste compost	mg kg ⁻¹	5,8E-03	1,0E-02	1,5E-03	6,4E-03	1,1E-03	1,7E-04	1,8E-03	1,9E-04	1,2E-03	2,3E-04	6,9E-04	9,2E-05	6,3E-04	1,2E-04
Shoots	Aubange	Cover crop restitution	mg kg ⁻¹	5,3E-03	1,1E-02	1,6E-03	6,4E-03	1,7E-03	5,5E-04	1,7E-03	3,2E-04	1,6E-03	4,1E-04	1,1E-03	1,6E-04	9,4E-04	1,5E-04
Plant	Vieusart	No application	mg kg ⁻¹	4,2E-01	9,2E-01	1,3E-01	5,3E-01	1,2E-01	2,5E-02	1,1E-01	1,5E-02	8,5E-02	1,5E-02	4,2E-02	6,3E-03	3,8E-02	5,4E-03

Appendices

Plant	Vieusart	Cattle manure		mg kg ⁻¹	1,3E-01	2,5E-01	3,0E-02	1,1E-01	2,3E-02	3,6E-03	2,0E-02	2,4E-03	1,3E-02	2,4E-03	6,5E-03	9,5E-04	6,4E-03	8,9E-04
Plant	Vieusart	Green waste compost		mg kg ⁻¹	1,6E-01	3,3E-01	4,0E-02	1,6E-01	3,2E-02	7,7E-03	3,0E-02	4,3E-03	2,7E-02	5,8E-03	1,6E-02	2,2E-03	1,5E-02	2,5E-03
Plant	Vieusart	Cover crop restitution		mg kg ⁻¹	6,9E-01	1,4E+00	1,7E-01	6,3E-01	1,2E-01	2,2E-02	1,1E-01	1,3E-02	8,1E-02	1,5E-02	4,4E-02	6,3E-03	4,3E-02	6,6E-03
Plant	Sainte-Walburge	No application		mg kg ⁻¹	1,2E-01	2,4E-01	2,9E-02	1,1E-01	2,4E-02	4,6E-03	2,2E-02	2,9E-03	1,5E-02	3,1E-03	8,5E-03	1,4E-03	7,7E-03	1,2E-03
Plant	Sainte-Walburge	Cattle manure		mg kg ⁻¹	9,9E-02	1,9E-01	2,3E-02	9,0E-02	1,7E-02	2,9E-03	1,4E-02	2,1E-03	1,2E-02	2,3E-03	6,3E-03	9,8E-04	6,6E-03	9,7E-04
Plant	Sainte-Walburge	Green waste compost		mg kg ⁻¹	2,2E-01	4,6E-01	5,2E-02	2,0E-01	4,3E-02	1,0E-02	4,7E-02	6,6E-03	4,1E-02	8,4E-03	2,3E-02	3,5E-03	2,1E-02	3,3E-03
Plant	Sainte-Walburge	Cover crop restitution		mg kg ⁻¹	7,8E-02	1,5E-01	1,8E-02	7,2E-02	1,3E-02	3,5E-03	1,4E-02	1,7E-03	1,2E-02	6,0E-03	5,8E-03	9,5E-04	5,8E-03	8,2E-04
Plant	Bressoux	No application		mg kg ⁻¹	2,7E-02	5,9E-02	6,6E-03	2,5E-02	4,9E-03	1,0E-03	4,4E-03	5,6E-04	3,3E-03	5,9E-04	1,9E-03	2,4E-04	1,7E-03	2,4E-04
Plant	Bressoux	Cattle manure		mg kg ⁻¹	7,1E-02	1,4E-01	1,6E-02	6,3E-02	1,2E-02	2,1E-03	1,2E-02	1,5E-03	8,4E-03	1,6E-03	4,2E-03	5,7E-04	3,9E-03	5,7E-04
Plant	Bressoux	Green waste compost		mg kg ⁻¹	6,0E-02	1,2E-01	1,5E-02	5,6E-02	1,1E-02	2,2E-03	1,1E-02	1,2E-03	6,9E-03	1,3E-03	3,6E-03	5,8E-04	3,5E-03	5,3E-04
Plant	Bressoux	Cover crop restitution		mg kg ⁻¹	2,8E-01	5,3E-01	6,5E-02	2,5E-01	5,1E-02	9,7E-03	4,9E-02	5,9E-03	3,3E-02	6,1E-03	1,7E-02	2,4E-03	1,5E-02	2,2E-03
Plant	Aubange	No application		mg kg ⁻¹	7,9E-02	2,6E-01	2,5E-02	1,0E-01	2,5E-02	6,8E-03	3,2E-02	5,1E-03	3,2E-02	6,4E-03	1,9E-02	2,9E-03	1,8E-02	2,6E-03
Plant	Aubange	Cattle manure		mg kg ⁻¹	1,0E-01	2,9E-01	2,9E-02	1,2E-01	2,7E-02	6,6E-03	2,8E-02	4,1E-03	2,5E-02	4,6E-03	1,3E-02	2,0E-03	1,3E-02	1,9E-03
Plant	Aubange	Green waste compost		mg kg ⁻¹	3,2E-01	1,3E+00	9,3E-02	3,7E-01	8,5E-02	1,9E-02	8,9E-02	1,3E-02	7,6E-02	1,4E-02	3,9E-02	5,9E-03	3,7E-02	5,1E-03
Plant	Aubange	Cover crop restitution		mg kg ⁻¹	2,2E-02	7,4E-02	6,4E-03	3,0E-02	8,6E-03	1,8E-03	7,1E-03	7,8E-04	5,1E-03	1,3E-03	3,2E-03	5,4E-04	4,0E-03	5,7E-04
Solution	Vieusart	No application	05-05-21	µg L ⁻¹	3,6E-01	2,0E-01	3,3E-02	1,3E-01	1,6E-02	9,2E-03	1,8E-02	1,5E-03	7,2E-03	2,4E-03	1,1E-02	2,8E-03	2,4E-02	6,0E-03
Solution	Vieusart	Cattle manure	05-05-21	µg L ⁻¹	1,1E-01	2,3E-02	4,2E-03	2,2E-02	2,6E-03	1,3E-02	1,1E-02	3,0E-03	4,5E-02	1,7E-02	6,8E-02	1,2E-02	9,3E-02	1,9E-02
Solution	Vieusart	Green waste compost	05-05-21	µg L ⁻¹	1,9E+00	1,2E+00	2,3E-01	9,6E-01	1,6E-01	3,6E-02	1,9E-01	2,4E-02	1,9E-01	6,0E-02	3,0E-01	7,1E-02	6,6E-01	1,4E-01
Solution	Vieusart	Cover crop restitution	05-05-21	µg L ⁻¹	5,1E-01	3,0E-01	5,6E-02	2,4E-01	4,1E-02	8,2E-03	5,5E-02	9,5E-03	1,1E-01	4,3E-02	2,2E-01	4,3E-02	3,7E-01	7,2E-02
Solution	Vieusart	No plant	05-05-21	µg L ⁻¹	2,3E+00	1,5E+00	2,7E-01	1,0E+00	1,4E-01	2,9E-02	1,8E-01	1,7E-02	9,1E-02	1,8E-02	4,9E-02	7,4E-03	6,0E-02	1,4E-02
Solution	Sainte-Walburge	No application	05-05-21	µg L ⁻¹	4,3E-02	5,9E-02	9,6E-03	4,3E-02	9,7E-03	2,6E-03	1,4E-02	3,0E-03	3,5E-02	1,1E-02	4,6E-02	7,5E-03	4,7E-02	8,4E-03
Solution	Sainte-Walburge	Cattle manure	05-05-21	µg L ⁻¹	5,5E-02	6,1E-02	1,2E-02	6,0E-02	1,6E-02	1,2E-02	2,8E-02	3,6E-03	3,7E-02	1,4E-02	6,7E-02	1,4E-02	1,2E-01	2,3E-02
Solution	Sainte-Walburge	Green waste compost	05-05-21	µg L ⁻¹	2,4E-02	3,4E-02	4,8E-03	2,7E-02	6,1E-03	1,1E-02	1,2E-02	2,4E-03	3,0E-02	1,3E-02	7,4E-02	1,6E-02	1,5E-01	2,9E-02
Solution	Sainte-Walburge	Cover crop restitution	05-05-21	µg L ⁻¹	3,3E-02	2,7E-02	5,0E-03	2,5E-02	5,3E-03	1,3E-02	1,3E-02	3,1E-03	3,7E-02	1,6E-02	8,4E-02	1,7E-02	1,5E-01	2,8E-02
Solution	Sainte-Walburge	No plant	05-05-21	µg L ⁻¹	3,1E-02	1,2E-02	3,6E-03	1,8E-02	4,7E-03	3,2E-03	7,9E-03	1,4E-03	1,7E-02	7,0E-03	3,6E-02	6,5E-03	5,4E-02	9,7E-03

Solution	Bressoux	No application	05-05-21	µg L ⁻¹	7,6E-03	6,4E-03	4,8E-04	2,5E-03	8,4E-04	7,2E-03	2,2E-03	7,9E-05	3,7E-04	2,8E-04	1,4E-03	1,8E-04	3,3E-03	7,7E-04
Solution	Bressoux	Cattle manure	05-05-21	µg L ⁻¹	8,6E-03	4,6E-03	5,0E-04	2,7E-03	1,9E-03	2,2E-02	7,0E-03	2,9E-04	1,2E-03	4,8E-04	2,5E-03	6,3E-04	6,9E-03	1,5E-03
Solution	Bressoux	Green waste compost	05-05-21	µg L ⁻¹	4,7E-02	3,2E-02	5,5E-03	2,5E-02	5,7E-03	8,4E-03	9,0E-03	3,2E-04	4,0E-03	9,6E-04	4,2E-03	8,9E-04	9,0E-03	1,8E-03
Solution	Bressoux	Cover crop restitution	05-05-21	µg L ⁻¹	3,1E-02	5,1E-02	5,6E-03	2,3E-02	3,2E-03	1,1E-02	4,0E-03	8,5E-04	6,0E-03	1,2E-03	5,6E-03	1,3E-03	1,0E-02	2,0E-03
Solution	Bressoux	No plant	05-05-21	µg L ⁻¹	3,8E-02	3,1E-02	6,3E-03	2,7E-02	5,5E-03	2,5E-03	7,9E-03	1,0E-03	7,6E-03	1,8E-03	6,2E-03	9,2E-04	6,1E-03	1,4E-03
Solution	Aubange	No application	05-05-21	µg L ⁻¹	1,6E-01	5,0E-02	2,0E-02	9,6E-02	2,0E-02	5,8E-03	3,9E-02	9,0E-03	1,1E-01	4,2E-02	1,8E-01	3,5E-02	2,7E-01	5,1E-02
Solution	Aubange	Cattle manure	05-05-21	µg L ⁻¹	1,3E-01	6,5E-02	1,9E-02	9,3E-02	1,8E-02	4,0E-03	2,1E-02	3,1E-03	2,8E-02	8,0E-03	3,0E-02	5,1E-03	3,8E-02	7,4E-03
Solution	Aubange	Green waste compost	05-05-21	µg L ⁻¹	3,1E-01	1,6E-01	4,4E-02	2,2E-01	5,6E-02	1,6E-02	9,4E-02	2,2E-02	2,4E-01	7,7E-02	3,2E-01	5,5E-02	4,2E-01	8,0E-02
Solution	Aubange	Cover crop restitution	05-05-21	µg L ⁻¹	5,0E-01	3,3E-01	6,2E-02	2,7E-01	4,4E-02	1,1E-02	6,5E-02	1,2E-02	1,3E-01	5,3E-02	2,7E-01	5,3E-02	4,3E-01	8,0E-02
Solution	Aubange	No plant	05-05-21	µg L ⁻¹	4,9E-01	1,9E-01	5,4E-02	2,3E-01	3,8E-02	9,0E-03	5,5E-02	9,9E-03	1,0E-01	3,4E-02	1,4E-01	2,5E-02	1,9E-01	3,6E-02
Solution	Vieusart	No application	22-06-21	µg L ⁻¹	2,5E-02	1,8E-02	3,4E-03	1,7E-02	4,5E-03	9,5E-04	7,6E-03	3,0E-03	3,1E-02	1,2E-02	4,6E-02	8,5E-03	6,1E-02	1,1E-02
Solution	Vieusart	Cattle manure	22-06-21	µg L ⁻¹	2,0E-02	1,7E-02	7,1E-03	4,4E-02	1,2E-02	4,1E-03	1,6E-02	3,9E-03	4,6E-02	1,5E-02	6,2E-02	1,0E-02	7,7E-02	1,5E-02
Solution	Vieusart	Green waste compost	22-06-21	µg L ⁻¹	6,2E-02	4,2E-02	1,8E-02	1,1E-01	2,9E-02	7,9E-03	4,7E-02	1,2E-02	1,4E-01	5,2E-02	2,4E-01	4,3E-02	3,5E-01	6,6E-02
Solution	Vieusart	Cover crop restitution	22-06-21	µg L ⁻¹	5,0E-02	4,3E-02	1,2E-02	5,9E-02	1,2E-02	2,2E-03	1,4E-02	2,3E-03	2,4E-02	8,8E-03	3,9E-02	7,3E-03	6,0E-02	1,2E-02
Solution	Vieusart	No plant	22-06-21	µg L ⁻¹	4,2E-01	3,9E-01	6,2E-02	2,5E-01	3,9E-02	8,7E-03	4,4E-02	5,0E-03	2,8E-02	6,8E-03	2,1E-02	3,0E-03	2,7E-02	5,0E-03
Solution	Sainte-Walburge	No application	22-06-21	µg L ⁻¹	3,1E-02	8,2E-03	6,8E-03	3,8E-02	1,2E-02	4,2E-03	2,8E-02	7,4E-03	1,0E-01	4,2E-02	2,2E-01	4,6E-02	4,1E-01	8,8E-02
Solution	Sainte-Walburge	Cattle manure	22-06-21	µg L ⁻¹	1,1E-01	1,8E-01	2,5E-02	1,2E-01	3,0E-02	3,5E-03	4,2E-02	7,2E-03	7,9E-02	3,2E-02	1,5E-01	3,0E-02	2,7E-01	5,6E-02
Solution	Sainte-Walburge	Green waste compost	22-06-21	µg L ⁻¹	2,9E-02	8,2E-03	5,8E-03	3,6E-02	1,4E-02	5,6E-03	2,9E-02	7,0E-03	8,6E-02	3,4E-02	1,7E-01	3,3E-02	2,8E-01	5,9E-02
Solution	Sainte-Walburge	Cover crop restitution	22-06-21	µg L ⁻¹	7,3E-03	2,4E-03	7,9E-04	3,2E-03	9,2E-05	2,4E-03	4,5E-03	2,4E-03	3,2E-02	1,4E-02	6,7E-02	1,3E-02	1,0E-01	2,1E-02
Solution	Sainte-Walburge	No plant	22-06-21	µg L ⁻¹	6,2E-03	3,1E-03	1,2E-03	5,2E-03	1,4E-03	1,8E-04	2,3E-03	4,0E-04	3,6E-03	1,1E-03	6,7E-03	1,2E-03	1,2E-02	2,3E-03
Solution	Bressoux	No application	22-06-21	µg L ⁻¹	6,5E-02	3,2E-02	6,1E-03	2,7E-02	4,5E-03	2,7E-03	6,7E-03	1,2E-03	1,1E-02	3,5E-03	1,9E-02	4,3E-03	4,2E-02	9,3E-03
Solution	Bressoux	Cattle manure	22-06-21	µg L ⁻¹	3,0E-02	2,6E-02	4,3E-03	2,1E-02	6,8E-03	1,9E-03	8,1E-03	6,9E-04	3,3E-03	7,9E-04	3,3E-03	6,9E-04	5,6E-03	1,3E-03
Solution	Bressoux	Green waste compost	22-06-21	µg L ⁻¹	4,4E-02	2,8E-02	5,4E-03	2,4E-02	4,1E-03	1,6E-03	6,3E-03	5,4E-04	7,3E-03	2,6E-03	1,4E-02	2,9E-03	2,9E-02	6,5E-03
Solution	Bressoux	Cover crop restitution	22-06-21	µg L ⁻¹	2,1E-02	3,9E-03	7,1E-04	7,8E-03	3,5E-03	1,4E-03	4,9E-03	6,3E-04	3,7E-03	1,8E-03	9,8E-03	1,9E-03	1,7E-02	4,3E-03
Solution	Bressoux	No plant	22-06-21	µg L ⁻¹	5,9E-03	2,1E-03	3,6E-04	4,6E-03	8,3E-04	9,5E-04	1,5E-03	2,4E-04	1,2E-03	5,3E-04	2,9E-03	4,0E-04	4,4E-03	1,1E-03

Appendices

Solution	Aubange	No application	22-06-21	µg L ⁻¹	2,3E-01	3,9E-01	4,9E-02	2,1E-01	4,0E-02	8,7E-03	4,4E-02	5,9E-03	3,7E-02	7,8E-03	2,4E-02	4,1E-03	3,3E-02	6,8E-03
Solution	Aubange	Cattle manure	22-06-21	µg L ⁻¹	1,1E-01	4,1E-02	1,1E-02	4,4E-02	6,2E-03	1,6E-03	7,1E-03	1,2E-03	1,9E-02	7,0E-03	3,6E-02	7,0E-03	6,1E-02	1,3E-02
Solution	Aubange	Green waste compost	22-06-21	µg L ⁻¹	1,8E-01	1,8E-01	2,1E-02	8,9E-02	1,4E-02	3,3E-03	2,0E-02	4,2E-03	4,7E-02	1,4E-02	6,2E-02	1,2E-02	9,9E-02	2,2E-02
Solution	Aubange	Cover crop restitution	22-06-21	µg L ⁻¹	3,7E-01	2,5E-01	3,5E-02	1,4E-01	1,7E-02	4,7E-03	2,6E-02	3,1E-03	2,3E-02	7,7E-03	3,1E-02	6,9E-03	5,9E-02	1,4E-02
Solution	Aubange	No plant	22-06-21	µg L ⁻¹	9,3E-02	1,7E-02	8,8E-03	3,5E-02	3,5E-03	1,1E-03	5,0E-03	5,4E-04	2,8E-03	7,0E-04	4,8E-03	7,4E-04	8,2E-03	1,6E-03
Tap water			19-05-21	µg L ⁻¹	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table VI-7 – Trace element contents in soil water-extracts and BCR fractions for the four soils (2 replicates).

Extraction	Site	Extracting solution	Targeted fraction	Unit	Sc	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	As	Se	Sr	Mo	Cd	Sn	Sb	Ba	Pb
Water extraction	Vieusart	Milli-Q water	Exchangeable	mg kg ⁻¹	3,9E-04	4,3E-02	1,1E-01	1,1E-02	2,8E-02	1,4E-03	5,0E-02	1,3E-01	6,2E-02	4,4E-02	Na	2,1E-01	1,9E-02	3,1E-03	8,5E-02	1,3E-02	5,2E-02	9,1E-04
Water extraction	Vieusart	Milli-Q water	Exchangeable	mg kg ⁻¹	1,1E-03	1,3E-01	1,5E-01	2,4E-02	1,7E-01	3,5E-03	5,2E-02	2,3E-01	1,8E-01	5,2E-02	Na	2,5E-01	1,7E-02	2,8E-03	5,7E-02	1,2E-02	2,1E-01	2,6E-02
Water extraction	Sainte-Walburge	Milli-Q water	Exchangeable	mg kg ⁻¹	2,0E-03	2,3E-01	5,0E-01	3,1E-02	5,4E-01	9,1E-03	1,2E-01	6,3E-01	2,4E+00	4,6E-01	Na	3,3E-01	1,0E-01	8,8E-03	3,1E-02	7,3E-02	6,7E-01	3,2E-01
Water extraction	Sainte-Walburge	Milli-Q water	Exchangeable	mg kg ⁻¹	2,1E-03	2,6E-01	5,3E-01	3,3E-02	6,5E-01	1,1E-02	1,0E-01	6,4E-01	2,6E+00	4,6E-01	Na	3,6E-01	1,0E-01	8,4E-03	3,3E-02	7,3E-02	7,8E-01	3,8E-01
Water extraction	Bressoux	Milli-Q water	Exchangeable	mg kg ⁻¹	2,6E-03	1,7E-01	5,8E-01	2,6E-02	1,2E+00	1,3E-02	1,1E-01	1,3E+00	4,3E+00	5,5E-01	Na	3,6E-01	4,4E-02	1,3E-02	3,8E-02	1,7E-01	5,8E-01	8,8E-01
Water extraction	Bressoux	Milli-Q water	Exchangeable	mg kg ⁻¹	1,8E-03	1,5E-01	5,7E-01	2,4E-02	9,8E-01	1,1E-02	1,1E-01	1,2E+00	3,9E+00	5,2E-01	Na	3,6E-01	4,4E-02	1,2E-02	3,7E-02	1,6E-01	5,2E-01	7,3E-01
Water extraction	Aubange	Milli-Q water	Exchangeable	mg kg ⁻¹	2,5E-03	8,8E-02	1,9E-01	2,9E-02	5,2E+00	2,5E-02	6,4E-02	9,0E-02	2,3E-01	1,0E-01	Na	1,8E-01	3,5E-02	1,4E-03	2,8E-02	4,1E-03	1,2E-01	8,4E-02
Water extraction	Aubange	Milli-Q water	Exchangeable	mg kg ⁻¹	2,0E-03	8,5E-02	2,0E-01	2,9E-02	6,9E+00	3,2E-02	7,1E-02	1,3E-01	2,8E-01	1,0E-01	Na	2,0E-01	3,6E-02	2,8E-03	2,4E-02	4,3E-03	1,4E-01	1,0E-01
BCR extraction	Vieusart	Acetic acid	Exchangeable	mg kg ⁻¹	2,0E-03	3,9E-02	6,6E-02	5,3E-02	3,5E+01	2,5E-01	5,5E-01	3,4E-01	3,4E+00	7,8E-02	Na	4,5E+00	1,6E-03	7,9E-02	4,8E-02	1,7E-02	8,9E+00	1,6E-01
BCR extraction	Vieusart	Acetic acid	Exchangeable	mg kg ⁻¹	<DL	5,5E-02	7,7E-02	4,9E-02	3,2E+01	2,6E-01	5,2E-01	3,6E-01	3,3E+00	9,3E-02	Na	4,3E+00	9,4E-04	7,3E-02	5,1E-02	1,5E-02	8,8E+00	1,7E-01
BCR extraction	Sainte-Walburge	Acetic acid	Exchangeable	mg kg ⁻¹	2,3E-03	4,5E-02	1,5E-01	4,4E-02	6,1E+01	3,1E-01	1,3E+00	1,3E+00	6,0E+01	1,0E+00	Na	8,4E+00	3,8E-03	4,6E-01	5,9E-02	5,6E-02	2,2E+01	1,1E+00
BCR extraction	Sainte-Walburge	Acetic acid	Exchangeable	mg kg ⁻¹	5,4E-03	6,4E-02	1,6E-01	5,3E-02	6,8E+01	3,7E-01	1,4E+00	1,3E+00	6,4E+01	1,1E+00	Na	8,2E+00	3,9E-03	4,8E-01	4,7E-02	5,2E-02	2,1E+01	1,0E+00
BCR extraction	Bressoux	Acetic acid	Exchangeable	mg kg ⁻¹	3,4E-03	7,9E-02	1,7E-01	4,5E-02	4,6E+01	2,1E-01	1,5E+00	2,8E+00	3,3E+02	1,6E+00	Na	1,7E+01	3,1E-03	1,0E+00	4,7E-02	1,5E-01	3,3E+01	2,8E+00
BCR extraction	Bressoux	Acetic acid	Exchangeable	mg kg ⁻¹	4,9E-03	8,1E-02	1,9E-01	4,6E-02	5,3E+01	2,5E-01	1,6E+00	3,0E+00	3,6E+02	1,8E+00	Na	1,8E+01	3,0E-03	1,1E+00	6,1E-02	1,7E-01	3,6E+01	3,1E+00
BCR extraction	Aubange	Acetic acid	Exchangeable	mg kg ⁻¹	2,8E-03	3,9E-02	1,7E-02	4,2E-02	7,9E+01	3,8E-02	1,5E+00	1,9E-01	3,6E+00	7,3E-02	Na	5,9E+00	2,3E-03	2,1E-02	4,8E-02	5,3E-03	2,7E+00	4,1E-02
BCR extraction	Aubange	Acetic acid	Exchangeable	mg kg ⁻¹	1,6E-03	3,4E-02	1,4E-02	3,7E-02	7,8E+01	3,8E-02	1,4E+00	1,8E-01	3,2E+00	5,7E-02	Na	5,9E+00	1,7E-03	2,0E-02	3,6E-02	5,4E-03	2,6E+00	4,2E-02
BCR extraction	Vieusart	Hydroxylamine	Reducible	mg kg ⁻¹	6,1E-03	1,5E+00	8,2E+00	1,4E+00	1,5E+02	2,2E+00	1,2E+00	3,0E+00	9,6E+00	6,7E-01	Na	2,6E+00	1,2E-02	1,4E-01	5,0E-02	2,5E-02	1,9E+01	1,1E+01
BCR extraction	Vieusart	Hydroxylamine	Reducible	mg kg ⁻¹	9,2E-03	1,7E+00	7,9E+00	1,4E+00	1,4E+02	2,0E+00	1,2E+00	3,0E+00	8,8E+00	6,7E-01	Na	2,6E+00	1,3E-02	1,3E-01	5,9E-02	2,5E-02	1,9E+01	1,1E+01
BCR extraction	Sainte-Walburge	Hydroxylamine	Reducible	mg kg ⁻¹	6,7E-03	1,5E+00	9,5E+00	1,3E+00	2,5E+02	4,3E+00	3,9E+00	2,1E+01	1,2E+02	3,0E+00	Na	7,5E+00	3,0E-02	9,5E-01	6,2E-02	1,1E-01	7,9E+01	8,7E+01
BCR extraction	Sainte-Walburge	Hydroxylamine	Reducible	mg kg ⁻¹	5,4E-03	1,5E+00	9,4E+00	1,4E+00	2,4E+02	4,3E+00	3,8E+00	2,1E+01	1,2E+02	2,9E+00	Na	6,9E+00	3,0E-02	9,2E-01	5,5E-02	1,0E-01	6,4E+01	8,3E+01

Appendices

BCR extraction	Bressoux	Hydroxylamine	Reducible	mg kg ⁻¹	1,6E-02	1,6E+00	1,5E+01	2,2E+00	6,1E+02	6,4E+00	4,9E+00	6,6E+01	4,1E+02	1,2E+01	Na	1,8E+01	6,9E-02	3,2E+00	1,4E-01	4,8E-01	1,5E+02	4,2E+02
BCR extraction	Bressoux	Hydroxylamine	Reducible	mg kg ⁻¹	1,4E-02	1,6E+00	1,5E+01	2,2E+00	6,3E+02	6,8E+00	5,0E+00	6,9E+01	4,2E+02	1,2E+01	Na	1,8E+01	7,0E-02	3,3E+00	1,2E-01	4,8E-01	1,6E+02	4,4E+02
BCR extraction	Aubange	Hydroxylamine	Reducible	mg kg ⁻¹	1,3E-02	5,7E-01	2,4E+01	1,4E+00	7,7E+03	3,5E+01	3,6E+01	2,3E+00	2,4E+01	1,6E+00	Na	5,5E+00	1,2E-01	2,7E-01	5,8E-02	1,8E-02	8,1E+01	4,4E+01
BCR extraction	Aubange	Hydroxylamine	Reducible	mg kg ⁻¹	1,5E-02	5,0E-01	2,3E+01	1,4E+00	7,7E+03	3,4E+01	3,7E+01	2,3E+00	2,4E+01	1,5E+00	Na	5,4E+00	1,2E-01	2,7E-01	5,6E-02	1,7E-02	7,9E+01	4,4E+01
BCR extraction	Vieusart	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	3,6E-01	7,3E+00	3,2E+00	3,8E+00	1,1E+01	2,7E-01	1,4E+00	7,9E-01	4,9E+00	1,7E-01	Na	5,9E-01	5,2E-02	4,3E-02	6,0E-02	2,2E-02	3,4E+00	7,3E-01
BCR extraction	Vieusart	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	4,0E-01	5,0E+00	2,6E+00	3,6E+00	1,1E+01	2,7E-01	1,3E+00	1,1E+00	5,7E+00	1,9E-01	Na	6,3E-01	1,3E-02	3,2E-02	6,0E-02	1,6E-02	3,5E+00	7,5E-01
BCR extraction	Sainte-Walburge	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	1,1E+00	2,4E+01	5,3E+00	4,0E+00	1,2E+01	5,4E-01	3,1E+00	1,2E+01	6,2E+01	9,5E-01	Na	2,1E+00	3,2E-01	8,7E-02	8,4E-03	3,4E-02	1,6E+01	7,8E+00
BCR extraction	Sainte-Walburge	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	1,1E+00	4,4E+00	4,1E+00	4,1E+00	1,2E+01	5,4E-01	3,2E+00	1,2E+01	6,2E+01	9,2E-01	Na	1,9E+00	2,8E-01	8,5E-02	1,2E-02	4,0E-02	9,9E+00	7,0E+00
BCR extraction	Bressoux	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	1,0E+00	5,0E+00	7,0E+00	5,0E+00	2,6E+01	5,9E-01	3,5E+00	8,4E+01	1,6E+02	2,4E+00	Na	4,0E+00	8,1E-01	1,9E-01	1,2E-01	1,6E-01	2,3E+01	5,5E+01
BCR extraction	Bressoux	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	9,3E-01	4,7E+00	7,6E+00	5,3E+00	2,4E+01	6,8E-01	3,7E+00	9,0E+01	1,8E+02	2,2E+00	Na	4,2E+00	8,4E-01	2,0E-01	1,0E-01	1,7E-01	2,4E+01	5,4E+01
BCR extraction	Aubange	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	1,1E+00	5,6E-01	3,2E+00	7,2E+00	1,0E+02	4,9E-01	4,3E+00	6,6E-01	5,2E+00	4,6E-01	Na	8,4E-01	1,9E-02	2,6E-02	<DL	9,8E-03	3,0E+00	1,9E+00
BCR extraction	Aubange	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	1,1E+00	5,3E-01	2,8E+00	6,9E+00	1,0E+02	5,0E-01	4,3E+00	6,4E-01	5,1E+00	4,8E-01	Na	8,6E-01	1,4E-02	2,0E-02	<DL	8,8E-03	3,0E+00	1,8E+00
BCR extraction	Vieusart	/	Residual	mg kg ⁻¹	2,1E+00	1,7E+03	4,1E+01	4,3E+01	9,0E+01	5,0E+00	1,2E+01	7,8E+00	2,7E+01	6,7E+00	Na	2,8E+01	3,2E+00	6,9E-03	9,9E-01	5,6E-01	2,3E+02	8,4E+00
BCR extraction	Vieusart	/	Residual	mg kg ⁻¹	2,0E+00	1,7E+03	4,2E+01	4,4E+01	1,0E+02	5,2E+00	1,2E+01	7,4E+00	2,7E+01	6,7E+00	Na	2,8E+01	3,2E+00	4,0E-02	9,8E-01	5,7E-01	2,3E+02	8,3E+00
BCR extraction	Sainte-Walburge	/	Residual	mg kg ⁻¹	6,2E+00	2,5E+03	6,9E+01	6,0E+01	1,4E+02	1,8E+01	3,3E+01	3,7E+01	1,1E+02	9,8E+00	Na	5,0E+01	2,8E+00	3,5E-01	1,3E+01	3,1E+00	2,2E+02	4,5E+01
BCR extraction	Sainte-Walburge	/	Residual	mg kg ⁻¹	6,2E+00	2,5E+03	7,0E+01	6,0E+01	1,4E+02	1,8E+01	3,3E+01	3,7E+01	1,0E+02	9,9E+00	Na	5,1E+01	2,9E+00	3,7E-01	1,3E+01	3,1E+00	2,5E+02	4,9E+01

BCR extraction	Bressoux	/	Residual	mg kg ⁻¹	7,6E+00	9,3E+02	8,6E+01	6,8E+01	3,3E+02	3,3E+01	5,9E+01	9,5E+01	3,7E+02	1,7E+01	Na	3,1E+01	2,1E+00	2,1E+00	5,6E+01	1,1E+01	1,9E+02	1,1E+02
BCR extraction	Bressoux	/	Residual	mg kg ⁻¹	7,7E+00	9,3E+02	8,5E+01	6,8E+01	3,0E+02	3,3E+01	5,9E+01	8,6E+01	3,2E+02	1,7E+01	Na	2,9E+01	2,1E+00	1,9E+00	5,6E+01	1,1E+01	1,8E+02	9,0E+01
BCR extraction	Aubange	/	Residual	mg kg ⁻¹	1,5E+01	2,5E+03	3,7E+02	1,2E+02	9,5E+02	2,7E+01	7,9E+01	1,2E+01	2,0E+02	1,4E+02	Na	3,8E+01	4,7E+00	1,0E-01	1,5E+00	9,5E-01	1,1E+02	2,0E+01
BCR extraction	Aubange	/	Residual	mg kg ⁻¹	1,6E+01	2,5E+03	3,7E+02	1,2E+02	1,0E+03	2,7E+01	7,8E+01	1,2E+01	2,0E+02	1,4E+02	Na	3,8E+01	4,7E+00	1,1E-01	1,5E+00	9,6E-01	1,1E+02	2,1E+01

Table VI-8 – Rare earth element contents in soil water-extracts and BCR fractions for the four soils (2 replicates).

Extraction	Site	Extracting solution	Targeted fraction	Unit	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Water extraction	Vieusart	Milli-Q water	Exchangeable	mg kg ⁻¹	5,9E-03	9,7E-03	2,0E-03	9,4E-03	1,8E-03	4,1E-04	1,9E-03	2,3E-04	1,3E-03	2,8E-04	7,8E-04	1,0E-04	6,2E-04	1,0E-04
Water extraction	Vieusart	Milli-Q water	Exchangeable	mg kg ⁻¹	1,8E-02	3,8E-02	5,8E-03	2,6E-02	5,3E-03	1,2E-03	5,2E-03	6,7E-04	3,7E-03	7,2E-04	1,9E-03	2,6E-04	1,6E-03	2,3E-04
Water extraction	Sainte-Walburge	Milli-Q water	Exchangeable	mg kg ⁻¹	3,3E-02	7,2E-02	1,0E-02	4,3E-02	9,5E-03	2,1E-03	9,3E-03	1,2E-03	6,8E-03	1,2E-03	3,4E-03	4,7E-04	2,7E-03	4,0E-04
Water extraction	Sainte-Walburge	Milli-Q water	Exchangeable	mg kg ⁻¹	4,1E-02	8,7E-02	1,2E-02	5,2E-02	1,1E-02	2,6E-03	1,1E-02	1,5E-03	8,5E-03	1,5E-03	4,1E-03	5,5E-04	3,3E-03	5,0E-04
Water extraction	Bressoux	Milli-Q water	Exchangeable	mg kg ⁻¹	1,4E-02	4,3E-02	3,8E-03	1,6E-02	3,5E-03	8,1E-04	3,7E-03	4,1E-04	2,2E-03	4,0E-04	1,2E-03	1,6E-04	9,7E-04	1,5E-04
Water extraction	Bressoux	Milli-Q water	Exchangeable	mg kg ⁻¹	1,2E-02	3,6E-02	3,2E-03	1,4E-02	3,1E-03	7,0E-04	3,3E-03	3,5E-04	1,9E-03	3,6E-04	1,1E-03	1,4E-04	9,1E-04	1,3E-04
Water extraction	Aubange	Milli-Q water	Exchangeable	mg kg ⁻¹	4,2E-02	7,2E-02	1,4E-02	6,0E-02	1,3E-02	2,8E-03	1,2E-02	1,7E-03	9,7E-03	1,8E-03	4,7E-03	6,8E-04	3,9E-03	5,5E-04
Water extraction	Aubange	Milli-Q water	Exchangeable	mg kg ⁻¹	4,7E-02	8,8E-02	1,6E-02	6,5E-02	1,4E-02	3,1E-03	1,3E-02	1,9E-03	1,1E-02	2,0E-03	5,3E-03	7,3E-04	4,3E-03	6,4E-04
BCR extraction	Vieusart	Acetic acid	Exchangeable	mg kg ⁻¹	6,8E-02	1,1E-01	1,9E-02	8,3E-02	1,8E-02	3,6E-03	1,7E-02	2,0E-03	1,2E-02	2,3E-03	6,1E-03	7,7E-04	4,6E-03	6,9E-04
BCR extraction	Vieusart	Acetic acid	Exchangeable	mg kg ⁻¹	6,6E-02	1,1E-01	1,8E-02	8,3E-02	1,8E-02	3,5E-03	1,7E-02	1,9E-03	1,1E-02	2,0E-03	5,7E-03	6,7E-04	4,5E-03	6,7E-04
BCR extraction	Sainte-Walburge	Acetic acid	Exchangeable	mg kg ⁻¹	2,7E-02	4,4E-02	7,2E-03	3,5E-02	9,0E-03	2,2E-03	9,5E-03	1,0E-03	5,6E-03	1,1E-03	3,3E-03	4,7E-04	3,0E-03	4,6E-04
BCR extraction	Sainte-Walburge	Acetic acid	Exchangeable	mg kg ⁻¹	2,8E-02	4,4E-02	7,0E-03	3,4E-02	7,5E-03	2,3E-03	8,7E-03	1,0E-03	5,5E-03	1,2E-03	3,2E-03	4,3E-04	3,0E-03	4,9E-04
BCR extraction	Bressoux	Acetic acid	Exchangeable	mg kg ⁻¹	1,2E-02	1,3E-02	2,4E-03	1,1E-02	2,7E-03	8,2E-04	3,0E-03	3,2E-04	1,6E-03	3,2E-04	9,2E-04	1,4E-04	8,0E-04	1,1E-04
BCR extraction	Bressoux	Acetic acid	Exchangeable	mg kg ⁻¹	1,4E-02	1,5E-02	2,6E-03	1,2E-02	2,8E-03	1,1E-03	3,6E-03	3,7E-04	1,6E-03	3,2E-04	9,5E-04	1,5E-04	1,0E-03	1,6E-04
BCR extraction	Aubange	Acetic acid	Exchangeable	mg kg ⁻¹	1,2E-01	1,5E-01	2,4E-02	1,0E-01	1,9E-02	4,3E-03	2,0E-02	2,4E-03	1,3E-02	2,7E-03	6,7E-03	9,0E-04	5,1E-03	7,7E-04
BCR extraction	Aubange	Acetic acid	Exchangeable	mg kg ⁻¹	1,1E-01	1,4E-01	2,2E-02	9,4E-02	1,7E-02	3,9E-03	1,9E-02	2,3E-03	1,2E-02	2,4E-03	6,1E-03	8,1E-04	4,5E-03	6,5E-04
BCR extraction	Vieusart	Hydroxylamine	Reducible	mg kg ⁻¹	4,8E+00	1,3E+01	1,4E+00	5,9E+00	1,2E+00	2,7E-01	1,2E+00	1,7E-01	9,7E-01	1,8E-01	4,7E-01	6,3E-02	3,6E-01	5,1E-02
BCR extraction	Vieusart	Hydroxylamine	Reducible	mg kg ⁻¹	4,8E+00	1,3E+01	1,4E+00	5,9E+00	1,2E+00	2,7E-01	1,2E+00	1,6E-01	9,6E-01	1,8E-01	4,6E-01	6,2E-02	3,5E-01	5,0E-02
BCR extraction	Sainte-Walburge	Hydroxylamine	Reducible	mg kg ⁻¹	5,8E+00	1,3E+01	1,4E+00	5,9E+00	1,3E+00	2,9E-01	1,5E+00	2,0E-01	1,2E+00	2,2E-01	5,7E-01	7,5E-02	4,2E-01	6,0E-02
BCR extraction	Sainte-Walburge	Hydroxylamine	Reducible	mg kg ⁻¹	5,9E+00	1,3E+01	1,5E+00	6,0E+00	1,3E+00	3,0E-01	1,5E+00	2,0E-01	1,2E+00	2,2E-01	5,8E-01	7,7E-02	4,3E-01	6,2E-02

BCR extraction	Bressoux	Hydroxylamine	Reducible	mg kg ⁻¹	4,9E+00	9,7E+00	9,5E-01	3,8E+00	7,9E-01	2,1E-01	1,1E+00	1,4E-01	7,9E-01	1,5E-01	3,8E-01	4,8E-02	2,6E-01	3,8E-02
BCR extraction	Bressoux	Hydroxylamine	Reducible	mg kg ⁻¹	4,9E+00	9,6E+00	9,5E-01	3,8E+00	8,0E-01	2,2E-01	1,1E+00	1,5E-01	8,2E-01	1,5E-01	3,9E-01	4,9E-02	2,8E-01	4,0E-02
BCR extraction	Aubange	Hydroxylamine	Reducible	mg kg ⁻¹	1,5E+01	8,1E+01	4,4E+00	1,8E+01	3,7E+00	8,5E-01	4,2E+00	5,4E-01	3,2E+00	6,0E-01	1,6E+00	2,2E-01	1,3E+00	1,9E-01
BCR extraction	Aubange	Hydroxylamine	Reducible	mg kg ⁻¹	1,5E+01	7,9E+01	4,4E+00	1,8E+01	3,7E+00	8,7E-01	4,3E+00	5,5E-01	3,2E+00	6,1E-01	1,6E+00	2,3E-01	1,3E+00	1,9E-01
BCR extraction	Vieusart	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	9,2E-01	2,2E+00	4,2E-01	2,0E+00	5,3E-01	1,2E-01	4,6E-01	6,4E-02	3,7E-01	6,8E-02	1,8E-01	2,6E-02	1,7E-01	2,5E-02
BCR extraction	Vieusart	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	9,2E-01	2,2E+00	4,1E-01	1,9E+00	5,1E-01	1,1E-01	4,4E-01	6,0E-02	3,5E-01	6,4E-02	1,8E-01	2,4E-02	1,6E-01	2,3E-02
BCR extraction	Sainte-Walburge	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	1,7E+00	4,6E+00	7,4E-01	3,4E+00	9,2E-01	2,1E-01	8,3E-01	1,1E-01	6,3E-01	1,1E-01	2,9E-01	4,1E-02	2,6E-01	3,8E-02
BCR extraction	Sainte-Walburge	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	1,8E+00	5,0E+00	7,7E-01	3,5E+00	9,5E-01	2,2E-01	8,6E-01	1,2E-01	6,5E-01	1,1E-01	3,0E-01	4,3E-02	2,7E-01	3,9E-02
BCR extraction	Bressoux	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	2,6E+00	7,4E+00	9,2E-01	4,0E+00	1,0E+00	2,7E-01	1,1E+00	1,4E-01	7,4E-01	1,3E-01	3,3E-01	4,4E-02	2,7E-01	3,9E-02
BCR extraction	Bressoux	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	2,5E+00	7,1E+00	9,0E-01	4,0E+00	1,1E+00	2,7E-01	1,1E+00	1,4E-01	7,5E-01	1,3E-01	3,3E-01	4,4E-02	2,7E-01	3,9E-02
BCR extraction	Aubange	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	2,4E+00	1,0E+01	1,1E+00	5,4E+00	1,4E+00	3,4E-01	1,4E+00	2,0E-01	1,2E+00	2,2E-01	5,9E-01	8,8E-02	5,7E-01	8,5E-02
BCR extraction	Aubange	Hydrogen peroxide and ammonium acetate	Oxidizable	mg kg ⁻¹	2,4E+00	9,9E+00	1,1E+00	5,4E+00	1,5E+00	3,4E-01	1,4E+00	2,0E-01	1,2E+00	2,2E-01	6,0E-01	8,7E-02	5,7E-01	8,3E-02
BCR extraction	Vieusart	/	Residual	mg kg ⁻¹	1,7E+01	3,4E+01	4,0E+00	1,5E+01	2,5E+00	3,5E-01	1,8E+00	2,1E-01	1,1E+00	2,1E-01	6,1E-01	9,7E-02	6,4E-01	2,6E-01
BCR extraction	Vieusart	/	Residual	mg kg ⁻¹	1,7E+01	3,5E+01	4,0E+00	1,5E+01	2,5E+00	3,6E-01	1,9E+00	2,1E-01	1,2E+00	2,1E-01	6,3E-01	1,0E-01	6,5E-01	2,6E-01
BCR extraction	Sainte-Walburge	/	Residual	mg kg ⁻¹	2,3E+01	4,0E+01	5,6E+00	2,1E+01	3,8E+00	5,9E-01	3,0E+00	3,4E-01	1,8E+00	3,6E-01	1,0E+00	1,5E-01	1,0E+00	2,3E-01
BCR extraction	Sainte-Walburge	/	Residual	mg kg ⁻¹	2,2E+01	4,0E+01	5,6E+00	2,1E+01	3,7E+00	5,8E-01	2,9E+00	3,4E-01	1,8E+00	3,5E-01	1,0E+00	1,4E-01	9,9E-01	2,3E-01

Appendices

BCR extraction	Bressoux	/	Residual	mg kg ⁻¹	1,4E+01	3,2E+01	4,2E+00	1,7E+01	3,5E+00	6,0E-01	2,6E+00	3,1E-01	1,7E+00	3,4E-01	9,4E-01	1,4E-01	9,1E-01	2,4E-01
BCR extraction	Bressoux	/	Residual	mg kg ⁻¹	1,4E+01	3,2E+01	4,2E+00	1,7E+01	3,4E+00	5,9E-01	2,6E+00	3,1E-01	1,7E+00	3,3E-01	9,2E-01	1,4E-01	8,9E-01	2,3E-01
BCR extraction	Aubange	/	Residual	mg kg ⁻¹	1,4E+01	1,2E+01	3,9E+00	1,5E+01	3,4E+00	7,9E-01	3,2E+00	5,5E-01	3,3E+00	6,4E-01	1,8E+00	3,0E-01	1,9E+00	4,9E-02
BCR extraction	Aubange	/	Residual	mg kg ⁻¹	1,4E+01	1,4E+01	3,9E+00	1,5E+01	3,3E+00	7,7E-01	3,1E+00	5,4E-01	3,2E+00	6,3E-01	1,8E+00	3,0E-01	1,9E+00	4,8E-02

Influence of organic matter

Table VI-9 – Proportion of available (water-extract) trace element contents supplied with the application of exogenous organic matter relative to soil (single pot, greenhouse).

	Vieusart		Sainte-Walburge		Bressoux		Aubange	
(%)	Cattle manure	Green waste compost	Cattle manure	Green waste compost	Cattle manure	Green waste compost	Cattle manure	Green waste compost
Sc	7	10	2	3	2	3	2	3
Ti	18	8	7	3	10	4	18	8
V	5	10	1	3	1	2	3	7
Cr	9	8	5	4	6	6	5	5
Mn	96	23	16	4	9	2	2	0
Co	52	48	13	12	11	10	5	4
Ni	12	8	6	4	6	4	9	6
Cu	18	8	5	2	3	1	29	13
Zn	104	60	5	3	3	2	49	28
As	7	14	1	1	1	1	3	7
Sr	15	8	10	6	10	5	18	10
Mo	113	64	20	11	46	26	57	32
Cd	12	5	4	2	3	1	17	8
Sn	0	0	1	0	1	0	1	1
Sb	4	5	1	1	0	0	11	15
Ba	8	4	1	1	2	1	8	4
Pb	32	11	1	0	1	0	5	2

Table VI-10 - Proportion of total trace element contents supplied with the application of exogenous organic matter relative to soil (single pot, greenhouse).

	Vieusart			Sainte-Walburge			Bressoux			Aubange		
(%)	Cattle manure	Green waste compost	Cover crop restitution	Cattle manure	Green waste compost	Cover crop restitution	Cattle manure	Green waste compost	Cover crop restitution	Cattle manure	Green waste compost	Cover crop restitution
Sc	0.6	1.8	0.0	0.2	0.6	0.0	0.2	0.5	0.0	0.1	0.3	0.0
Ti	0.4	1.0	0.0	0.2	0.7	0.0	0.6	1.8	0.0	0.2	0.7	0.0
V	0.2	0.7	0.0	0.2	0.5	0.0	0.1	0.3	0.0	0.0	0.1	0.0
Cr	0.9	0.8	0.0	0.7	0.6	0.0	0.6	0.5	0.0	0.3	0.3	0.0
Mn	1.2	2.1	0.0	0.8	1.3	0.0	0.3	0.6	0.0	0.0	0.1	0.0
Co	0.3	2.4	0.0	0.1	0.8	0.0	0.1	0.5	0.0	0.0	0.3	0.0
Ni	0.5	1.1	0.0	0.2	0.4	0.0	0.1	0.2	0.0	0.1	0.1	0.0
Cu	2.5	3.8	0.1	0.4	0.6	0.0	0.1	0.2	0.0	2.0	3.1	0.0
Zn	3.7	6.1	0.1	0.5	0.8	0.0	0.1	0.2	0.0	0.7	1.2	0.0
As	0.3	0.9	0.0	0.2	0.5	0.0	0.1	0.2	0.0	0.0	0.0	0.0
Sr	2.5	4.0	0.2	1.3	2.1	0.1	1.3	2.0	0.1	1.8	2.8	0.1
Mo	1.9	0.9	0.1	1.9	1.0	0.1	2.0	1.0	0.1	1.3	0.6	0.1
Cd	1.8	3.7	0.1	0.3	0.5	0.0	0.1	0.2	0.0	1.2	2.4	0.1
Sn	0.7	2.9	0.0	0.1	0.3	0.0	0.0	0.1	0.0	0.5	2.0	0.0
Sb	0.5	2.0	0.0	0.1	0.4	0.0	0.0	0.1	0.0	0.3	1.3	0.0
Ba	0.4	1.0	0.0	0.3	0.8	0.0	0.3	0.7	0.0	0.6	1.4	0.0
Pb	0.3	2.9	0.0	0.0	0.4	0.0	0.0	0.1	0.0	0.1	0.9	0.0

Table VI-11 - Proportion of total carbon and nitrogen contents supplied with the application of exogenous organic matter relative to soil (single pot, greenhouse).

	Vieusart			Sainte-Walburge			Bressoux			Aubange		
%	Cattle manure	Green waste compost	Cover crop restitution	Cattle manure	Green waste compost	Cover crop restitution	Cattle manure	Green waste compost	Cover crop restitution	Cattle manure	Green waste compost	Cover crop restitution
C	49	36	7	6	4	1	4	3	1	25	18	4
N	39	25	5	14	9	2	9	6	1	22	14	3

Table VI-12 - Change in pH with the application of exogenous organic matter compared to the modality without application (after the greenhouse experiment).

	pH _{H₂O}	Δ pH _{H₂O}		
	No application	Cattle manure	Green waste compost	Cover crop restitution
Vieusart	6.6	+0.3	+0.2	-0.1
Sainte-Walburge	6.5	+0.6	+0.8	+0.6
Bressoux	6.1	+0.3	+0.1	-0.1
Aubange	6.5	+0.3	+0.2	+0.1

Table VI-13 - Change in dissolved organic carbon (DOC) concentrations with the application of exogenous organic matter compared to the modality without application (after the greenhouse experiment).

	DOC (mg L ⁻¹)	Δ DOC (mg L ⁻¹)		
	No application	Cattle manure	Green waste compost	Cover crop restitution
Vieusart	9.6	+51.2	+19.7	+0.3
Sainte-Walburge	13.3	+68.5	+44.5	+5.0
Bressoux	16.9	+83.0	+39.6	+6.0
Aubange	7.7	+38.2	+16.2	+9.9

Organic matter characterization

Table. VI-14 - Rock-Eval parameters for soil, EOM, and soil + EOM samples.

Type	Site	Modality	Replicate	S1 (mg/g)	S2 (mg/g)	PI	Tmax(°C)	TpkS2(°C)	S3CO (mg/g)	S3'CO (mg/g)	S3 (mg/g)	S3' (mg/g)	PC(%)	RC(%)	TOC(%)	HI	OI	MINC(%)	TOC+MinC
Soil + EOM	Vieusart	Green waste compost	A	0,03	1,62	0,02	382	424	0,73	0,6	3,66	4,3	0,28	1,16	1,44	112	254	0,15	1,59
Soil + EOM	Vieusart	Green waste compost	B	0,09	1,73	0,05	383	425	0,71	0,6	3,33	4,0	0,29	1,10	1,39	124	240	0,14	1,53
Soil + EOM	Vieusart	Green waste compost	C	0,02	1,63	0,01	389	431	0,74	0,6	3,41	4,0	0,27	1,13	1,40	116	244	0,15	1,55
Soil + EOM	Vieusart	Cattle manure	A	0,02	1,74	0,01	380	422	0,75	0,6	3,53	4,3	0,29	1,18	1,47	118	240	0,35	1,82
Soil + EOM	Vieusart	Cattle manure	B	0,03	1,64	0,02	378	420	0,69	0,6	3,38	4,0	0,27	1,06	1,33	123	254	0,16	1,49
Soil + EOM	Vieusart	Cattle manure	C	0,03	1,74	0,02	382,00	424,00	0,72	0,60	3,46	4,05	0,29	1,08	1,37	127,50	253,00	0,18	1,54
Soil + EOM	Vieusart	Cover crop restitution	A	0,03	0,98	0,03	367	409	0,58	0,4	3,01	3,6	0,20	0,70	0,90	109	334	0,13	1,03
Soil + EOM	Vieusart	Cover crop restitution	B	0,06	1,20	0,05	371	413	0,63	0,4	2,83	3,3	0,22	0,79	1,01	119	280	0,12	1,13
Soil + EOM	Vieusart	Cover crop restitution	C	0,02	1,16	0,02	369	411	0,62	0,4	2,85	3,5	0,21	0,80	1,01	115	282	0,13	1,14
Soil + EOM	Vieusart	No application	A	0,07	1,09	0,06	367	409	0,53	0,5	2,77	3,4	0,21	0,74	0,95	115	292	0,12	1,07
Soil + EOM	Vieusart	No application	B	0,02	0,99	0,02	372	414	0,57	0,4	2,75	3,3	0,19	0,74	0,93	106	296	0,15	1,08
Soil + EOM	Vieusart	No application	C	0,02	0,93	0,02	365	407	0,51	0,4	2,71	3,4	0,18	0,75	0,93	100	291	0,14	1,07
Soil	Vieusart	Soil	/	0,04	0,96	0,04	369	411	0,53	0,4	2,81	3,4	0,19	0,71	0,90	107	312	0,14	1,04
Soil + EOM	Sainte-Walburge	Green waste compost	A	0,13	4,15	0,03	408	450	0,97	1,6	4,58	6,6	0,56	9,23	9,79	42	47	1,28	11,07
Soil + EOM	Sainte-Walburge	Green waste compost	B	0,06	3,79	0,01	404	446	1,10	1,3	4,44	6,8	0,52	8,78	9,30	41	48	1,03	10,33
Soil + EOM	Sainte-Walburge	Green waste compost	C	0,08	4,52	0,02	415,00	457,00	1,17	1,65	4,81	7,00	0,60	9,69	10,29	44,00	47,00	1,28	11,57
Soil + EOM	Sainte-Walburge	Cattle manure	A	0,05	5,28	0,01	404	446	1,44	1,3	4,99	6,6	0,67	9,70	10,37	51	48	1,43	11,80
Soil + EOM	Sainte-Walburge	Cattle manure	B	0,06	3,98	0,02	389	431	1,13	1,4	4,38	6,2	0,53	8,70	9,23	43	47	1,17	10,40
Soil + EOM	Sainte-Walburge	Cattle manure	C	0,08	4,70	0,02	406	448	1,17	1,5	4,54	6,1	0,60	9,49	10,09	47	45	1,05	11,14
Soil + EOM	Sainte-Walburge	Cover crop restitution	A	0,08	3,23	0,03	517	559	0,99	1,4	4,51	6,9	0,47	10,22	10,69	30	42	1,63	12,32
Soil + EOM	Sainte-Walburge	Cover crop restitution	B	0,06	3,65	0,02	517	559	0,98	1,4	3,90	6,1	0,49	10,92	11,41	32	34	1,83	13,24
Soil + EOM	Sainte-Walburge	Cover crop restitution	C	0,09	3,53	0,02	515	557	0,79	1,5	3,98	6,2	0,48	9,73	10,21	35	39	1,31	11,52
Soil + EOM	Sainte-Walburge	No application	A	0,11	3,30	0,04	395,50	437,50	0,80	1,30	3,86	5,95	0,45	8,15	8,60	38,50	44,50	1,14	9,74

Appendices

Soil + EOM	Sainte-Walburge	No application	B	0,10	3,38	0,03	393	435	0,99	1,4	4,35	6,5	0,48	8,04	8,52	40	51	0,85	9,37
Soil + EOM	Sainte-Walburge	No application	C	0,06	3,04	0,02	513	555	0,91	1,3	3,61	5,8	0,42	9,06	9,48	32	38	1,62	11,10
Soil	Sainte-Walburge	Soil	/	0,10	3,24	0,03	520	562	0,90	1,4	3,83	5,8	0,45	9,54	9,99	32	38	1,90	11,89
Soil + EOM	Bressoux	Green waste compost	A	0,15	7,22	0,02	418	460	1,78	2,3	7,99	10,2	0,96	18,39	19,35	37	41	3,06	22,41
Soil + EOM	Bressoux	Green waste compost	B	0,13	7,52	0,02	420	462	1,95	2,3	8,04	10,7	0,99	15,62	16,61	45	48	1,87	18,48
Soil + EOM	Bressoux	Green waste compost	C	0,13	7,72	0,02	413	455	1,94	2,4	8,42	10,9	1,02	15,59	16,61	46	51	2,13	18,74
Soil + EOM	Bressoux	Cattle manure	A	0,13	7,01	0,02	413,50	455,50	1,84	2,35	8,88	11,65	0,97	14,71	15,68	44,50	56,50	1,96	17,64
Soil + EOM	Bressoux	Cattle manure	B	0,15	8,54	0,02	334	376	2,07	2,5	10,18	12,2	1,14	15,37	16,51	52	62	1,98	18,49
Soil + EOM	Bressoux	Cattle manure	C	0,15	8,35	0,02	332	374	1,87	2,2	8,08	9,8	1,05	14,86	15,91	52	51	2,02	17,93
Soil + EOM	Bressoux	Cover crop restitution	A	0,17	6,13	0,03	413	455	1,59	2,2	7,47	10,3	0,84	13,99	14,83	41	50	1,84	16,67
Soil + EOM	Bressoux	Cover crop restitution	B	0,12	6,02	0,02	415	457	1,64	2,3	7,57	11,0	0,84	15,55	16,39	37	46	1,97	18,36
Soil + EOM	Bressoux	Cover crop restitution	C	0,20	6,65	0,03	416,67	458,67	1,63	2,33	8,41	11,37	0,92	14,55	15,47	43,00	54,33	2,48	17,95
Soil + EOM	Bressoux	No application	A	0,11	5,47	0,02	423	465	1,63	2,3	7,77	11,4	0,79	16,06	16,85	32	46	2,09	18,94
Soil + EOM	Bressoux	No application	B	0,20	6,22	0,03	418,50	460,50	1,55	2,35	8,75	11,75	0,89	13,95	14,84	42,00	59,00	1,69	16,53
Soil + EOM	Bressoux	No application	C	0,20	6,14	0,03	415	457	1,64	2,3	7,71	10,7	0,86	14,21	15,07	41	51	1,96	17,03
Soil	Bressoux	Soil	/	0,22	6,06	0,04	419	461	1,70	2,3	8,05	11,0	0,86	14,10	14,96	41	54	1,72	16,68
Soil + EOM	Aubange	Green waste compost	A	0,15	1,93	0,07	376	418	1,03	0,8	10,78	12,6	0,53	1,32	1,85	104	583	0,42	2,27
Soil + EOM	Aubange	Green waste compost	B	0,04	1,84	0,02	376	418	1,03	0,8	10,75	12,5	0,51	1,40	1,91	96	563	0,41	2,32
Soil + EOM	Aubange	Green waste compost	C	0,04	1,87	0,02	378	420	1,10	0,9	10,74	12,4	0,52	1,37	1,89	99	568	0,42	2,31
Soil + EOM	Aubange	Cattle manure	A	0,05	1,85	0,02	374	416	1,09	0,8	10,11	11,6	0,50	1,25	1,75	106	578	0,38	2,13
Soil + EOM	Aubange	Cattle manure	B	0,06	1,84	0,03	376	418	1,06	0,8	11,09	13,0	0,52	1,20	1,72	107	645	0,42	2,14
Soil + EOM	Aubange	Cattle manure	C	0,04	1,83	0,03	375,00	417,00	1,07	0,75	10,95	12,55	0,52	1,21	1,73	106,00	635,00	0,42	2,15
Soil + EOM	Aubange	Cover crop restitution	A	0,03	1,42	0,02	378	420	0,89	0,7	10,06	11,7	0,45	0,97	1,42	100	708	0,38	1,80
Soil + EOM	Aubange	Cover crop restitution	B	0,02	1,37	0,02	377	419	0,91	0,6	10,22	12,1	0,45	0,95	1,40	98	730	0,39	1,79
Soil + EOM	Aubange	Cover crop restitution	C	0,0	1,4	0,0	380,5	422,5	0,9	0,6	10,4	12,2	0,5	0,9	1,4	100,5	743,0	0,4	1,8
Soil + EOM	Aubange	No application	A	0,05	1,38	0,03	377	419	0,89	0,6	10,00	11,9	0,44	1,02	1,46	95	685	0,57	2,03
Soil + EOM	Aubange	No application	B	0,07	1,39	0,05	376	418	0,93	0,6	10,25	11,9	0,45	0,89	1,34	104	765	0,40	1,74

Greenhouse experiment

Soil + EOM	Aubange	No application	C	0,05	1,32	0,03	381	423	0,91	0,6	10,09	12,0	0,44	0,90	1,34	99	753	0,38	1,72
Soil	Aubange	Soil	/	0,07	1,19	0,06	381	423	0,80	0,5	9,67	11,7	0,41	0,86	1,27	94	761	0,36	1,63
EOM	/	Cattle manure	/	0,1	90,8	0,0	292,7	334,7	16,8	7,4	76,9	43,5	10,5	20,8	31,3	289,3	246,7	1,4	32,7
EOM	/	Cover crop restitution	/	2,5	111,9	0,0	295,3	337,3	20,2	7,2	103,6	41,6	13,3	20,0	33,3	335,7	311,0	1,3	34,7
EOM	/	Green waste compost	/	0,1	59,8	0,0	356,3	398,3	10,1	9,5	41,7	40,9	6,7	17,0	23,7	251,7	175,7	1,4	25,1

Table VI-15 – Py-GCMS parameters for soil, EOM, and soil + EOM samples.

Type	Site	Modality	Replicate	SCV	(Ac/Ad)V	(Ac/Ad)S	S/V	C/V	Acv + Acs / Acv + Ads
Soil + EOM	Vieusart	Green waste compost	A	12,00	1,71	2,41	0,49	0,73	1,90
Soil + EOM	Vieusart	Cattle manure	A	11,36	1,56	2,41	0,92	1,18	1,91
Soil + EOM	Vieusart	Cover crop restitution	A	7,81	1,74	3,26	0,71	0,95	2,21
Soil + EOM	Vieusart	No application	A	8,24	1,82	3,19	0,60	0,83	2,22
Soil	Vieusart	Soil	/	8,16	1,47	2,09	0,69	0,84	1,69
Soil + EOM	Sainte-Walburge	Green waste compost	A	2,11	3,11	2,93	0,48	0,44	3,05
Soil + EOM	Sainte-Walburge	Cattle manure	A	3,31	1,42	1,72	1,06	0,62	1,56
Soil + EOM	Sainte-Walburge	Cover crop restitution	A	1,64	1,55	1,85	0,84	0,28	1,68
Soil + EOM	Sainte-Walburge	No application	A	0,72	2,59	4,05	0,90	0,42	3,16
Soil	Sainte-Walburge	Soil	/	1,55	2,10	1,40	0,53	0,26	1,82
Soil + EOM	Bressoux	Green waste compost	A	2,27	2,40	3,76	0,88	0,61	2,93
Soil + EOM	Bressoux	Cattle manure	A	2,05	1,68	2,17	1,09	0,36	1,92
Soil + EOM	Bressoux	Cover crop restitution	A	0,93	3,00	4,03	0,86	0,56	3,42
Soil + EOM	Bressoux	No application	A	1,36	2,09	2,27	1,06	0,35	2,18
Soil	Bressoux	Soil	/	3,39	1,98	2,70	1,12	0,61	2,32
Soil + EOM	Aubange	Green waste compost	A	4,46	1,16	1,42	0,83	0,41	1,27
Soil + EOM	Aubange	Cattle manure	A	8,16	0,89	1,30	0,97	0,40	1,07
Soil + EOM	Aubange	Cover crop restitution	A	6,94	0,95	1,26	0,85	0,41	1,08
Soil + EOM	Aubange	No application	A	7,11	0,86	1,18	0,84	0,47	0,99
Soil	Aubange	Soil	/	7,07	1,09	1,74	0,88	0,53	1,35

Greenhouse experiment

EOM	/	Green waste compost	/	3,24	2,68	2,87	0,46	0,37	2,74
EOM	/	Cattle manure	/	12,85	1,09	2,02	1,07	1,94	1,49
EOM	/	Cover crop restitution	/	6,46	2,18	1,39	0,26	1,74	1,97
Maize Root	/	No application	/	8,93	0,96	2,69	1,27	1,71	1,66

Table. VI-16 - Distribution of organic compounds in soil samples with and without exogenous organic matter.

Site	Modality	alkyl (%)	O-alkyl (%)	aromatic (%)	carbonyl (%)	alkyl/O-alkyl	aro/O-alkyl
Vieusart	No application	22,44	49,85	23,03	4,68	0,45	0,46
Sainte-Walburge	No application	23,33	24,34	51,22	1,11	0,96	2,10
Bressoux	No application	22,29	21,17	55,03	1,51	1,05	2,60
Vieusart	Cattle manure	30,49	41,98	23,11	4,43	0,73	0,55
Sainte-Walburge	Cattle manure	23,59	24,00	50,69	1,72	0,98	2,11
Bressoux	Cattle manure	19,83	27,83	49,81	2,53	0,71	1,79
Vieusart	Green waste compost	26,92	44,03	24,25	4,81	0,61	0,55
Sainte-Walburge	Green waste compost	23,24	17,34	56,56	2,85	1,34	3,26
Bressoux	Green waste compost	24,69	11,51	63,21	0,59	2,15	5,49
Vieusart	Cover crop restitution	22,94	45,97	27,81	3,27	0,50	0,60
Sainte-Walburge	Cover crop restitution	17,23	23,99	58,33	0,00	0,72	2,43
Bressoux	Cover crop restitution	24,98	18,04	56,26	0,72	1,39	3,12

Isotopic data

Sample	Site	Modality	Replicate	$\delta^{65}\text{Cu}$	2SD	$\delta^{66}\text{Zn}$	2SD	$\delta^{56}\text{Fe}$	2SD	Pb208/204	Pb207/204	Pb206/204	Pb208/206	Pb207/206
Soil	Vieusart	/	/	0,13	0,05	0,08	0,02	-0,07	0,04	38,543	15,631	18,526	2,081	0,844
Soil	Bressoux	/	/	0,16	0,02	0,39	0,03	0,09	0,06	38,100	15,607	18,105	2,104	0,862
Soil	Bressoux	/	/	0,12	0,06	0,54	0,02	0,16	0,04	38,082	15,606	18,088	2,105	0,863
Soil	Aubange	/	/	-0,01	0,03	0,29	0,03	-0,44	0,04	38,593	15,620	18,526	2,083	0,843
Maize roots	Vieusart	No application	A	-2,91	0,05	0,15	0,00	-0,23	0,05	38,498	15,616	18,575	2,073	0,841
Maize roots	Bressoux	No application	A	-0,82	0,04	0,50	0,02	0,08	0,04	38,450	15,624	18,571	2,070	0,841
Maize roots	Aubange	No application	A	-2,59	0,04	0,19	0,03	-0,44	0,08	38,400	15,612	18,459	2,080	0,846
Maize roots	Vieusart	Cattle manure	A	-2,28	0,03	0,31	0,03	-0,06	0,08	38,144	15,614	18,156	2,101	0,860
Maize roots	Bressoux	Cattle manure	A	-0,59	0,05	0,69	0,02	0,03	0,07	38,135	15,612	18,152	2,101	0,860
Maize roots	Aubange	Cattle manure	A	-2,06	0,02	0,29	0,03	-0,47	0,04	38,128	15,613	18,135	2,102	0,861
Maize roots	Vieusart	Green waste compost	A	-3,00	0,02	0,26	0,03	-0,03	0,07	38,472	15,621	18,506	2,079	0,844
Maize roots	Bressoux	Green waste compost	A	-2,59	0,06	0,67	0,02	0,13	0,07	38,376	15,613	18,404	2,085	0,848
Maize roots	Aubange	Green waste compost	A	-2,29	0,04	0,20	0,01	-0,37	0,05	38,528	15,625	18,513	2,081	0,844
Maize leaves	Vieusart	No application	A	-1,08	0,05	0,48	0,04	0,04	0,02	38,147	15,609	18,253	2,090	0,855
Maize leaves	Bressoux	No application	A	-0,59	0,11	0,04	0,04	0,17	0,06	38,191	15,612	18,259	2,092	0,855
Maize leaves	Aubange	No application	A	-1,54	0,02	0,59	0,03	0,03	0,04	38,144	15,607	18,267	2,088	0,854
Maize leaves	Vieusart	Cattle manure	A	-0,08	0,05	0,48	0,02	0,26	0,10	38,137	15,606	18,192	2,096	0,858
Maize leaves	Bressoux	Cattle manure	A	-1,17	0,03	-0,04	0,03	0,39	0,02	38,247	15,612	18,389	2,080	0,849
Maize leaves	Aubange	Cattle manure	A	-1,35	0,01	0,37	0,03	-0,02	0,04	38,300	15,609	18,431	2,078	0,847

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Maize leaves	Vieusart	Green waste compost	A	-0,01	0,07	0,32	0,02	0,16	0,03	38,386	15,612	18,454	2,080	0,846
Maize leaves	Bressoux	Green waste compost	A	-1,82	0,03	0,12	0,02	0,16	0,03	38,218	15,610	18,301	2,088	0,853
Maize leaves	Aubange	Green waste compost	A	-1,16	0,03	0,38	0,01	-0,01	0,06	38,203	15,619	18,436	2,072	0,847
Cattle manure	/	/	/	-2,42	0,02	0,34	0,02	0,11	0,04	38,374	15,623	18,527	2,071	0,843
Green waste compost	/	/	/	-1,15	0,04	0,03	0,04	0,08	0,04	38,206	15,613	18,233	2,095	0,856
Standard SRM 2709	/	/	/	0,22	0,03	0,17	0,05	0,15	0,03	38,982	15,670	19,102	2,041	0,820
Standard BHVO-2	/	/	/	0,32	0,00	0,02	0,02	0,11	0,06	38,269	15,550	18,618	2,056	0,835
Standard NIST 1515	/	/	/	-0,22	0,01	-0,13	0,01	-0,32	0,03	38,516	15,648	18,788	2,050	0,833

2. Field experiments

Experiment 1: rare earth elements as trace element tracers

Table. VI-17 – Trace element contents/concentrations in soil, plant parts, earthworms, soil extraction, soil solution, and snow samples for the field experiment (plot n°2).

Sample	Compartment	Species	Date	Sub-area	Units	Ba	Cd	Co	Cr	Cu	Mn	Pb	Sr	Tl	V	Zn
soil	0-30 cm		Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	2,2E+05	3,3E+02	9,3E+03	6,0E+04	1,5E+04	3,4E+05	2,1E+04	3,6E+04	2,3E+06	6,8E+04	4,6E+04
soil	0-30 cm		Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	2,4E+05	3,0E+02	9,5E+03	6,0E+04	1,3E+04	3,1E+05	2,0E+04	4,0E+04	2,3E+06	6,7E+04	4,7E+04
soil	0-30 cm		Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	2,3E+05	3,5E+02	8,3E+03	5,4E+04	1,3E+04	2,9E+05	2,3E+04	3,7E+04	1,6E+06	5,8E+04	4,5E+04
soil	30-50 cm		Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	2,4E+05	2,1E+02	9,7E+03	6,2E+04	1,3E+04	3,4E+05	1,6E+04	3,9E+04	2,7E+06	6,7E+04	3,8E+04
soil	30-50 cm		Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	2,2E+05	1,7E+02	1,1E+04	6,6E+04	1,3E+04	2,8E+05	1,5E+04	3,1E+04	3,0E+06	7,1E+04	3,7E+04
soil	30-50 cm		Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	2,2E+05	1,5E+02	7,6E+03	6,1E+04	1,1E+04	1,7E+05	1,4E+04	2,7E+04	2,2E+06	5,6E+04	3,3E+04
plant	root	Trifolium resupinatum	Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	3,2E+04	4,9E+02	1,0E+03	1,0E+04	1,7E+04	6,2E+04	2,1E+03	3,3E+04	3,5E+04	9,0E+03	5,3E+04
plant	root	Trifolium resupinatum	Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	3,1E+04	3,1E+02	9,5E+02	8,7E+03	1,3E+04	4,8E+04	2,0E+03	2,4E+04	2,9E+04	8,5E+03	7,0E+04
plant	root	Trifolium resupinatum	Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	2,9E+04	2,6E+02	8,9E+02	9,8E+03	1,2E+04	5,7E+04	2,2E+03	2,1E+04	2,1E+04	6,8E+03	2,1E+05
plant	root	Trifolium resupinatum	Dec. 15, 2020	A	$\mu\text{g kg}^{-1}$	3,6E+04	5,9E+02	1,5E+03	1,8E+04	2,3E+04	1,1E+05	3,8E+03	2,9E+04	1,1E+05	1,2E+04	4,5E+04
plant	root	Trifolium resupinatum	Dec. 15, 2020	B	$\mu\text{g kg}^{-1}$	4,3E+04	5,7E+02	1,4E+03	1,4E+04	1,8E+04	6,9E+04	3,3E+03	2,8E+04	1,5E+05	1,6E+04	5,4E+04
plant	root	Trifolium resupinatum	Dec. 15, 2020	C	$\mu\text{g kg}^{-1}$	3,7E+04	5,4E+02	1,4E+03	1,6E+04	1,8E+04	7,6E+04	3,5E+03	2,5E+04	2,3E+05	1,2E+04	4,6E+04
plant	root	Trifolium resupinatum	Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	6,8E+04	6,9E+02	2,0E+03	2,3E+04	2,3E+04	1,3E+05	4,7E+03	3,9E+04	5,8E+05	1,8E+04	6,8E+04
plant	root	Trifolium resupinatum	Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	5,9E+04	4,7E+02	1,7E+03	2,3E+04	2,1E+04	1,0E+05	4,1E+03	3,8E+04	3,6E+05	1,8E+04	7,5E+04
plant	root	Trifolium resupinatum	Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	5,8E+04	7,8E+02	1,6E+03	2,1E+04	2,3E+04	8,6E+04	4,6E+03	3,6E+04	3,7E+05	1,8E+04	6,7E+04
plant	root	Triticum spelta	Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	7,8E+04	5,9E+02	2,3E+03	2,1E+04	1,4E+04	1,3E+05	6,0E+03	2,6E+04	8,6E+04	1,8E+04	8,5E+04
plant	root	Triticum spelta	Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	1,1E+05	2,9E+02	3,3E+03	3,4E+04	1,2E+04	1,7E+05	8,6E+03	2,6E+04	1,2E+05	2,8E+04	1,0E+05
plant	root	Triticum spelta	Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	8,2E+04	2,7E+02	2,0E+03	3,3E+04	9,2E+03	9,9E+04	6,8E+03	1,9E+04	8,0E+04	1,8E+04	3,9E+04
plant	root	Triticum spelta	Dec. 15, 2020	A	$\mu\text{g kg}^{-1}$	1,2E+05	4,6E+02	3,6E+03	1,6E+05	1,9E+04	1,6E+05	2,0E+04	2,7E+04	7,8E+05	2,9E+04	5,8E+04
plant	root	Triticum spelta	Dec. 15, 2020	B	$\mu\text{g kg}^{-1}$	6,1E+04	3,6E+02	1,9E+03	3,6E+04	1,1E+04	9,7E+04	5,9E+03	1,9E+04	3,3E+05	1,7E+04	3,2E+04
plant	root	Triticum spelta	Dec. 15, 2020	C	$\mu\text{g kg}^{-1}$	5,4E+04	3,8E+02	1,7E+03	2,6E+04	1,1E+04	8,7E+04	4,1E+03	1,7E+04	4,2E+05	1,5E+04	3,4E+04
plant	root	Triticum spelta	Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	8,0E+04	5,8E+02	2,8E+03	3,2E+04	1,3E+04	2,0E+05	6,9E+03	2,3E+04	4,9E+05	2,5E+04	5,6E+04
plant	root	Triticum spelta	Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	7,7E+04	4,6E+02	2,7E+03	2,6E+04	1,2E+04	1,5E+05	6,1E+03	2,3E+04	5,6E+05	2,3E+04	4,9E+04
plant	root	Triticum spelta	Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	4,2E+04	1,0E+02	1,1E+03	1,3E+04	6,5E+03	7,7E+04	3,4E+03	1,7E+04	3,1E+05	9,7E+03	3,2E+04
plant	root	Vicia faba	Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	7,4E+04	3,0E+02	1,8E+03	2,1E+04	9,0E+03	1,0E+05	4,7E+03	3,0E+04	4,3E+04	1,4E+04	3,9E+04
plant	root	Vicia faba	Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	3,6E+04	1,5E+02	1,1E+03	1,1E+04	8,8E+03	5,0E+04	2,3E+03	1,9E+04	2,9E+04	7,9E+03	2,4E+04
plant	root	Vicia faba	Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	2,9E+04	1,3E+02	9,5E+02	8,4E+03	1,0E+04	4,7E+04	2,1E+03	1,9E+04	2,8E+04	6,1E+03	2,5E+04

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plant	root	Vicia faba	Dec. 15, 2020	A	$\mu\text{g kg}^{-1}$	7,3E+04	7,1E+02	2,4E+03	1,9E+04	1,7E+04	1,2E+05	5,5E+03	3,8E+04	5,9E+05	2,0E+04	4,1E+04
plant	root	Vicia faba	Dec. 15, 2020	B	$\mu\text{g kg}^{-1}$	8,4E+04	4,7E+02	2,5E+03	2,0E+04	1,8E+04	1,1E+05	5,6E+03	3,5E+04	5,4E+05	2,0E+04	3,5E+04
plant	root	Vicia faba	Dec. 15, 2020	C	$\mu\text{g kg}^{-1}$	4,2E+04	2,2E+02	1,1E+03	1,0E+04	1,5E+04	5,4E+04	3,0E+03	2,5E+04	2,9E+05	8,6E+03	3,6E+04
plant	root	Vicia faba	Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	7,5E+04	3,1E+02	2,2E+03	3,0E+04	2,3E+04	1,3E+05	5,0E+03	3,8E+04	4,7E+05	1,7E+04	4,5E+04
plant	root	Vicia faba	Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	8,9E+04	3,5E+02	2,4E+03	3,5E+04	2,2E+04	1,2E+05	5,5E+03	3,8E+04	5,1E+05	1,9E+04	5,4E+04
plant	root	Vicia faba	Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	4,9E+04	2,2E+02	1,2E+03	2,5E+04	2,8E+04	7,1E+04	3,2E+03	3,1E+04	5,5E+05	9,9E+03	4,3E+04
plant	shoot	Trifolium resupinatum	Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	1,6E+04	4,9E+01	3,2E+02	3,6E+03	6,9E+03	4,6E+04	6,7E+02	2,8E+04	2,0E+04	2,1E+03	4,1E+04
plant	shoot	Trifolium resupinatum	Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	1,5E+04	4,2E+01	3,7E+02	3,4E+03	5,8E+03	3,7E+04	7,3E+02	2,4E+04	1,2E+04	2,5E+03	7,2E+04
plant	shoot	Trifolium resupinatum	Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	1,2E+04	3,8E+01	2,7E+02	2,7E+03	6,3E+03	3,5E+04	8,6E+02	2,5E+04	4,9E+03	1,7E+03	7,1E+04
plant	shoot	Trifolium resupinatum	Dec. 15, 2020	A	$\mu\text{g kg}^{-1}$	2,4E+04	7,3E+01	4,5E+02	6,6E+03	7,9E+03	4,0E+04	1,2E+03	3,2E+04	1,7E+05	3,3E+03	3,2E+04
plant	shoot	Trifolium resupinatum	Dec. 15, 2020	B	$\mu\text{g kg}^{-1}$	2,6E+04	6,7E+01	5,1E+02	6,3E+03	6,8E+03	3,8E+04	1,4E+03	2,9E+04	1,6E+05	4,0E+03	3,0E+04
plant	shoot	Trifolium resupinatum	Dec. 15, 2020	C	$\mu\text{g kg}^{-1}$	2,0E+04	4,1E+01	4,1E+02	9,5E+03	8,9E+03	3,2E+04	1,3E+03	2,5E+04	1,2E+05	3,1E+03	3,1E+04
plant	shoot	Trifolium resupinatum	Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	3,3E+04	8,2E+01	7,8E+02	9,1E+03	1,1E+04	6,1E+04	2,1E+03	3,1E+04	2,7E+05	5,8E+03	4,8E+04
plant	shoot	Trifolium resupinatum	Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	2,2E+04	5,2E+01	4,9E+02	5,3E+03	9,4E+03	4,1E+04	1,2E+03	2,8E+04	1,9E+05	3,6E+03	4,9E+04
plant	shoot	Trifolium resupinatum	Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	2,9E+04	6,9E+01	6,9E+02	8,6E+03	1,0E+04	5,2E+04	2,1E+03	2,5E+04	2,3E+05	5,3E+03	4,6E+04
plant	shoot	Triticum spelta	Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	2,1E+04	1,0E+02	1,9E+02	3,2E+03	6,1E+03	3,8E+04	5,6E+02	1,5E+04	1,0E+04	1,5E+03	5,2E+04
plant	shoot	Triticum spelta	Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	2,4E+04	1,2E+02	3,4E+02	4,8E+03	6,2E+03	4,2E+04	9,2E+02	1,2E+04	4,7E+04	2,7E+03	4,2E+04
plant	shoot	Triticum spelta	Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	2,1E+04	1,5E+02	2,4E+02	7,2E+03	7,4E+03	3,7E+04	8,3E+02	1,4E+04	1,9E+04	2,0E+03	3,8E+04
plant	shoot	Triticum spelta	Dec. 15, 2020	A	$\mu\text{g kg}^{-1}$	2,4E+04	6,6E+01	5,3E+02	9,7E+03	5,8E+03	4,9E+04	1,5E+03	1,0E+04	1,8E+05	4,3E+03	2,5E+04
plant	shoot	Triticum spelta	Dec. 15, 2020	B	$\mu\text{g kg}^{-1}$	2,2E+04	6,8E+01	3,8E+02	7,2E+03	5,6E+03	3,5E+04	1,3E+03	1,0E+04	1,3E+05	3,3E+03	2,2E+04
plant	shoot	Triticum spelta	Dec. 15, 2020	C	$\mu\text{g kg}^{-1}$	2,7E+04	8,4E+01	5,4E+02	7,6E+03	5,0E+03	4,2E+04	1,5E+03	1,0E+04	2,0E+05	4,5E+03	2,4E+04
plant	shoot	Triticum spelta	Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	2,9E+04	9,1E+01	7,4E+02	9,4E+03	6,2E+03	6,7E+04	2,1E+03	1,5E+04	2,6E+05	6,2E+03	3,1E+04
plant	shoot	Triticum spelta	Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	1,8E+04	7,5E+01	4,8E+02	5,8E+03	5,3E+03	4,2E+04	1,2E+03	9,4E+03	7,3E+04	3,9E+03	2,9E+04
plant	shoot	Triticum spelta	Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	6,7E+04	5,0E+02	2,3E+03	2,7E+04	1,3E+04	1,4E+05	6,6E+03	2,2E+04	4,5E+05	2,2E+04	5,0E+04
plant	shoot	Vicia faba	Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	9,4E+03	4,3E+01	3,7E+02	3,9E+03	6,9E+03	4,7E+04	7,3E+02	1,1E+04	6,3E+03	1,5E+03	4,5E+04
plant	shoot	Vicia faba	Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	8,4E+03	3,5E+01	4,1E+02	3,3E+03	9,1E+03	3,7E+04	5,1E+02	1,5E+04	1,4E+04	2,2E+03	4,5E+04
plant	shoot	Vicia faba	Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	7,3E+03	3,4E+01	3,6E+02	2,7E+03	8,8E+03	3,6E+04	5,3E+02	1,3E+04	1,2E+04	1,1E+03	5,6E+04
plant	shoot	Vicia faba	Dec. 15, 2020	A	$\mu\text{g kg}^{-1}$	7,0E+03	3,6E+01	2,7E+02	3,2E+03	8,3E+03	2,6E+04	7,6E+02	1,1E+04	5,8E+04	1,0E+03	2,8E+04
plant	shoot	Vicia faba	Dec. 15, 2020	B	$\mu\text{g kg}^{-1}$	6,7E+03	4,0E+01	2,7E+02	3,1E+03	1,0E+04	2,6E+04	7,0E+02	1,0E+04	3,7E+04	9,7E+02	3,1E+04
plant	shoot	Vicia faba	Dec. 15, 2020	C	$\mu\text{g kg}^{-1}$	6,9E+03	3,5E+01	2,6E+02	2,9E+03	9,6E+03	2,7E+04	6,9E+02	1,4E+04	3,2E+04	8,7E+02	3,3E+04
plant	shoot	Vicia faba	Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	2,2E+04	7,3E+01	6,4E+02	9,6E+03	1,2E+04	4,9E+04	1,6E+03	1,9E+04	1,1E+05	4,1E+03	3,6E+04
plant	shoot	Vicia faba	Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	1,8E+04	8,2E+01	5,7E+02	8,2E+03	1,2E+04	4,2E+04	1,6E+03	1,5E+04	1,2E+05	3,7E+03	4,0E+04
plant	shoot	Vicia faba	Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	1,6E+04	8,3E+01	5,1E+02	6,7E+03	1,1E+04	3,8E+04	1,6E+03	1,4E+04	1,5E+05	3,1E+03	3,7E+04
earthworm			Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	3,3E+03	7,2E+03	4,3E+03	6,5E+02	7,3E+03	3,2E+04	7,0E+02	1,2E+04	1,3E+04	7,2E+02	3,4E+05
earthworm			Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	2,2E+03	6,6E+03	3,4E+03	7,7E+02	7,2E+03	1,3E+04	3,2E+02	6,1E+03	1,4E+04	7,1E+02	3,4E+05
earthworm			Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	2,4E+03	5,7E+03	2,7E+03	6,3E+02	7,0E+03	1,4E+04	4,1E+02	7,4E+03	1,5E+04	7,1E+02	3,2E+05
soil extraction	0-30 cm		Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	2,4E+02	1,1E-01	2,4E-01	1,5E+00	9,0E+00	1,1E+01	4,5E-01	1,3E+01	1,8E+01	1,0E+01	1,7E+02
soil extraction	0-30 cm		Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	1,5E+02	4,6E-02	1,4E-01	9,9E-01	7,0E+00	4,1E+00	2,1E-01	1,1E+01	1,0E+01	7,1E+00	8,2E+01

soil extraction	0-30 cm		Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	1,9E+01	9,7E-02	4,7E-01	3,0E+00	8,9E+00	2,4E+01	3,0E+00	1,2E+01	3,4E+01	1,1E+01	1,0E+01
soil extraction	30-50 cm		Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	3,6E+01	5,7E-02	6,9E-01	4,9E+00	5,1E+00	3,3E+01	2,3E+00	1,1E+01	7,9E+01	9,3E+00	1,0E+01
soil extraction	30-50 cm		Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	1,4E+02	2,3E-02	2,9E-01	2,2E+00	2,9E+00	6,7E+00	4,2E-01	9,9E+00	4,3E+01	2,9E+00	6,4E+01
soil extraction	30-50 cm		Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	1,2E+01	2,6E-02	4,0E-01	3,3E+00	4,4E+00	1,1E+01	9,4E-01	7,5E+00	5,7E+01	4,3E+00	5,8E+00
soil solution			Oct. 21, 2020	A	$\mu\text{g L}^{-1}$	4,1E+01	2,2E-02	2,3E-01	5,1E-01	5,1E+00	2,0E+00	5,4E-04	9,2E+01	3,4E-01	3,8E+00	3,4E+02
soil solution			Oct. 21, 2020	B	$\mu\text{g L}^{-1}$	2,7E+01	2,4E-02	2,0E-01	4,9E-01	4,8E+00	8,5E-01	5,4E-04	9,5E+01	2,5E-01	3,4E+00	1,3E+02
soil solution			Oct. 21, 2020	C	$\mu\text{g L}^{-1}$	2,9E+01	2,4E-02	2,2E-01	4,9E-01	6,8E+00	2,0E+00	4,1E-02	8,9E+01	8,7E-01	3,5E+00	2,0E+02
soil solution			Nov. 16, 2020	A	$\mu\text{g L}^{-1}$	1,6E+01	1,9E-02	1,6E-01	5,4E-01	5,0E+00	7,7E-01	2,0E-03	8,1E+01	3,7E-01	3,5E+00	1,6E+02
soil solution			Nov. 16, 2020	B	$\mu\text{g L}^{-1}$	2,2E+01	1,8E-02	1,4E-01	3,6E-01	4,3E+00	5,6E-01	5,4E-04	7,1E+01	2,4E-01	2,9E+00	1,1E+02
soil solution			Nov. 16, 2020	C	$\mu\text{g L}^{-1}$	1,4E+01	2,5E-02	1,6E-01	4,6E-01	7,4E+00	1,4E+00	5,2E-02	7,3E+01	8,9E-01	2,9E+00	1,4E+02
soil solution			Dec. 15, 2020	A	$\mu\text{g L}^{-1}$	2,3E+01	2,7E-02	1,7E-01	5,2E-01	4,5E+00	4,0E+00	1,0E-01	8,4E+01	1,3E+00	3,1E+00	1,2E+02
soil solution			Dec. 15, 2020	B	$\mu\text{g L}^{-1}$	2,0E+01	1,7E-02	1,1E-01	3,1E-01	3,6E+00	7,9E-01	2,5E-02	7,3E+01	4,8E-01	2,4E+00	1,1E+02
soil solution			Dec. 15, 2020	C	$\mu\text{g L}^{-1}$	1,7E+01	3,2E-02	2,3E-01	6,3E-01	1,1E+01	8,9E+00	4,8E-01	6,4E+01	3,7E+00	3,3E+00	1,5E+02
soil solution			Jan. 14, 2021	A	$\mu\text{g L}^{-1}$	1,9E+01	2,3E-02	1,5E-01	7,1E-01	4,1E+00	3,2E+00	4,7E-02	7,9E+01	7,7E-01	2,5E+00	9,6E+01
soil solution			Jan. 14, 2021	B	$\mu\text{g L}^{-1}$	1,9E+01	2,1E-02	1,5E-01	2,9E-01	3,1E+00	2,8E+00	4,6E-02	7,9E+01	3,2E-01	1,8E+00	7,4E+01
soil solution			Jan. 14, 2021	C	$\mu\text{g L}^{-1}$	1,7E+01	2,3E-02	1,2E-01	3,5E-01	5,4E+00	2,2E+00	2,7E-01	6,4E+01	9,5E-01	2,3E+00	8,6E+01
soil solution			Feb. 4, 2021	A	$\mu\text{g L}^{-1}$	2,6E+01	1,6E-02	1,0E-01	4,0E-01	3,2E+00	9,7E-01	3,3E-02	8,4E+01	6,7E-01	2,8E+00	2,3E+02
soil solution			Feb. 4, 2021	B	$\mu\text{g L}^{-1}$	3,0E+01	1,9E-02	1,4E-01	5,4E-01	2,9E+00	4,3E+00	3,6E-02	8,8E+01	5,3E-01	2,7E+00	3,5E+02
soil solution			Feb. 4, 2021	C	$\mu\text{g L}^{-1}$	1,9E+01	2,1E-02	1,4E-01	4,1E-01	4,1E+00	2,1E+00	3,4E-02	7,7E+01	6,4E-01	2,6E+00	1,1E+02
snow			Jan. 14, 2021		$\mu\text{g L}^{-1}$	1,7E+00	2,8E-02	1,0E-01	6,6E-01	2,8E+00	9,7E+00	1,2E+00	1,5E+00	1,8E+00	4,3E-01	3,4E+01

Appendices

Table. VI-18 – Rare earth element contents/concentrations in soil, plant parts, earthworms, soil extraction, soil solution, and snow samples for the field experiment (plot n°2).

Sample	Type	Species	Date	Sub-area	Unit	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ZREE	LREE/HREE	Ce anomaly	Eu anomaly	Tb anomaly	Yb anomaly
soil	0-30 cm		Oct. 16, 2020	A	µg kg ⁻¹	2,1E+04	4,7E+04	5,7E+03	2,2E+04	4,2E+03	7,1E+02	3,6E+03	4,5E+02	2,6E+03	4,7E+02	1,3E+03	1,9E+02	1,1E+03	1,6E+02	1,1E+05	1,22	1,02	0,79	0,82	0,99
soil	0-30 cm		Oct. 16, 2020	B	µg kg ⁻¹	2,4E+04	5,5E+04	6,4E+03	2,5E+04	4,6E+03	7,6E+02	3,9E+03	4,6E+02	2,7E+03	5,0E+02	1,4E+03	2,0E+02	1,3E+03	1,9E+02	1,3E+05	1,27	1,03	0,78	0,79	1,01
soil	0-30 cm		Oct. 16, 2020	C	µg kg ⁻¹	1,9E+04	4,2E+04	5,0E+03	1,9E+04	3,7E+03	6,6E+02	3,2E+03	3,9E+02	2,2E+03	4,1E+02	1,2E+03	1,7E+02	1,1E+03	1,6E+02	9,7E+04	1,22	1,02	0,84	0,83	0,99
soil	30-50 cm		Oct. 16, 2020	A	µg kg ⁻¹	2,2E+04	5,0E+04	6,1E+03	2,4E+04	4,5E+03	7,2E+02	3,7E+03	4,7E+02	2,7E+03	5,0E+02	1,4E+03	2,0E+02	1,2E+03	1,8E+02	1,2E+05	1,22	1,01	0,77	0,83	0,99
soil	30-50 cm		Oct. 16, 2020	B	µg kg ⁻¹	1,9E+04	4,5E+04	5,4E+03	2,1E+04	4,2E+03	6,9E+02	3,5E+03	4,5E+02	2,6E+03	4,9E+02	1,3E+03	2,0E+02	1,3E+03	1,8E+02	1,1E+05	1,14	1,04	0,78	0,82	1,02
soil	30-50 cm		Oct. 16, 2020	C	µg kg ⁻¹	1,7E+04	4,0E+04	4,9E+03	1,9E+04	3,9E+03	7,7E+02	3,4E+03	4,1E+02	2,4E+03	4,3E+02	1,2E+03	1,7E+02	1,1E+03	1,6E+02	9,6E+04	1,19	1,01	0,92	0,81	1,00
plant	root	Trifolium resupinatum	Oct. 16, 2020	A	µg kg ⁻¹	2,7E+03	5,2E+03	6,6E+02	2,7E+03	5,5E+02	1,1E+02	5,4E+02	6,6E+01	3,9E+02	7,5E+01	2,1E+02	3,1E+01	2,0E+02	2,9E+01	1,3E+04	0,97	0,91	0,88	0,79	1,02
plant	root	Trifolium resupinatum	Oct. 16, 2020	B	µg kg ⁻¹	2,9E+03	5,8E+03	6,7E+02	2,6E+03	5,1E+02	9,6E+01	4,9E+02	5,8E+01	3,3E+02	6,3E+01	1,8E+02	2,6E+01	1,7E+02	2,5E+01	1,4E+04	1,12	0,97	0,83	0,79	1,02
plant	root	Trifolium resupinatum	Oct. 16, 2020	C	µg kg ⁻¹	2,5E+03	5,0E+03	5,7E+02	2,2E+03	4,1E+02	8,0E+01	4,1E+02	4,9E+01	2,9E+02	5,5E+01	1,6E+02	2,3E+01	1,4E+02	2,2E+01	1,2E+04	1,08	0,98	0,85	0,79	0,96
plant	root	Trifolium resupinatum	Dec. 15, 2020	A	µg kg ⁻¹	3,3E+03	6,4E+03	8,2E+02	3,3E+03	6,7E+02	1,3E+02	6,5E+02	8,3E+01	5,0E+02	9,5E+01	2,7E+02	3,9E+01	2,5E+02	3,6E+01	1,7E+04	0,94	0,91	0,84	0,82	1,00
plant	root	Trifolium resupinatum	Dec. 15, 2020	B	µg kg ⁻¹	4,0E+03	8,2E+03	9,8E+02	3,8E+03	7,5E+02	1,4E+02	7,0E+02	9,2E+01	5,5E+02	1,1E+02	3,0E+02	4,5E+01	2,8E+02	4,2E+01	2,0E+04	0,98	0,97	0,81	0,83	0,97
plant	root	Trifolium resupinatum	Dec. 15, 2020	C	µg kg ⁻¹	3,3E+03	6,6E+03	8,0E+02	3,1E+03	6,1E+02	1,1E+02	5,7E+02	7,3E+01	4,3E+02	8,3E+01	2,3E+02	3,3E+01	2,1E+02	3,2E+01	1,6E+04	1,03	0,96	0,83	0,82	0,99
plant	root	Trifolium resupinatum	Feb. 4, 2021	A	µg kg ⁻¹	7,0E+03	1,4E+04	1,7E+03	6,8E+03	1,3E+03	2,5E+02	1,3E+03	1,6E+02	9,4E+02	1,8E+02	5,2E+02	7,5E+01	4,9E+02	7,4E+01	3,5E+04	1,00	0,96	0,83	0,84	0,99
plant	root	Trifolium resupinatum	Feb. 4, 2021	B	µg kg ⁻¹	6,0E+03	1,2E+04	1,4E+03	5,6E+03	1,1E+03	2,0E+02	1,0E+03	1,3E+02	7,4E+02	1,4E+02	4,0E+02	5,9E+01	3,8E+02	5,7E+01	3,0E+04	1,07	1,00	0,83	0,82	1,01
plant	root	Trifolium resupinatum	Feb. 4, 2021	C	µg kg ⁻¹	6,4E+03	1,3E+04	1,5E+03	5,8E+03	1,1E+03	1,9E+02	1,0E+03	1,3E+02	7,1E+02	1,4E+02	3,8E+02	5,5E+01	3,6E+02	5,4E+01	3,1E+04	1,13	0,99	0,79	0,85	1,02

Field experiments

plant	root	Triticum spelta	Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	7,8E+03	1,6E+04	2,0E+03	7,8E+03	1,6E+03	3,0E+02	1,5E+03	1,8E+02	1,1E+03	2,1E+02	5,9E+02	8,7E+01	5,5E+02	8,2E+01	4,0E+04	1,01	0,96	0,85	0,81	1,00
plant	root	Triticum spelta	Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	8,0E+03	1,7E+04	2,2E+03	8,7E+03	1,8E+03	3,3E+02	1,6E+03	2,0E+02	1,2E+03	2,4E+02	6,9E+02	9,8E+01	6,4E+02	9,6E+01	4,3E+04	0,98	0,99	0,87	0,83	1,00
plant	root	Triticum spelta	Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	7,1E+03	1,5E+04	1,7E+03	6,5E+03	1,2E+03	2,3E+02	1,1E+03	1,4E+02	8,1E+02	1,5E+02	4,5E+02	6,3E+01	4,1E+02	6,1E+01	3,5E+04	1,14	1,00	0,84	0,80	1,00
plant	root	Triticum spelta	Dec. 15, 2020	A	$\mu\text{g kg}^{-1}$	9,5E+03	2,1E+04	2,4E+03	9,4E+03	1,8E+03	3,4E+02	1,7E+03	2,1E+02	1,3E+03	2,4E+02	6,9E+02	1,0E+02	6,5E+02	1,0E+02	4,9E+04	1,04	1,01	0,84	0,78	0,98
plant	root	Triticum spelta	Dec. 15, 2020	B	$\mu\text{g kg}^{-1}$	6,2E+03	1,3E+04	1,5E+03	6,0E+03	1,2E+03	2,1E+02	1,0E+03	1,3E+02	7,7E+02	1,5E+02	4,1E+02	6,0E+01	3,9E+02	6,0E+01	3,1E+04	1,09	0,98	0,82	0,83	0,98
plant	root	Triticum spelta	Dec. 15, 2020	C	$\mu\text{g kg}^{-1}$	5,2E+03	1,0E+04	1,3E+03	5,0E+03	1,0E+03	1,9E+02	9,4E+02	1,2E+02	7,3E+02	1,3E+02	3,9E+02	5,7E+01	3,6E+02	5,4E+01	2,6E+04	1,00	0,95	0,84	0,82	1,00
plant	root	Triticum spelta	Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	1,0E+04	2,1E+04	2,5E+03	9,9E+03	2,0E+03	3,7E+02	1,9E+03	2,4E+02	1,4E+03	2,7E+02	7,4E+02	1,1E+02	6,8E+02	1,1E+02	5,2E+04	1,02	0,97	0,84	0,83	0,97
plant	root	Triticum spelta	Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	1,0E+04	2,1E+04	2,4E+03	9,2E+03	1,8E+03	3,2E+02	1,7E+03	2,1E+02	1,2E+03	2,4E+02	6,6E+02	9,7E+01	6,2E+02	9,4E+01	5,0E+04	1,07	1,00	0,81	0,83	0,98
plant	root	Triticum spelta	Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	3,9E+03	7,9E+03	8,9E+02	3,4E+03	6,5E+02	1,2E+02	6,3E+02	8,2E+01	4,9E+02	9,5E+01	2,7E+02	4,0E+01	2,6E+02	4,0E+01	1,9E+04	0,99	1,00	0,81	0,83	1,00
plant	root	Vicia faba	Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	6,8E+03	1,4E+04	1,7E+03	6,4E+03	1,2E+03	2,3E+02	1,2E+03	1,4E+02	8,3E+02	1,6E+02	4,5E+02	6,4E+01	4,2E+02	6,1E+01	3,3E+04	1,09	0,98	0,82	0,81	1,01
plant	root	Vicia faba	Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	3,0E+03	6,2E+03	7,2E+02	2,8E+03	5,4E+02	1,0E+02	5,3E+02	6,8E+01	4,1E+02	7,8E+01	2,3E+02	3,4E+01	2,1E+02	3,2E+01	1,5E+04	0,97	1,00	0,84	0,82	0,99
plant	root	Vicia faba	Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	2,4E+03	4,9E+03	5,5E+02	2,1E+03	4,0E+02	7,7E+01	3,9E+02	4,8E+01	2,9E+02	5,6E+01	1,6E+02	2,4E+01	1,5E+02	2,4E+01	1,2E+04	1,03	1,00	0,84	0,80	0,98
plant	root	Vicia faba	Dec. 15, 2020	A	$\mu\text{g kg}^{-1}$	5,9E+03	1,2E+04	1,5E+03	6,2E+03	1,3E+03	2,5E+02	1,2E+03	1,6E+02	9,7E+02	1,9E+02	5,5E+02	7,7E+01	4,9E+02	7,3E+01	3,1E+04	0,91	0,93	0,90	0,84	1,00
plant	root	Vicia faba	Dec. 15, 2020	B	$\mu\text{g kg}^{-1}$	6,5E+03	1,4E+04	1,7E+03	6,7E+03	1,3E+03	2,6E+02	1,2E+03	1,6E+02	9,9E+02	1,9E+02	5,5E+02	8,2E+01	5,2E+02	7,7E+01	3,4E+04	0,95	0,97	0,88	0,83	1,00
plant	root	Vicia faba	Dec. 15, 2020	C	$\mu\text{g kg}^{-1}$	3,7E+03	7,6E+03	9,0E+02	3,5E+03	6,7E+02	1,2E+02	6,4E+02	8,1E+01	4,7E+02	8,9E+01	2,5E+02	3,7E+01	2,3E+02	3,7E+01	1,8E+04	1,05	0,97	0,82	0,82	0,97
plant	root	Vicia faba	Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	8,6E+03	1,6E+04	2,1E+03	8,3E+03	1,6E+03	2,7E+02	1,5E+03	1,9E+02	1,0E+03	2,0E+02	5,5E+02	7,8E+01	5,1E+02	7,8E+01	4,1E+04	1,09	0,87	0,76	0,84	1,00
plant	root	Vicia faba	Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	8,2E+03	1,8E+04	2,0E+03	7,9E+03	1,5E+03	2,7E+02	1,4E+03	1,8E+02	1,1E+03	2,1E+02	6,0E+02	8,7E+01	5,7E+02	8,7E+01	4,2E+04	1,02	1,02	0,81	0,84	1,00
plant	root	Vicia faba	Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	5,0E+03	1,0E+04	1,2E+03	4,6E+03	8,7E+02	1,5E+02	7,8E+02	1,0E+02	5,7E+02	1,1E+02	3,2E+02	4,8E+01	3,1E+02	4,9E+01	2,4E+04	1,08	0,99	0,78	0,84	0,99

Appendices

plant	shoot	Trifolium resupinatum	Oct. 16, 2020	A	µg kg ⁻¹	1,0E+03	2,0E+03	2,3E+02	8,9E+02	1,7E+02	3,0E+01	1,7E+02	1,9E+01	1,2E+02	2,3E+01	6,4E+01	9,4E+00	6,0E+01	9,0E+00	4,8E+03	1,06	0,99	0,78	0,77	1,00
plant	shoot	Trifolium resupinatum	Oct. 16, 2020	B	µg kg ⁻¹	9,6E+02	2,0E+03	2,2E+02	8,6E+02	1,7E+02	3,1E+01	1,6E+02	1,9E+01	1,1E+02	2,2E+01	6,5E+01	9,2E+00	6,0E+01	9,2E+00	4,7E+03	1,07	1,01	0,83	0,78	0,99
plant	shoot	Trifolium resupinatum	Oct. 16, 2020	C	µg kg ⁻¹	6,9E+02	1,4E+03	1,6E+02	6,2E+02	1,2E+02	2,2E+01	1,1E+02	1,2E+01	8,0E+01	1,6E+01	4,6E+01	7,1E+00	4,6E+01	6,7E+00	3,3E+03	1,05	0,99	0,86	0,75	1,01
plant	shoot	Trifolium resupinatum	Dec. 15, 2020	A	µg kg ⁻¹	1,7E+03	3,6E+03	4,3E+02	1,6E+03	3,2E+02	5,2E+01	2,9E+02	3,6E+01	2,1E+02	4,0E+01	1,1E+02	1,6E+01	1,0E+02	1,6E+01	8,5E+03	1,10	0,98	0,74	0,81	0,99
plant	shoot	Trifolium resupinatum	Dec. 15, 2020	B	µg kg ⁻¹	1,5E+03	3,2E+03	3,8E+02	1,5E+03	3,0E+02	6,0E+01	2,9E+02	3,7E+01	2,4E+02	4,4E+01	1,3E+02	2,0E+01	1,3E+02	2,0E+01	7,9E+03	0,91	0,99	0,88	0,81	0,98
plant	shoot	Trifolium resupinatum	Dec. 15, 2020	C	µg kg ⁻¹	1,3E+03	2,8E+03	3,3E+02	1,3E+03	2,3E+02	4,4E+01	2,1E+02	2,7E+01	1,6E+02	3,1E+01	8,7E+01	1,3E+01	8,7E+01	1,4E+01	6,6E+03	1,08	1,00	0,87	0,83	0,99
plant	shoot	Trifolium resupinatum	Feb. 4, 2021	A	µg kg ⁻¹	2,7E+03	5,7E+03	6,7E+02	2,6E+03	5,2E+02	9,2E+01	4,7E+02	6,1E+01	3,5E+02	6,9E+01	2,0E+02	3,0E+01	1,9E+02	2,8E+01	1,4E+04	1,02	1,00	0,81	0,83	1,01
plant	shoot	Trifolium resupinatum	Feb. 4, 2021	B	µg kg ⁻¹	1,5E+03	3,1E+03	3,5E+02	1,3E+03	2,6E+02	5,0E+01	2,4E+02	3,2E+01	1,8E+02	3,7E+01	1,1E+02	1,7E+01	1,0E+02	1,6E+01	7,3E+03	0,99	1,00	0,85	0,85	0,93
plant	shoot	Trifolium resupinatum	Feb. 4, 2021	C	µg kg ⁻¹	2,8E+03	5,6E+03	6,3E+02	2,4E+03	4,5E+02	8,2E+01	4,1E+02	5,1E+01	3,0E+02	6,0E+01	1,7E+02	2,6E+01	1,7E+02	2,7E+01	1,3E+04	1,09	0,99	0,83	0,82	0,98
plant	shoot	Triticum spelta	Oct. 16, 2020	A	µg kg ⁻¹	8,3E+02	1,7E+03	2,0E+02	7,7E+02	1,4E+02	2,6E+01	1,3E+02	1,5E+01	8,5E+01	1,6E+01	4,2E+01	6,0E+00	3,9E+01	5,8E+00	4,0E+03	1,30	0,98	0,82	0,76	0,99
plant	shoot	Triticum spelta	Oct. 16, 2020	B	µg kg ⁻¹	1,2E+03	2,4E+03	2,8E+02	1,1E+03	2,1E+02	3,8E+01	2,0E+02	2,4E+01	1,4E+02	2,7E+01	7,8E+01	1,2E+01	7,3E+01	1,1E+01	5,8E+03	1,08	1,00	0,81	0,78	0,99
plant	shoot	Triticum spelta	Oct. 16, 2020	C	µg kg ⁻¹	9,0E+02	1,8E+03	2,1E+02	8,0E+02	1,5E+02	2,7E+01	1,4E+02	1,7E+01	1,1E+02	2,1E+01	6,2E+01	9,1E+00	5,9E+01	8,7E+00	4,4E+03	1,03	1,01	0,81	0,79	1,01
plant	shoot	Triticum spelta	Dec. 15, 2020	A	µg kg ⁻¹	2,5E+03	5,1E+03	6,0E+02	2,3E+03	4,4E+02	7,1E+01	4,0E+02	5,0E+01	2,9E+02	5,4E+01	1,5E+02	2,3E+01	1,5E+02	2,3E+01	1,2E+04	1,09	0,99	0,74	0,82	1,00
plant	shoot	Triticum spelta	Dec. 15, 2020	B	µg kg ⁻¹	1,5E+03	3,1E+03	3,6E+02	1,3E+03	2,5E+02	4,3E+01	2,3E+02	2,9E+01	1,6E+02	3,1E+01	8,5E+01	1,2E+01	8,1E+01	1,2E+01	7,2E+03	1,16	0,99	0,79	0,83	1,00
plant	shoot	Triticum spelta	Dec. 15, 2020	C	µg kg ⁻¹	2,2E+03	4,6E+03	5,5E+02	2,1E+03	4,2E+02	6,7E+01	3,8E+02	4,8E+01	2,7E+02	5,2E+01	1,5E+02	2,2E+01	1,4E+02	2,2E+01	1,1E+04	1,06	0,97	0,73	0,83	0,98
plant	shoot	Triticum spelta	Feb. 4, 2021	A	µg kg ⁻¹	2,7E+03	5,7E+03	6,6E+02	2,5E+03	4,9E+02	9,3E+01	4,7E+02	6,0E+01	3,5E+02	6,9E+01	2,0E+02	2,8E+01	1,9E+02	3,0E+01	1,4E+04	1,00	1,00	0,84	0,83	1,01
plant	shoot	Triticum spelta	Feb. 4, 2021	B	µg kg ⁻¹	1,4E+03	2,9E+03	3,3E+02	1,3E+03	2,6E+02	4,7E+01	2,5E+02	3,3E+01	1,9E+02	3,7E+01	1,0E+02	1,5E+01	9,6E+01	1,5E+01	7,0E+03	0,98	1,02	0,80	0,84	0,98
plant	shoot	Triticum spelta	Feb. 4, 2021	C	µg kg ⁻¹	7,7E+03	1,6E+04	1,8E+03	6,8E+03	1,3E+03	2,5E+02	1,2E+03	1,6E+02	9,5E+02	1,8E+02	6,2E+02	7,4E+01	4,7E+02	7,0E+01	3,7E+04	1,02	0,99	0,84	0,84	0,98

plant	shoot	Vicia faba	Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	8,5E+02	1,7E+03	2,0E+02	7,6E+02	1,4E+02	2,5E+01	1,3E+02	1,5E+01	9,4E+01	1,8E+01	5,1E+01	7,2E+00	4,7E+01	7,3E+00	4,0E+03	1,14	0,97	0,78	0,73	1,00
plant	shoot	Vicia faba	Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	6,0E+02	1,2E+03	1,3E+02	5,0E+02	9,6E+01	1,8E+01	9,0E+01	1,0E+01	6,8E+01	1,3E+01	3,7E+01	5,4E+00	3,5E+01	5,5E+00	2,8E+03	1,08	0,97	0,82	0,73	0,99
plant	shoot	Vicia faba	Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	6,9E+02	1,3E+03	1,5E+02	5,4E+02	9,9E+01	1,7E+01	9,7E+01	1,1E+01	6,9E+01	1,3E+01	3,8E+01	5,4E+00	3,7E+01	5,6E+00	3,1E+03	1,14	0,99	0,76	0,73	1,04
plant	shoot	Vicia faba	Dec. 15, 2020	A	$\mu\text{g kg}^{-1}$	5,0E+02	1,0E+03	1,3E+02	4,6E+02	8,6E+01	1,5E+01	8,0E+01	1,1E+01	6,8E+01	1,3E+01	3,6E+01	5,3E+00	3,7E+01	5,5E+00	2,5E+03	0,98	0,96	0,78	0,81	1,06
plant	shoot	Vicia faba	Dec. 15, 2020	B	$\mu\text{g kg}^{-1}$	3,8E+02	7,6E+02	9,0E+01	3,4E+02	6,4E+01	1,2E+01	7,1E+01	8,7E+00	5,5E+01	1,0E+01	3,1E+01	4,7E+00	3,1E+01	4,8E+00	1,9E+03	0,86	0,96	0,78	0,78	1,00
plant	shoot	Vicia faba	Dec. 15, 2020	C	$\mu\text{g kg}^{-1}$	6,2E+02	1,2E+03	1,4E+02	5,3E+02	9,8E+01	1,5E+01	8,8E+01	9,8E+00	5,4E+01	9,9E+00	3,1E+01	4,2E+00	2,7E+01	4,8E+00	2,9E+03	1,29	0,97	0,68	0,78	0,92
plant	shoot	Vicia faba	Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	2,0E+03	4,2E+03	5,0E+02	1,9E+03	3,7E+02	6,1E+01	3,4E+02	4,2E+01	2,4E+02	5,6E+01	1,4E+02	2,0E+01	1,3E+02	2,0E+01	1,0E+04	1,04	0,99	0,74	0,82	0,97
plant	shoot	Vicia faba	Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	1,7E+03	3,4E+03	3,9E+02	1,5E+03	2,9E+02	4,9E+01	2,5E+02	3,3E+01	1,9E+02	3,6E+01	1,0E+02	1,5E+01	1,0E+02	1,5E+01	8,0E+03	1,10	0,99	0,78	0,85	1,01
plant	shoot	Vicia faba	Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	1,4E+03	2,8E+03	3,3E+02	1,3E+03	2,4E+02	4,3E+01	2,2E+02	2,9E+01	1,6E+02	3,1E+01	8,7E+01	1,3E+01	8,1E+01	1,3E+01	6,7E+03	1,08	0,98	0,80	0,84	0,94
earthworm			Feb. 4, 2021	A	$\mu\text{g kg}^{-1}$	2,5E+02	2,9E+02	5,4E+01	2,3E+02	4,5E+01	1,0E+01	5,2E+01	7,0E+00	4,4E+01	9,0E+00	2,7E+01	3,4E+00	2,2E+01	3,5E+00	1,0E+03	0,71	0,59	0,92	0,82	0,98
earthworm			Feb. 4, 2021	B	$\mu\text{g kg}^{-1}$	2,0E+02	3,2E+02	4,3E+01	1,7E+02	3,6E+01	7,8E+00	3,9E+01	5,1E+00	3,1E+01	7,2E+00	1,9E+01	2,5E+00	1,4E+01	2,2E+00	9,0E+02	0,83	0,80	0,91	0,83	0,89
earthworm			Feb. 4, 2021	C	$\mu\text{g kg}^{-1}$	2,4E+02	3,6E+02	5,3E+01	2,1E+02	5,1E+01	9,1E+00	7,2E+01	1,4E+01	1,0E+02	2,2E+01	6,7E+01	9,3E+00	5,4E+01	7,8E+00	1,3E+03	0,32	0,76	0,64	0,90	0,96
soil extraction	0-30 cm		Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	6,1E-01	1,1E+00	1,7E-01	7,5E-01	1,6E-01	5,1E-02	1,8E-01	2,2E-02	1,4E-01	2,7E-02	7,7E-02	1,1E-02	6,8E-02	1,0E-02	3,4E+00	0,82	0,78	1,25	0,78	0,96
soil extraction	0-30 cm		Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	3,9E-01	6,3E-01	1,1E-01	5,0E-01	1,1E-01	3,0E-02	1,1E-01	1,5E-02	8,9E-02	1,7E-02	5,2E-02	7,6E-03	4,7E-02	7,2E-03	2,1E+00	0,78	0,72	1,14	0,83	0,97
soil extraction	0-30 cm		Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	1,7E+00	3,5E+00	4,8E-01	2,0E+00	4,2E-01	9,3E-02	4,4E-01	5,6E-02	3,2E-01	6,2E-02	1,7E-01	2,3E-02	1,3E-01	1,9E-02	9,3E+00	0,93	0,91	0,93	0,82	0,97
soil extraction	30-50 cm		Oct. 16, 2020	A	$\mu\text{g kg}^{-1}$	3,9E+00	5,9E+00	1,6E+00	7,2E+00	1,6E+00	3,4E-01	1,6E+00	2,0E-01	1,1E+00	2,2E-01	5,8E-01	7,6E-02	4,5E-01	6,7E-02	2,5E+01	0,85	0,54	0,95	0,85	0,95
soil extraction	30-50 cm		Oct. 16, 2020	B	$\mu\text{g kg}^{-1}$	1,1E+00	1,8E+00	2,7E-01	1,1E+00	2,4E-01	6,0E-02	2,3E-01	3,0E-02	1,7E-01	3,3E-02	9,2E-02	1,3E-02	8,2E-02	1,2E-02	5,2E+00	0,96	0,80	1,11	0,83	0,97
soil extraction	30-50 cm		Oct. 16, 2020	C	$\mu\text{g kg}^{-1}$	1,6E+00	3,1E+00	5,5E-01	2,3E+00	4,8E-01	1,0E-01	4,5E-01	6,2E-02	3,3E-01	6,2E-02	1,7E-01	2,4E-02	1,4E-01	2,1E-02	9,4E+00	0,96	0,76	0,95	0,90	0,93

Appendices

soil solution			Oct. 21, 2020	A	µg L ⁻¹	3,0E-02	4,3E-02	8,9E-03	5,2E-02	1,3E-02	2,6E-03	1,5E-02	1,2E-03	1,4E-02	3,3E-03	1,0E-02	1,5E-03	9,9E-03	1,7E-03	2,1E-01	0,42	0,61	0,81	0,45	0,97
soil solution			Oct. 21, 2020	B	µg L ⁻¹	2,9E-02	2,5E-02	9,3E-03	5,1E-02	1,2E-02	2,6E-03	1,5E-02	1,1E-03	1,2E-02	2,6E-03	8,1E-03	1,3E-03	9,6E-03	1,4E-03	1,8E-01	0,45	0,36	0,83	0,44	1,10
soil solution			Oct. 21, 2020	C	µg L ⁻¹	5,6E-02	9,8E-02	1,7E-02	8,8E-02	2,0E-02	3,8E-03	2,0E-02	1,9E-03	1,5E-02	3,4E-03	1,0E-02	1,5E-03	1,0E-02	1,7E-03	3,5E-01	0,64	0,73	0,83	0,61	0,98
soil solution			Nov. 16, 2020	A	µg L ⁻¹	3,7E-02	3,9E-02	1,3E-02	7,0E-02	1,7E-02	3,7E-03	2,0E-02	1,2E-03	1,4E-02	3,4E-03	1,1E-02	1,5E-03	1,0E-02	1,7E-03	2,4E-01	0,52	0,42	0,85	0,39	0,97
soil solution			Nov. 16, 2020	B	µg L ⁻¹	4,7E-02	3,2E-02	1,4E-02	7,9E-02	1,9E-02	4,4E-03	2,1E-02	1,5E-03	1,4E-02	3,3E-03	1,0E-02	1,5E-03	1,0E-02	1,5E-03	2,6E-01	0,60	0,29	0,94	0,48	1,02
soil solution			Nov. 16, 2020	C	µg L ⁻¹	6,7E-02	9,6E-02	2,1E-02	1,0E-01	2,3E-02	5,2E-03	2,4E-02	2,0E-03	1,8E-02	3,7E-03	1,1E-02	1,6E-03	1,1E-02	1,8E-03	3,9E-01	0,69	0,59	0,95	0,53	1,01
soil solution			Dec. 15, 2020	A	µg L ⁻¹	1,1E-01	1,8E-01	3,2E-02	1,5E-01	3,5E-02	7,9E-03	3,8E-02	3,8E-03	2,9E-02	5,7E-03	1,7E-02	2,5E-03	1,5E-02	2,4E-03	6,3E-01	0,71	0,72	0,93	0,65	0,95
soil solution			Dec. 15, 2020	B	µg L ⁻¹	5,2E-02	5,4E-02	1,6E-02	8,2E-02	1,8E-02	4,4E-03	2,2E-02	1,9E-03	1,7E-02	3,4E-03	1,1E-02	1,4E-03	1,1E-02	1,5E-03	2,9E-01	0,60	0,43	0,94	0,55	1,15
soil solution			Dec. 15, 2020	C	µg L ⁻¹	2,6E-01	5,7E-01	7,5E-02	3,1E-01	6,7E-02	1,4E-02	6,8E-02	7,6E-03	4,9E-02	9,1E-03	2,6E-02	3,6E-03	2,2E-02	3,2E-03	1,5E+00	0,94	0,96	0,92	0,73	1,01
soil solution			Jan. 14, 2021	A	µg L ⁻¹	5,4E-02	7,0E-02	1,7E-02	8,6E-02	2,1E-02	4,6E-03	2,3E-02	1,7E-03	1,8E-02	3,7E-03	1,1E-02	1,6E-03	1,0E-02	1,7E-03	3,2E-01	0,62	0,54	0,92	0,49	0,94
soil solution			Jan. 14, 2021	B	µg L ⁻¹	6,0E-02	6,4E-02	1,9E-02	9,6E-02	2,3E-02	4,9E-03	2,5E-02	2,6E-03	2,1E-02	4,9E-03	1,4E-02	2,0E-03	1,3E-02	1,8E-03	3,5E-01	0,55	0,44	0,88	0,63	1,00
soil solution			Jan. 14, 2021	C	µg L ⁻¹	6,7E-02	1,1E-01	2,1E-02	9,9E-02	1,9E-02	4,7E-03	2,4E-02	1,7E-03	1,7E-02	3,4E-03	1,0E-02	1,3E-03	9,1E-03	1,5E-03	3,9E-01	0,73	0,71	0,94	0,48	0,98
soil solution			Feb. 4, 2021	A	µg L ⁻¹	4,4E-02	6,2E-02	1,4E-02	6,8E-02	1,7E-02	4,0E-03	2,0E-02	1,4E-03	1,4E-02	3,3E-03	9,5E-03	1,3E-03	9,3E-03	1,6E-03	2,7E-01	0,58	0,59	0,93	0,47	0,98
soil solution			Feb. 4, 2021	B	µg L ⁻¹	5,9E-02	7,4E-02	1,8E-02	8,6E-02	2,0E-02	3,8E-03	1,9E-02	1,6E-03	1,6E-02	3,3E-03	9,8E-03	1,4E-03	8,1E-03	1,4E-03	3,2E-01	0,68	0,54	0,85	0,50	0,88
soil solution			Feb. 4, 2021	C	µg L ⁻¹	5,3E-02	7,4E-02	1,6E-02	7,9E-02	1,9E-02	3,7E-03	1,8E-02	9,5E-04	1,4E-02	3,0E-03	8,1E-03	1,1E-03	7,8E-03	1,2E-03	3,0E-01	0,75	0,59	0,87	0,34	1,05
snow			Jan. 14, 2021		µg L ⁻¹	1,4E-01	3,4E-01	4,1E-02	1,7E-01	4,0E-02	8,5E-03	3,9E-02	4,7E-03	3,2E-02	5,7E-03	1,5E-02	1,8E-03	1,3E-02	1,5E-03	8,6E-01	0,93	1,03	0,93	0,74	1,21

Experiment 2: trace element dynamics assessment

Table. VI-19 - Trace element contents/concentrations in soil, exogenous organic matter, plant parts, and soil solution samples for the 2 years field experiment (plot n°3).

Sample	Modality	Sub-area	Date	Replicate	Year	Units	Sc	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	As	Se	Sr	Mo	Cd	Sn	Sb	Ba	Pb
Soil	Cover crop restitution	Z1	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	7,3E+00	2,6E+03	5,0E+01	4,2E+01	4,9E+02	7,7E+00	1,7E+01	1,0E+01	5,4E+01	9,3E+00	1,5E-01	8,0E+01	1,1E+00	3,5E-01	1,9E+00	7,3E-01	3,5E+02	2,6E+01
Soil	Cover crop restitution	Z1	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	7,7E+00	2,5E+03	5,0E+01	4,1E+01	5,4E+02	8,7E+00	1,7E+01	9,6E+00	5,1E+01	8,6E+00	1,3E-01	8,5E+01	8,8E-01	3,5E-01	1,6E+00	6,6E-01	3,8E+02	2,6E+01
Soil	Cover crop restitution	Z2	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	8,4E+00	2,7E+03	5,7E+01	4,8E+01	4,8E+02	8,9E+00	2,1E+01	1,1E+01	5,5E+01	9,9E+00	1,6E-01	8,1E+01	1,0E+00	3,3E-01	1,9E+00	6,9E-01	3,5E+02	2,5E+01
Soil	Cover crop restitution	Z2	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	9,3E+00	2,7E+03	5,9E+01	4,9E+01	5,0E+02	9,1E+00	2,4E+01	1,3E+01	5,3E+01	1,0E+01	1,6E-01	8,5E+01	9,6E-01	2,7E-01	1,8E+00	7,2E-01	3,6E+02	2,3E+01
Soil	Cover crop restitution	Z3	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	8,3E+00	2,6E+03	5,3E+01	4,4E+01	4,9E+02	8,2E+00	2,0E+01	1,1E+01	5,2E+01	9,3E+00	6,5E-01	8,5E+01	8,2E-01	3,1E-01	1,6E+00	6,5E-01	3,4E+02	2,3E+01
Soil	Cover crop restitution	Z3	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	8,8E+00	2,4E+03	5,0E+01	4,3E+01	5,0E+02	8,6E+00	1,9E+01	9,5E+00	4,4E+01	9,3E+00	1,3E+00	9,9E+01	7,7E-01	2,5E-01	1,5E+00	6,2E-01	3,5E+02	2,1E+01
Soil	Cattle manure	Z1	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	7,1E+00	2,4E+03	4,5E+01	3,8E+01	4,9E+02	7,0E+00	1,6E+01	9,7E+00	5,0E+01	7,8E+00	1,6E-01	8,2E+01	7,8E-01	3,1E-01	2,0E+00	2,0E+00	3,6E+02	2,4E+01
Soil	Cattle manure	Z1	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	4,8E+00	2,2E+03	4,6E+01	3,8E+01	4,7E+02	7,5E+00	1,6E+01	8,8E+00	4,6E+01	7,3E+00	9,6E-01	6,6E+01	7,2E-01	3,1E-01	1,8E+00	1,5E+00	3,3E+02	2,5E+01
Soil	Cattle manure	Z2	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	9,0E+00	2,7E+03	5,8E+01	4,7E+01	4,9E+02	8,9E+00	2,2E+01	1,1E+01	5,4E+01	9,5E+00	1,6E-01	8,0E+01	7,6E-01	2,9E-01	2,0E+00	1,4E+00	3,6E+02	2,4E+01
Soil	Cattle manure	Z2	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	9,6E+00	2,9E+03	5,8E+01	5,0E+01	4,9E+02	9,1E+00	2,5E+01	1,2E+01	5,0E+01	1,1E+01	1,5E-01	8,9E+01	7,4E-01	1,9E-01	1,9E+00	1,1E+00	4,0E+02	1,8E+01
Soil	Cattle manure	Z3	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	8,6E+00	2,6E+03	5,4E+01	4,5E+01	4,8E+02	7,8E+00	2,0E+01	1,1E+01	5,1E+01	9,8E+00	1,6E-01	8,6E+01	7,0E-01	3,1E-01	2,0E+00	1,2E+00	3,5E+02	2,3E+01
Soil	Cattle manure	Z3	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	8,8E+00	2,7E+03	5,2E+01	4,6E+01	4,6E+02	7,9E+00	2,0E+01	1,0E+01	4,4E+01	1,0E+01	5,5E-01	9,4E+01	6,7E-01	2,2E-01	1,9E+00	9,9E-01	3,5E+02	1,8E+01
Soil	Green waste compost	Z1	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	7,7E+00	2,5E+03	4,7E+01	3,9E+01	5,2E+02	8,0E+00	1,6E+01	9,1E+00	4,9E+01	7,4E+00	6,2E-01	8,1E+01	6,3E-01	2,9E-01	1,7E+00	9,3E-01	3,6E+02	2,4E+01
Soil	Green waste compost	Z1	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	7,4E+00	2,6E+03	4,4E+01	3,7E+01	5,7E+02	8,8E+00	1,5E+01	9,1E+00	4,7E+01	8,6E+00	1,3E+00	8,7E+01	6,4E-01	2,8E-01	1,7E+00	9,7E-01	3,8E+02	2,4E+01
Soil	Green waste compost	Z2	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	9,0E+00	2,7E+03	5,6E+01	4,7E+01	6,1E+02	1,2E+01	2,2E+01	1,2E+01	5,5E+01	9,5E+00	1,5E+00	8,3E+01	7,0E-01	2,9E-01	1,9E+00	9,0E-01	3,6E+02	2,5E+01
Soil	Green waste compost	Z2	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	1,0E+01	3,2E+03	6,2E+01	5,5E+01	5,2E+02	1,0E+01	2,7E+01	1,3E+01	5,2E+01	1,1E+01	1,0E+00	8,9E+01	7,1E-01	1,9E-01	1,8E+00	8,5E-01	4,1E+02	1,9E+01

Appendices

Soil	Green waste compost	Z3	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	8,5E+00	2,5E+03	5,6E+01	4,6E+01	4,9E+02	8,4E+00	2,0E+01	1,0E+01	5,0E+01	8,9E+00	1,4E+00	8,6E+01	5,8E-01	2,9E-01	1,7E+00	8,2E-01	3,4E+02	2,2E+01
Soil	Green waste compost	Z3	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	9,9E+00	3,0E+03	6,0E+01	5,1E+01	5,2E+02	1,0E+01	2,4E+01	1,1E+01	4,8E+01	1,2E+01	1,6E-01	8,4E+01	6,3E-01	2,0E-01	1,8E+00	7,9E-01	3,5E+02	1,8E+01
Soil	No application	Z1	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	7,7E+00	2,4E+03	4,2E+01	3,7E+01	5,0E+02	6,6E+00	1,4E+01	9,8E+00	4,6E+01	6,8E+00	1,5E+00	7,8E+01	5,3E-01	2,6E-01	1,4E+00	7,1E-01	3,5E+02	2,2E+01
Soil	No application	Z1	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	7,5E+00	2,5E+03	3,9E+01	3,6E+01	6,6E+02	7,9E+00	1,3E+01	6,6E+00	4,4E+01	7,2E+00	1,5E-01	8,2E+01	4,9E-01	2,3E-01	1,5E+00	5,6E-01	3,7E+02	1,8E+01
Soil	No application	Z2	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	9,2E+00	2,6E+03	5,4E+01	4,4E+01	4,6E+02	1,0E+01	2,1E+01	1,1E+01	5,3E+01	1,0E+01	1,3E+00	8,1E+01	5,5E-01	2,6E-01	1,8E+00	7,4E-01	3,5E+02	2,2E+01
Soil	No application	Z2	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	9,9E+00	3,1E+03	6,1E+01	5,4E+01	4,7E+02	9,0E+00	2,5E+01	1,3E+01	5,0E+01	1,1E+01	1,6E-01	8,8E+01	5,6E-01	1,7E-01	1,7E+00	6,6E-01	4,0E+02	1,7E+01
Soil	No application	Z3	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	8,9E+00	2,9E+03	5,8E+01	4,8E+01	5,2E+02	1,2E+01	2,2E+01	1,1E+01	5,6E+01	9,2E+00	1,6E-01	9,3E+01	5,6E-01	3,3E-01	1,9E+00	7,8E-01	3,5E+02	2,2E+01
Soil	No application	Z3	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	9,2E+00	2,8E+03	5,7E+01	5,1E+01	5,0E+02	1,0E+01	2,4E+01	1,1E+01	4,9E+01	1,1E+01	1,6E-01	9,6E+01	5,6E-01	1,7E-01	1,7E+00	6,4E-01	3,7E+02	1,6E+01
EOM	Cover crop restitution	/	24-03-22	A	Year 1	mg kg ⁻¹	5,5E-02	2,8E+01	8,6E-01	1,4E+00	9,0E+01	1,9E-01	1,3E+02	9,4E+00	5,3E+01	2,5E-01	1,6E-01	1,4E+01	2,3E+00	1,5E+00	1,8E-01	2,1E-01	1,0E+01	3,9E-01
EOM	Cover crop restitution	/	24-03-22	B	Year 1	mg kg ⁻¹	5,6E-02	1,7E+01	3,6E-01	1,1E+00	8,3E+01	1,0E-01	3,6E+01	9,3E+00	5,3E+01	1,8E-01	1,6E-01	1,3E+01	2,2E+00	1,5E+00	2,0E-01	1,6E-01	1,0E+01	3,5E-01
EOM	Cattle manure	/	24-03-22	A	Year 1	mg kg ⁻¹	6,5E-01	3,1E+02	5,5E+00	6,1E+00	3,4E+02	7,8E-01	6,6E+01	1,4E+01	5,9E+01	7,6E-01	1,6E-01	5,0E+01	3,9E+00	3,0E-01	4,8E-01	4,2E-01	6,8E+01	2,3E+00
EOM	Cattle manure	/	24-03-22	B	Year 1	mg kg ⁻¹	6,3E-01	3,0E+02	5,4E+00	6,0E+00	3,3E+02	7,4E-01	5,7E+01	1,4E+01	6,0E+01	9,1E-01	3,3E-01	4,9E+01	3,4E+00	2,0E-01	3,9E-01	2,8E-01	6,6E+01	2,3E+00
EOM	Green waste compost	/	24-03-22	A	Year 1	mg kg ⁻¹	4,4E+00	2,1E+03	3,7E+01	4,2E+01	4,8E+02	5,2E+00	4,1E+02	3,7E+01	1,9E+02	5,7E+00	2,9E+00	8,1E+01	2,7E+00	5,4E-01	2,5E+00	1,0E+00	2,6E+02	4,2E+01
EOM	Green waste compost	/	24-03-22	B	Year 1	mg kg ⁻¹	5,1E+00	1,9E+03	4,0E+01	5,0E+01	5,2E+02	5,8E+00	6,6E+02	4,0E+01	2,0E+02	6,0E+00	1,4E+00	7,9E+01	2,4E+00	5,1E-01	2,9E+00	9,0E-01	2,3E+02	3,9E+01
Solution	No application	Z1	23-05-22	A	Year 1	mg L ⁻¹	5,6E-05	6,4E-04	8,1E-04	5,0E-04	8,9E-02	3,4E-04	8,5E-03	5,3E-03	3,8E-01	4,9E-04	1,6E-04	1,2E-01	4,6E-05	4,5E-04	4,6E-05	2,8E-04	9,1E-02	9,8E-05
Solution	No application	Z1	23-05-22	BC	Year 1	mg L ⁻¹	8,9E-05	9,5E-04	4,0E-03	4,9E-04	9,9E-02	6,2E-04	9,8E-03	4,9E-03	3,9E+00	4,9E-04	2,8E-04	2,0E-01	1,0E-04	4,3E-04	6,0E-05	2,5E-04	2,5E-01	1,3E-05
Solution	No application	Z1	23-05-22	DE	Year 1	mg L ⁻¹	9,8E-05	1,2E-03	2,3E-03	5,8E-04	2,6E-01	5,7E-04	1,2E-02	5,7E-03	1,4E+00	6,1E-04	4,0E-04	2,2E-01	7,2E-05	8,2E-04	5,5E-05	3,0E-04	2,5E-01	1,2E-04
Solution	No application	Z2	23-05-22	ACD	Year 1	mg L ⁻¹	7,4E-05	5,4E-03	4,2E-03	8,6E-04	1,1E-02	9,5E-04	6,2E-03	8,6E-03	4,4E+00	6,7E-04	4,5E-04	1,6E-01	1,9E-04	1,0E-04	2,5E-04	2,8E-04	1,7E-01	3,1E-04
Solution	No application	Z2	23-05-22	B	Year 1	mg L ⁻¹	5,6E-05	7,0E-04	2,7E-03	6,1E-04	5,6E-03	3,7E-04	4,5E-03	7,1E-03	1,7E+00	8,1E-04	2,2E-04	6,3E-02	1,8E-04	4,0E-05	1,1E-04	3,2E-04	1,0E-01	2,0E-05
Solution	No application	Z2	23-05-22	E	Year 1	mg L ⁻¹	6,6E-05	1,3E-03	2,9E-03	6,2E-04	7,3E-03	6,3E-04	5,4E-03	6,3E-03	3,0E+00	6,6E-04	3,1E-04	1,7E-01	1,2E-04	6,3E-05	7,5E-05	2,7E-04	1,2E-01	4,1E-05
Solution	No application	Z3	23-05-22	ACE	Year 1	mg L ⁻¹	7,0E-05	2,8E-03	5,5E-03	6,7E-04	8,3E-03	1,1E-03	4,2E-03	7,9E-03	4,0E+00	1,1E-03	4,4E-04	1,6E-01	6,3E-04	5,7E-05	2,3E-04	5,2E-04	1,4E-01	1,9E-04

Field experiments

Solution	Green waste compost	Z1	23-05-22	A	Year 1	mg L ⁻¹	6,6E-05	8,2E-04	2,2E-03	8,5E-04	6,8E-03	4,3E-04	7,5E-03	1,4E-02	9,7E-01	1,6E-03	7,3E-04	1,0E-01	3,7E-04	1,1E-04	6,0E-05	5,1E-04	8,3E-02	3,2E-05
Solution	Green waste compost	Z1	23-05-22	BCE	Year 1	mg L ⁻¹	1,1E-04	1,8E-03	3,6E-03	9,8E-04	6,0E-02	7,5E-04	9,7E-03	1,3E-02	1,7E+00	2,1E-03	6,0E-04	1,9E-01	6,5E-04	2,7E-04	1,1E-04	4,4E-04	1,0E-01	2,8E-04
Solution	Green waste compost	Z1	23-05-22	D	Year 1	mg L ⁻¹	8,0E-05	7,7E-04	1,8E-03	8,4E-04	3,8E-02	4,7E-04	8,0E-03	1,4E-02	8,4E-01	1,4E-03	5,0E-04	8,5E-02	2,3E-04	1,8E-04	8,5E-05	4,3E-04	5,9E-02	1,6E-04
Solution	Green waste compost	Z2	23-05-22	A	Year 1	mg L ⁻¹	4,8E-05	1,0E-03	2,6E-03	8,6E-04	2,4E-03	6,2E-04	1,0E-02	1,4E-02	1,0E+00	1,5E-03	6,0E-04	7,7E-02	9,2E-04	6,8E-05	5,6E-05	4,8E-04	7,7E-02	4,5E-05
Solution	Green waste compost	Z2	23-05-22	BC	Year 1	mg L ⁻¹	1,2E-04	1,4E-03	2,5E-03	1,0E-03	3,6E-02	7,6E-04	1,2E-02	1,5E-02	6,6E-01	2,1E-03	6,7E-04	2,0E-01	5,8E-04	2,1E-04	1,2E-04	4,6E-04	1,2E-01	2,0E-04
Solution	Green waste compost	Z2	23-05-22	D	Year 1	mg L ⁻¹	8,1E-05	1,1E-03	2,3E-03	1,0E-03	7,9E-03	5,7E-04	1,0E-02	1,5E-02	8,1E-01	1,9E-03	6,3E-04	1,1E-01	5,1E-04	1,2E-04	8,2E-05	5,1E-04	6,0E-02	7,4E-05
Solution	Green waste compost	Z3	23-05-22	AD	Year 1	mg L ⁻¹	7,8E-05	4,3E-03	6,7E-03	1,3E-03	2,2E-02	1,7E-03	1,0E-02	1,5E-02	4,2E+00	2,5E-03	3,8E-04	1,4E-01	1,9E-03	1,1E-04	2,9E-04	6,8E-04	1,4E-01	6,0E-04
Solution	Green waste compost	Z3	23-05-22	E	Year 1	mg L ⁻¹	9,0E-05	7,4E-04	2,9E-03	8,1E-04	2,9E-02	9,4E-04	1,1E-02	1,5E-02	4,6E-01	2,5E-03	4,8E-04	2,0E-01	5,4E-04	1,2E-04	1,1E-04	4,9E-04	8,3E-02	6,3E-05
Solution	Cattle manure	Z1	23-05-22	ABC	Year 1	mg L ⁻¹	8,8E-05	1,4E-03	3,2E-03	1,1E-03	1,4E-01	8,1E-04	1,1E-02	1,2E-02	1,8E+00	1,5E-03	4,9E-04	1,1E-01	3,2E-04	4,2E-04	5,5E-04	5,5E-04	1,3E-01	2,8E-04
Solution	Cattle manure	Z1	23-05-22	D	Year 1	mg L ⁻¹	9,8E-05	1,2E-03	4,6E-03	1,2E-03	9,1E-02	7,9E-04	1,2E-02	1,4E-02	3,0E+00	1,9E-03	5,5E-04	1,6E-01	2,9E-04	3,8E-04	1,4E-04	5,1E-04	1,0E-01	5,3E-05
Solution	Cattle manure	Z1	23-05-22	E	Year 1	mg L ⁻¹	9,6E-05	2,3E-03	3,7E-03	1,2E-03	3,8E-02	7,1E-04	1,4E-02	1,7E-02	1,5E+00	2,0E-03	6,8E-04	1,3E-01	6,4E-04	2,8E-04	2,3E-04	6,4E-04	1,1E-01	1,4E-04
Solution	Cattle manure	Z2	23-05-22	AB	Year 1	mg L ⁻¹	1,7E-04	6,3E-03	9,1E-03	1,0E-03	1,2E-01	2,0E-03	1,3E-02	1,4E-02	5,9E+00	1,9E-03	4,9E-04	3,7E-01	9,9E-04	2,9E-04	1,7E-04	3,8E-04	2,9E-01	7,3E-04
Solution	Cattle manure	Z2	23-05-22	C	Year 1	mg L ⁻¹	7,0E-05	9,5E-04	2,1E-03	6,1E-04	2,3E-02	5,2E-04	9,0E-03	1,2E-02	1,0E+00	1,2E-03	3,5E-04	1,2E-01	6,7E-04	1,6E-04	8,7E-05	3,5E-04	1,0E-01	3,9E-05
Solution	Cattle manure	Z2	23-05-22	E	Year 1	mg L ⁻¹	7,9E-05	1,0E-03	3,7E-03	8,4E-04	7,6E-03	6,7E-04	1,1E-02	1,5E-02	1,5E+00	2,2E-03	6,8E-04	1,0E-01	8,0E-04	7,0E-05	1,4E-04	4,7E-04	9,4E-02	2,3E-05
Solution	Cattle manure	Z3	23-05-22	AB	Year 1	mg L ⁻¹	8,0E-05	2,0E-03	3,3E-03	1,4E-03	8,7E-03	1,1E-03	1,1E-02	1,8E-02	1,5E+00	1,3E-03	4,7E-04	2,0E-01	5,0E-04	8,2E-05	1,1E-04	4,1E-04	1,3E-01	2,7E-04
Solution	Cattle manure	Z3	23-05-22	C	Year 1	mg L ⁻¹	6,5E-05	1,9E-03	3,8E-03	6,6E-04	6,8E-03	8,4E-04	5,6E-03	7,8E-03	2,6E+00	9,7E-04	2,5E-04	1,6E-01	3,4E-04	4,2E-05	8,0E-05	3,1E-04	1,0E-01	2,1E-04
Solution	Cattle manure	Z3	23-05-22	DE	Year 1	mg L ⁻¹	1,1E-04	2,1E-03	5,2E-03	1,1E-03	8,3E-03	1,2E-03	1,2E-02	1,5E-02	3,9E+00	2,3E-03	5,8E-04	1,6E-01	7,2E-04	9,1E-05	2,5E-04	5,5E-04	1,5E-01	8,1E-05
Solution	Cover crop restitution	Z1	23-05-22	AB	Year 1	mg L ⁻¹	1,2E-04	5,6E-03	4,2E-03	1,2E-03	4,3E-02	1,0E-03	1,3E-02	1,5E-02	2,3E+00	1,2E-03	5,9E-04	8,8E-02	2,8E-04	2,6E-04	2,1E-04	4,4E-04	9,5E-02	7,8E-04
Solution	Cover crop restitution	Z1	23-05-22	C	Year 1	mg L ⁻¹	7,5E-05	1,5E-03	3,4E-03	1,1E-03	1,1E-02	5,4E-04	8,5E-03	1,0E-02	2,5E+00	8,9E-04	4,6E-04	7,5E-02	3,2E-04	1,5E-04	1,3E-04	3,9E-04	1,5E-01	8,6E-05
Solution	Cover crop restitution	Z1	23-05-22	DE	Year 1	mg L ⁻¹	1,2E-04	3,1E-03	4,9E-03	1,4E-03	1,3E-02	1,6E-03	1,3E-02	2,0E-02	4,1E+00	1,3E-03	4,5E-04	3,4E-02	9,4E-04	1,2E-04	2,6E-04	5,3E-04	1,6E-01	2,5E-04

Appendices

Solution	Cover crop restitution	Z2	23-05-22	A	Year 1	mg L ⁻¹	6,2E-05	1,2E-03	2,3E-03	6,1E-04	1,9E-02	5,6E-04	8,2E-03	1,0E-02	1,4E+00	1,1E-03	4,8E-04	1,5E-01	1,4E-04	1,3E-04	6,2E-05	2,9E-04	8,9E-02	5,0E-05
Solution	Cover crop restitution	Z2	23-05-22	BC	Year 1	mg L ⁻¹	7,1E-05	1,5E-03	3,0E-03	6,6E-04	6,7E-02	3,0E-03	1,6E-02	3,0E-02	1,4E+00	1,2E-03	5,9E-04	1,7E-01	2,4E-04	1,7E-04	2,6E-04	3,7E-04	1,4E-01	8,0E-05
Solution	Cover crop restitution	Z2	23-05-22	DE	Year 1	mg L ⁻¹	5,1E-05	1,5E-03	3,9E-03	6,6E-04	4,5E-03	5,8E-04	6,3E-03	1,1E-02	2,7E+00	9,1E-04	3,2E-04	4,5E-02	1,6E-04	4,2E-05	8,0E-05	3,1E-04	1,5E-01	5,4E-05
Solution	Cover crop restitution	Z3	23-05-22	ABC	Year 1	mg L ⁻¹	1,7E-04	8,9E-03	1,2E-02	1,0E-03	3,2E-02	2,0E-03	1,1E-02	1,2E-02	8,5E+00	1,4E-03	5,8E-04	3,4E-01	5,7E-04	1,2E-04	2,6E-04	4,7E-04	2,4E-01	7,0E-04
Solution	Cover crop restitution	Z3	23-05-22	D	Year 1	mg L ⁻¹	1,2E-04	5,9E-03	5,8E-03	8,8E-04	6,3E-02	1,2E-03	7,8E-03	9,0E-03	4,4E+00	9,7E-04	5,5E-04	2,7E-01	2,9E-04	1,1E-04	9,7E-05	3,5E-04	1,9E-01	5,3E-04
Solution	Cover crop restitution	Z3	23-05-22	E	Year 1	mg L ⁻¹	2,1E-04	1,2E-02	1,2E-02	1,4E-03	9,3E-02	2,6E-03	8,9E-03	8,7E-03	8,6E+00	1,3E-03	3,9E-04	3,6E-01	3,5E-04	1,4E-04	5,6E-05	3,1E-04	3,6E-01	2,4E-03
Barley roots	No application	Z1	25-05-22	/	Year 1	mg kg ⁻¹	5,9E+00	2,7E+03	3,6E+01	3,7E+01	3,7E+02	5,4E+00	8,7E+02	1,1E+01	5,0E+01	6,6E+00	1,7E+00	6,6E+01	4,1E-01	3,9E-01	1,4E+00	5,8E-01	2,4E+02	1,6E+01
Barley roots	No application	Z2	25-05-22	/	Year 1	mg kg ⁻¹	4,9E+00	2,0E+03	4,2E+01	4,1E+01	3,0E+02	5,4E+00	5,8E+02	1,4E+01	5,2E+01	7,0E+00	1,5E+00	5,0E+01	4,4E-01	4,3E-01	1,4E+00	5,4E-01	2,2E+02	1,4E+01
Barley roots	No application	Z3	25-05-22	/	Year 1	mg kg ⁻¹	6,6E+00	2,5E+03	4,4E+01	4,4E+01	4,0E+02	6,2E+00	5,5E+02	1,2E+01	6,0E+01	7,5E+00	1,5E+00	6,3E+01	6,5E-01	3,2E-01	1,4E+00	5,3E-01	2,4E+02	1,4E+01
Barley roots	Green waste compost	Z1	25-05-22	/	Year 1	mg kg ⁻¹	4,9E+00	2,3E+03	3,5E+01	3,5E+01	3,5E+02	4,9E+00	6,7E+02	1,2E+01	5,7E+01	5,6E+00	2,1E+00	5,6E+01	5,6E-01	3,9E-01	1,3E+00	5,3E-01	2,5E+02	1,6E+01
Barley roots	Green waste compost	Z2	25-05-22	/	Year 1	mg kg ⁻¹	5,7E+00	2,4E+03	4,6E+01	4,5E+01	3,4E+02	5,8E+00	5,8E+02	1,6E+01	8,1E+01	7,5E+00	2,1E+00	5,6E+01	8,2E-01	5,4E-01	1,8E+00	6,1E-01	2,3E+02	1,7E+01
Barley roots	Green waste compost	Z3	25-05-22	/	Year 1	mg kg ⁻¹	6,3E+00	2,5E+03	4,3E+01	4,5E+01	3,7E+02	5,6E+00	5,8E+02	1,3E+01	8,2E+01	7,4E+00	2,6E+00	6,3E+01	7,0E-01	3,4E-01	1,5E+00	5,6E-01	2,5E+02	1,5E+01
Barley roots	Cattle manure	Z1	25-05-22	/	Year 1	mg kg ⁻¹	3,8E+00	2,1E+03	3,9E+01	4,1E+01	3,6E+02	5,4E+00	6,8E+02	1,2E+01	6,0E+01	6,1E+00	1,9E+00	5,0E+01	5,3E-01	6,0E-01	1,4E+00	5,6E-01	2,2E+02	1,5E+01
Barley roots	Cattle manure	Z2	25-05-22	/	Year 1	mg kg ⁻¹	3,3E+00	2,0E+03	4,5E+01	4,6E+01	2,8E+02	5,6E+00	5,5E+02	1,5E+01	5,7E+01	7,0E+00	1,9E+00	4,3E+01	6,4E-01	5,1E-01	1,5E+00	5,5E-01	1,9E+02	1,4E+01
Barley roots	Cattle manure	Z3	25-05-22	/	Year 1	mg kg ⁻¹	5,1E+00	2,3E+03	4,2E+01	4,0E+01	3,0E+02	5,5E+00	5,9E+02	1,3E+01	5,9E+01	6,7E+00	1,5E+00	5,3E+01	6,2E-01	5,0E-01	1,4E+00	5,2E-01	2,1E+02	1,4E+01
Barley roots	Cover crop restitution	Z1	25-05-22	/	Year 1	mg kg ⁻¹	5,1E+00	2,4E+03	4,0E+01	4,4E+01	3,7E+02	5,4E+00	6,1E+02	1,1E+01	5,6E+01	6,8E+00	2,5E+00	5,8E+01	4,6E-01	4,9E-01	1,4E+00	5,9E-01	2,3E+02	1,7E+01
Barley roots	Cover crop restitution	Z2	25-05-22	/	Year 1	mg kg ⁻¹	3,9E+00	1,7E+03	3,6E+01	3,6E+01	2,7E+02	4,7E+00	6,2E+02	1,2E+01	5,0E+01	5,4E+00	1,9E+00	4,3E+01	4,0E-01	3,9E-01	1,2E+00	4,6E-01	1,8E+02	1,3E+01
Barley roots	Cover crop restitution	Z3	25-05-22	/	Year 1	mg kg ⁻¹	3,4E+00	1,6E+03	3,7E+01	3,9E+01	2,6E+02	4,7E+00	6,1E+02	1,2E+01	5,3E+01	5,8E+00	1,5E+00	4,4E+01	4,5E-01	4,1E-01	8,3E+00	4,7E-01	1,8E+02	1,2E+01
Barley shoots	No application	Z1	25-05-22	/	Year 1	mg kg ⁻¹	1,9E-01	8,2E+01	1,4E+00	1,9E+00	5,8E+01	1,6E-01	4,0E+01	8,9E+00	4,2E+01	2,3E-01	1,6E-02	1,5E+01	3,4E-01	1,8E-01	7,0E-02	2,6E-02	1,5E+01	5,3E-01
Barley shoots	No application	Z2	25-05-22	/	Year 1	mg kg ⁻¹	3,5E-01	1,2E+02	2,5E+00	2,9E+00	4,9E+01	3,0E-01	1,2E+02	9,5E+00	4,2E+01	4,0E-01	7,3E-02	1,5E+01	5,4E-01	1,0E-01	1,1E-01	3,5E-02	2,2E+01	7,7E-01
Barley shoots	No application	Z3	25-05-22	/	Year 1	mg kg ⁻¹	5,7E-01	2,1E+02	4,1E+00	4,1E+00	8,0E+01	4,8E-01	5,1E+01	9,0E+00	4,6E+01	6,4E-01	7,7E-02	2,1E+01	1,7E+00	1,4E-01	2,1E-01	4,8E-02	2,2E+01	1,2E+00

Field experiments

Barley shoots	Green waste compost	Z1	25-05-22	/	Year 1	mg kg ⁻¹	2,6E-01	1,0E+02	1,9E+00	2,0E+00	5,7E+01	2,2E-01	3,2E+01	9,3E+00	5,1E+01	3,4E-01	4,1E-02	1,4E+01	1,8E+00	2,0E-01	1,1E-01	2,8E-02	1,7E+01	6,4E-01
Barley shoots	Green waste compost	Z2	25-05-22	/	Year 1	mg kg ⁻¹	4,0E-01	2,0E+02	3,9E+00	4,2E+00	6,4E+01	4,7E-01	1,2E+02	8,5E+00	4,2E+01	6,5E-01	2,7E-01	1,5E+01	1,4E+00	1,7E-01	2,1E-01	1,5E-01	2,6E+01	1,2E+00
Barley shoots	Green waste compost	Z3	25-05-22	/	Year 1	mg kg ⁻¹	4,7E-01	2,7E+02	4,9E+00	5,2E+00	8,7E+01	5,8E-01	8,1E+01	9,5E+00	5,2E+01	8,2E-01	1,5E-01	1,9E+01	2,1E+00	1,9E-01	2,0E-01	1,1E-01	2,5E+01	1,4E+00
Barley shoots	Cattle manure	Z1	25-05-22	/	Year 1	mg kg ⁻¹	2,1E-01	9,7E+01	1,5E+00	2,0E+00	5,3E+01	2,1E-01	2,3E+02	6,6E+00	3,3E+01	2,9E-01	8,3E-02	1,2E+01	1,1E+00	1,5E-01	9,6E-02	5,4E-02	1,6E+01	5,8E-01
Barley shoots	Cattle manure	Z2	25-05-22	/	Year 1	mg kg ⁻¹	2,9E-01	1,2E+02	2,2E+00	2,6E+00	4,4E+01	2,6E-01	3,2E+01	6,5E+00	2,6E+01	3,8E-01	1,2E-01	1,1E+01	1,1E+00	9,9E-02	1,0E-01	5,2E-02	1,9E+01	7,0E-01
Barley shoots	Cattle manure	Z3	25-05-22	/	Year 1	mg kg ⁻¹	1,6E-01	4,9E+01	9,4E-01	1,2E+00	5,0E+01	1,1E-01	5,7E+01	7,8E+00	3,6E+01	1,9E-01	3,8E-02	1,4E+01	2,4E+00	1,6E-01	6,1E-02	3,4E-02	1,2E+01	3,1E-01
Barley shoots	Cover crop restitution	Z1	25-05-22	/	Year 1	mg kg ⁻¹	1,6E-01	5,5E+01	1,2E+00	1,3E+00	3,9E+01	1,5E-01	1,3E+02	6,5E+00	3,2E+01	2,0E-01	6,3E-02	1,1E+01	1,5E+00	1,4E-01	6,6E-02	2,9E-02	1,1E+01	4,5E-01
Barley shoots	Cover crop restitution	Z2	25-05-22	/	Year 1	mg kg ⁻¹	3,5E-01	1,4E+02	2,6E+00	2,9E+00	4,2E+01	3,0E-01	3,2E+01	7,3E+00	3,3E+01	4,4E-01	1,2E-01	1,2E+01	1,7E+00	1,0E-01	9,9E-02	4,5E-02	1,8E+01	8,0E-01
Barley shoots	Cover crop restitution	Z3	25-05-22	/	Year 1	mg kg ⁻¹	4,2E-01	1,4E+02	6,8E+00	7,0E+00	7,2E+01	8,2E-01	6,4E+01	7,9E+00	4,0E+01	1,1E+00	3,5E-01	1,8E+01	1,4E+00	1,7E-01	2,0E-01	7,9E-02	2,5E+01	2,0E+00
Barley roots	No application	Z1	25-07-22	/	Year 1	mg kg ⁻¹	6,3E+00	3,0E+03	3,8E+01	4,0E+01	3,7E+02	4,9E+00	6,6E+02	1,1E+01	4,6E+01	6,5E+00	2,7E+00	5,2E+01	5,8E-01	4,3E-01	1,1E+00	6,0E-01	2,3E+02	1,2E+01
Barley roots	No application	Z2	25-07-22	/	Year 1	mg kg ⁻¹	6,2E+00	2,5E+03	3,8E+01	3,9E+01	2,9E+02	4,6E+00	6,0E+02	1,1E+01	4,1E+01	6,3E+00	2,7E+00	4,8E+01	6,2E-01	3,4E-01	1,0E+00	4,2E-01	2,0E+02	1,1E+01
Barley roots	No application	Z3	25-07-22	/	Year 1	mg kg ⁻¹	6,4E+00	2,6E+03	4,1E+01	4,2E+01	3,2E+02	4,9E+00	5,5E+02	1,0E+01	4,0E+01	6,7E+00	3,0E+00	5,5E+01	1,1E+00	2,7E-01	1,1E+00	4,4E-01	2,1E+02	1,2E+01
Barley roots	Green waste compost	Z1	25-07-22	/	Year 1	mg kg ⁻¹	3,2E+00	1,3E+03	2,4E+01	2,7E+01	2,4E+02	3,0E+00	4,1E+02	1,1E+01	6,0E+01	3,7E+00	1,2E+00	3,4E+01	1,4E+00	6,0E-01	6,8E-01	1,4E+00	1,3E+02	9,3E+00
Barley roots	Green waste compost	Z2	25-07-22	/	Year 1	mg kg ⁻¹	4,1E+00	1,7E+03	3,2E+01	3,5E+01	2,5E+02	4,0E+00	6,0E+02	1,2E+01	4,6E+01	5,0E+00	1,8E+00	3,7E+01	1,2E+00	4,7E-01	8,9E-01	3,8E-01	1,5E+02	9,4E+00
Barley roots	Green waste compost	Z3	25-07-22	/	Year 1	mg kg ⁻¹	4,3E+00	2,3E+03	3,8E+01	4,7E+01	2,8E+02	4,6E+00	5,5E+02	1,2E+01	4,7E+01	5,9E+00	2,1E+00	4,3E+01	1,7E+00	3,7E-01	9,9E-01	4,0E-01	1,7E+02	1,1E+01
Barley roots	Cattle manure	Z1	25-07-22	/	Year 1	mg kg ⁻¹	5,7E+00	2,8E+03	3,9E+01	4,2E+01	3,4E+02	4,8E+00	5,8E+02	1,1E+01	4,6E+01	6,3E+00	3,0E+00	4,9E+01	7,9E-01	6,0E-01	1,1E+00	4,4E-01	2,1E+02	1,3E+01
Barley roots	Cattle manure	Z2	25-07-22	/	Year 1	mg kg ⁻¹	6,0E+00	2,4E+03	3,8E+01	4,0E+01	3,0E+02	4,6E+00	6,0E+02	1,1E+01	4,3E+01	6,3E+00	2,5E+00	4,8E+01	7,2E-01	4,3E-01	1,0E+00	4,2E-01	2,0E+02	1,1E+01
Barley roots	Cattle manure	Z3	25-07-22	/	Year 1	mg kg ⁻¹	6,7E+00	2,8E+03	4,4E+01	4,8E+01	3,4E+02	5,3E+00	5,4E+02	1,1E+01	4,4E+01	7,4E+00	2,6E+00	5,1E+01	6,8E-01	3,9E-01	1,1E+00	4,6E-01	2,1E+02	1,2E+01
Barley roots	Cover crop restitution	Z1	25-07-22	/	Year 1	mg kg ⁻¹	5,9E+00	2,6E+03	3,6E+01	4,0E+01	3,5E+02	4,7E+00	6,1E+02	1,1E+01	4,8E+01	6,3E+00	2,6E+00	4,9E+01	5,4E-01	4,8E-01	1,1E+00	4,4E-01	2,1E+02	1,3E+01
Barley roots	Cover crop restitution	Z2	25-07-22	/	Year 1	mg kg ⁻¹	5,2E+00	2,3E+03	3,8E+01	4,8E+01	2,9E+02	4,6E+00	7,7E+02	1,2E+01	5,1E+01	6,3E+00	2,6E+00	4,3E+01	8,5E-01	5,3E-01	1,2E+00	7,0E-01	1,8E+02	1,1E+01

Appendices

Barley roots	Cover crop restitution	Z3	25-07-22	/	Year 1	mg kg ⁻¹	5,1E+00	2,3E+03	3,3E+01	4,1E+01	2,7E+02	4,2E+00	6,0E+02	1,4E+01	5,7E+01	5,7E+00	2,3E+00	4,7E+01	1,1E+00	4,1E-01	1,0E+00	5,1E-01	1,7E+02	9,7E+00
Barley shoots	No application	Z1	25-07-22	/	Year 1	mg kg ⁻¹	2,6E-01	1,0E+02	1,6E+00	2,0E+00	5,9E+01	1,9E-01	3,6E+01	6,2E+00	2,4E+01	2,6E-01	1,6E-02	1,6E+01	5,8E-01	2,0E-01	1,6E-01	8,8E-02	2,6E+01	6,4E-01
Barley shoots	No application	Z2	25-07-22	/	Year 1	mg kg ⁻¹	2,7E-01	1,1E+02	2,0E+00	2,9E+00	4,6E+01	2,3E-01	4,3E+01	5,9E+00	1,9E+01	3,1E-01	1,6E-01	2,0E+01	7,3E-01	1,3E-01	1,7E-01	9,1E-02	4,4E+01	7,7E-01
Barley shoots	No application	Z3	25-07-22	/	Year 1	mg kg ⁻¹	3,1E-01	1,3E+02	2,2E+00	2,9E+00	5,6E+01	2,5E-01	1,9E+01	5,8E+00	1,9E+01	3,7E-01	1,4E-01	2,5E+01	2,2E+00	1,1E-01	1,6E-01	7,7E-02	3,1E+01	7,4E-01
Barley shoots	Green waste compost	Z1	25-07-22	/	Year 1	mg kg ⁻¹	3,3E-01	1,6E+02	2,4E+00	9,1E+00	6,4E+01	3,5E-01	2,4E+01	6,1E+00	3,2E+01	4,3E-01	5,0E-02	2,0E+01	1,8E+00	2,1E-01	2,2E-01	1,3E-01	4,0E+01	1,1E+00
Barley shoots	Green waste compost	Z2	25-07-22	/	Year 1	mg kg ⁻¹	2,2E-01	9,8E+01	1,5E+00	2,8E+00	3,5E+01	1,9E-01	1,1E+01	5,5E+00	2,2E+01	2,7E-01	5,7E-02	1,3E+01	1,9E+00	1,4E-01	1,2E-01	6,2E-02	3,4E+01	6,0E-01
Barley shoots	Green waste compost	Z3	25-07-22	/	Year 1	mg kg ⁻¹	2,2E-01	6,7E+01	1,6E+00	3,3E+00	4,1E+01	2,0E-01	2,2E+01	5,3E+00	2,0E+01	3,1E-01	7,8E-02	1,7E+01	2,8E+00	1,2E-01	1,3E-01	5,5E-02	2,7E+01	6,7E-01
Barley shoots	Cattle manure	Z1	25-07-22	/	Year 1	mg kg ⁻¹	2,6E-01	9,5E+01	1,7E+00	3,7E+00	5,9E+01	2,1E-01	2,0E+01	5,2E+00	1,9E+01	2,7E-01	1,1E-01	1,8E+01	1,8E+00	2,3E-01	1,6E-01	7,2E-02	3,8E+01	7,8E-01
Barley shoots	Cattle manure	Z2	25-07-22	/	Year 1	mg kg ⁻¹	2,8E-01	1,0E+02	2,1E+00	5,9E+00	5,5E+01	2,7E-01	1,5E+01	6,2E+00	2,2E+01	3,8E-01	1,5E-01	1,9E+01	1,8E+00	1,7E-01	1,8E-01	6,8E-02	4,8E+01	8,3E-01
Barley shoots	Cattle manure	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,8E-01	7,0E+01	1,2E+00	9,8E+00	4,1E+01	2,1E-01	1,3E+01	5,1E+00	1,8E+01	2,4E-01	5,6E-02	1,7E+01	2,1E+00	1,3E-01	1,2E-01	4,4E-02	2,8E+01	4,4E-01
Barley shoots	Cover crop restitution	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,3E-01	5,4E+01	8,2E-01	1,3E+00	4,5E+01	1,1E-01	1,2E+01	5,3E+00	2,6E+01	1,6E-01	1,6E-02	1,6E+01	1,3E+00	2,2E-01	9,3E-02	3,6E-02	2,5E+01	4,5E-01
Barley shoots	Cover crop restitution	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,7E-01	7,2E+01	1,3E+00	1,9E+00	3,2E+01	1,5E-01	1,8E+01	5,0E+00	2,2E+01	2,5E-01	1,4E-01	1,5E+01	1,4E+00	1,5E-01	1,2E-01	5,0E-02	3,2E+01	6,0E-01
Barley shoots	Cover crop restitution	Z3	25-07-22	/	Year 1	mg kg ⁻¹	3,9E-01	1,7E+02	2,9E+00	8,7E+00	5,7E+01	3,7E-01	3,3E+01	8,9E+00	4,8E+01	5,0E-01	1,6E-01	2,3E+01	1,7E+00	1,6E-01	1,4E-01	5,1E-02	3,1E+01	8,9E-01
Barley heads	No application	Z1	25-07-22	/	Year 1	mg kg ⁻¹	2,9E-02	2,1E+01	8,8E-01	4,9E-01	3,3E+01	1,4E+01	7,8E-01	6,6E+00	3,6E+01	7,4E-02	1,6E-02	3,5E+00	4,4E-01	4,2E-02	1,9E-02	9,0E-03	6,4E+00	1,0E-01
Barley heads	No application	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,7E-02	2,8E+01	1,2E+00	5,5E-01	2,6E+01	1,3E+01	8,3E-01	6,0E+00	3,1E+01	1,1E-01	1,5E-02	3,4E+00	5,7E-01	2,4E-02	1,8E-02	1,1E-02	1,0E+01	1,4E-01
Barley heads	No application	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,2E-02	1,4E+01	8,0E-01	3,3E-01	2,7E+01	5,0E+00	4,5E-01	6,1E+00	3,5E+01	8,5E-02	1,6E-02	5,1E+00	1,2E+00	2,4E-02	1,3E-02	7,3E-03	6,7E+00	9,5E-02
Barley heads	Green waste compost	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,7E-02	1,1E+01	6,4E-01	3,1E-01	2,3E+01	3,8E+00	4,1E-01	5,3E+00	3,4E+01	8,4E-02	1,6E-02	1,9E+00	6,8E-01	2,7E-02	1,1E-02	6,7E-03	4,7E+00	9,3E-02
Barley heads	Green waste compost	Z2	25-07-22	/	Year 1	mg kg ⁻¹	4,0E-02	9,4E+00	4,4E-01	2,3E-01	2,3E+01	6,7E+00	4,2E-01	5,6E+00	3,4E+01	8,4E-02	6,4E-02	3,4E+00	7,9E-01	3,5E-02	2,2E-01	3,2E-01	1,2E+01	9,3E-02
Barley heads	Green waste compost	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,6E-02	6,1E+00	2,6E-01	2,7E-01	2,3E+01	3,6E+00	3,5E-01	5,7E+00	4,0E+01	6,1E-02	1,6E-02	4,0E+00	1,1E+00	4,0E-02	1,2E-01	1,8E-01	7,5E+00	7,7E-02
Barley heads	Cattle manure	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,5E-02	4,6E+00	2,4E-01	1,6E-01	2,5E+01	9,9E+00	4,8E-01	6,0E+00	3,7E+01	4,8E-02	1,5E-02	2,7E+00	7,5E-01	5,5E-02	8,5E-02	1,1E-01	7,1E+00	1,5E-01

Barley heads	Cattle manure	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,6E-02	8,0E+00	3,9E-01	2,1E-01	2,0E+01	4,1E+00	4,0E-01	6,1E+00	3,5E+01	7,0E-02	1,6E-02	2,5E+00	5,5E-01	3,9E-02	8,0E-02	8,6E-02	8,3E+00	2,0E-01
Barley heads	Cattle manure	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,1E-02	1,3E+01	6,2E-01	3,0E-01	2,2E+01	3,8E+00	4,0E-01	5,8E+00	3,3E+01	9,0E-02	1,6E-02	2,4E+00	5,4E-01	3,7E-02	5,6E-02	6,2E-02	4,8E+00	1,3E-01
Barley heads	Cover crop restitution	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,6E-02	4,9E+01	1,7E+00	8,3E-01	2,8E+01	7,5E+00	9,0E-01	6,8E+00	4,2E+01	1,2E-01	1,6E-02	2,5E+00	5,5E-01	7,5E-02	6,4E-02	6,7E-02	5,2E+00	1,5E-01
Barley heads	Cover crop restitution	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,7E-02	3,5E+01	1,6E+00	7,2E-01	2,8E+01	3,0E+00	7,4E-01	6,2E+00	3,6E+01	1,4E-01	1,6E-02	3,4E+00	4,2E-01	3,4E-02	4,3E-02	4,8E-02	9,0E+00	1,1E-01
Barley heads	Cover crop restitution	Z3	25-07-22	/	Year 1	mg kg ⁻¹	2,8E-02	2,0E+01	1,2E+00	5,2E-01	3,0E+01	3,2E+01	1,3E+00	8,6E+00	4,9E+01	1,7E-01	1,6E-02	5,4E+00	7,1E-01	2,0E-02	4,4E-02	4,1E-02	7,5E+00	1,3E-01
Solution	Cover crop restitution	Z2	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	7,2E-05	2,6E-03	3,8E-03	1,5E-03	3,1E-03	2,0E-04	7,3E-03	1,4E-02	7,0E-02	7,1E-04	4,9E-04	1,7E-02	4,3E-04	1,2E-04	7,0E-04	4,5E-04	2,2E-02	4,8E-04
Solution	Cover crop restitution	Z3	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	4,9E-05	5,4E-03	4,7E-03	1,3E-03	7,2E-03	3,2E-04	9,4E-03	1,4E-02	2,1E-01	1,2E-03	1,0E-03	1,7E-02	2,2E-04	5,9E-05	2,0E-04	5,8E-04	2,3E-02	4,7E-04
Solution	Cattle manure	Z1	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	1,7E-04	7,0E-03	5,9E-03	1,9E-03	5,4E-03	5,6E-04	1,2E-02	2,2E-02	3,8E-01	2,0E-03	7,8E-04	2,1E-02	5,8E-04	1,1E-04	4,6E-04	7,5E-04	7,8E-02	5,9E-04
Solution	Cattle manure	Z2	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	6,0E-05	2,2E-03	4,5E-03	9,8E-04	7,4E-03	3,8E-04	7,4E-03	1,5E-02	4,9E-01	2,1E-03	1,4E-04	2,2E-02	6,2E-04	9,1E-05	1,8E-04	5,7E-04	5,2E-02	7,6E-04
Solution	Cattle manure	Z3	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	8,2E-05	4,0E-03	5,1E-03	1,2E-03	2,4E-02	6,1E-04	1,0E-02	1,4E-02	2,4E-01	1,7E-03	6,6E-04	3,1E-02	4,6E-04	8,2E-05	3,2E-04	5,8E-04	7,2E-02	8,7E-04
Solution	Green waste compost	Z1	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	1,0E-04	2,3E-03	2,6E-03	1,4E-03	1,7E-03	5,6E-04	1,0E-02	2,0E-02	8,1E-02	2,1E-03	6,4E-04	2,4E-02	5,4E-04	9,8E-05	2,8E-04	7,4E-04	3,1E-02	1,7E-04
Solution	Green waste compost	Z2	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	6,0E-05	2,6E-03	2,7E-03	1,1E-03	3,7E-03	4,3E-04	9,7E-03	1,5E-02	1,1E-01	1,6E-03	5,0E-04	2,8E-02	1,0E-03	7,1E-05	2,1E-04	6,0E-04	3,1E-02	2,2E-04
Solution	Green waste compost	Z3	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	1,1E-04	1,2E-02	1,3E-02	1,8E-03	1,4E-01	1,4E-03	8,3E-03	1,2E-02	5,7E-01	2,2E-03	4,1E-04	5,7E-02	2,1E-03	1,3E-04	1,1E-03	6,6E-04	1,0E-01	1,8E-03
Solution	No application	Z1	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	3,7E-05	1,0E-03	2,9E-03	7,9E-04	2,4E-03	1,8E-04	3,5E-03	8,3E-03	2,1E-01	6,0E-04	3,8E-04	1,1E-02	1,2E-04	4,1E-05	1,6E-04	3,5E-04	2,8E-02	2,4E-04
Solution	No application	Z2	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	4,1E-05	1,3E-03	2,4E-03	8,8E-04	2,4E-03	2,7E-04	5,3E-03	1,1E-02	1,9E-01	6,9E-04	4,0E-04	1,3E-02	1,3E-04	3,6E-05	1,7E-04	4,0E-04	5,0E-02	2,5E-04
Solution	No application	Z3	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	7,7E-05	3,9E-03	5,3E-03	1,4E-03	2,4E-02	6,3E-04	3,6E-03	8,2E-03	2,0E-01	1,6E-03	5,7E-04	1,1E-01	9,3E-04	4,4E-05	1,5E-04	5,7E-04	2,8E-02	1,0E-03
Solution	No application	Z1	13-01-23	B	Interculture	mg L ⁻¹	3,3E-05	1,9E-03	8,5E-04	6,5E-04	2,9E-03	1,5E-04	2,5E-03	6,2E-03	3,3E-01	4,7E-04	1,0E-04	1,0E-02	6,8E-05	2,5E-05	3,9E-05	2,6E-04	9,3E-03	1,1E-04
Solution	No application	Z1	13-01-23	C	Interculture	mg L ⁻¹	4,3E-05	4,9E-04	1,5E-03	5,5E-04	6,7E-04	1,7E-04	2,2E-03	5,2E-03	9,0E-01	3,5E-04	1,5E-04	1,4E-02	7,6E-05	2,6E-05	2,2E-05	2,4E-04	2,9E-02	4,6E-05
Solution	No application	Z1	13-01-23	D	Interculture	mg L ⁻¹	6,3E-05	7,8E-04	7,1E-04	6,7E-04	1,5E-03	1,6E-04	3,4E-03	6,7E-03	1,7E-01	5,8E-04	1,9E-04	2,2E-02	6,9E-05	4,6E-05	2,9E-05	2,7E-04	2,4E-02	7,6E-05
Solution	No application	Z1	13-01-23	E	Interculture	mg L ⁻¹	2,4E-05	1,8E-03	1,3E-03	5,4E-04	3,9E-03	1,3E-04	2,8E-03	5,9E-03	1,6E-01	5,2E-04	2,1E-04	2,8E-02	5,3E-05	4,1E-05	2,0E-05	2,7E-04	1,2E-02	1,0E-04
Solution	No application	Z2	13-01-23	A	Interculture	mg L ⁻¹	2,2E-05	2,6E-03	1,6E-03	5,9E-04	9,7E-03	2,5E-04	2,6E-03	4,5E-03	8,2E-01	4,9E-04	1,7E-04	1,1E-02	9,0E-05	2,1E-05	3,1E-05	1,9E-04	2,2E-02	3,2E-04

Appendices

Solution	No application	Z2	13-01-23	C	Interculture	mg L ⁻¹	2,6E-05	7,3E-04	1,4E-03	5,5E-04	1,3E-03	1,8E-04	3,3E-03	6,8E-03	6,8E-01	4,8E-04	2,3E-04	1,8E-02	9,9E-05	2,2E-05	4,6E-05	2,5E-04	1,4E-02	9,5E-05
Solution	No application	Z2	13-01-23	D	Interculture	mg L ⁻¹	4,6E-05	4,2E-03	1,6E-03	8,0E-04	9,5E-03	3,1E-04	3,0E-03	5,1E-03	6,4E-01	4,9E-04	1,9E-04	1,2E-02	7,1E-05	2,2E-05	2,3E-05	2,3E-04	1,2E-02	4,8E-04
Solution	No application	Z2	13-01-23	E	Interculture	mg L ⁻¹	3,3E-05	7,2E-04	1,2E-03	1,3E-03	1,2E-03	1,6E-04	3,2E-03	5,6E-03	3,5E-01	4,3E-04	1,8E-04	1,7E-02	1,2E-04	1,9E-05	3,1E-05	2,2E-04	1,7E-02	4,5E-05
Solution	No application	Z3	13-01-23	A	Interculture	mg L ⁻¹	2,8E-05	4,5E-04	2,5E-03	7,5E-04	7,6E-04	1,9E-04	1,6E-03	3,3E-03	6,8E-01	1,1E-03	1,3E-04	7,9E-02	7,8E-04	1,4E-05	4,6E-05	3,4E-04	1,5E-02	4,6E-05
Solution	No application	Z3	13-01-23	B	Interculture	mg L ⁻¹	3,5E-05	6,3E-04	2,7E-03	7,0E-04	1,9E-03	2,1E-04	1,8E-03	4,2E-03	8,5E-01	9,6E-04	2,7E-04	9,2E-02	9,0E-04	2,2E-05	8,2E-05	3,3E-04	4,1E-02	9,9E-05
Solution	No application	Z3	13-01-23	D	Interculture	mg L ⁻¹	2,9E-05	1,9E-04	1,9E-03	7,3E-04	4,4E-04	1,9E-04	1,2E-03	2,8E-03	4,5E-01	5,8E-04	1,1E-04	8,4E-02	4,1E-04	9,4E-06	2,2E-05	2,6E-04	1,1E-02	2,4E-05
Solution	No application	Z3	13-01-23	E	Interculture	mg L ⁻¹	2,9E-05	4,6E-04	3,9E-03	5,6E-04	8,8E-04	3,8E-04	1,4E-03	3,1E-03	1,6E+00	7,7E-04	2,3E-04	6,8E-02	7,2E-04	1,3E-05	3,6E-05	2,8E-04	3,1E-02	5,9E-05
Solution	Green waste compost	Z1	13-01-23	A	Interculture	mg L ⁻¹	4,3E-05	5,6E-04	1,2E-03	5,1E-04	7,7E-04	1,7E-04	3,6E-03	7,3E-03	1,7E-01	9,3E-04	2,0E-04	4,3E-02	3,3E-04	1,4E-04	2,9E-05	3,1E-04	1,6E-02	6,2E-05
Solution	Green waste compost	Z1	13-01-23	B	Interculture	mg L ⁻¹	7,9E-05	1,2E-02	2,5E-03	1,2E-03	2,4E-02	5,1E-04	4,8E-03	1,2E-02	2,4E-01	1,3E-03	3,2E-04	3,5E-02	5,2E-04	4,8E-05	1,8E-05	3,3E-04	1,6E-02	9,1E-04
Solution	Green waste compost	Z1	13-01-23	C	Interculture	mg L ⁻¹	2,6E-04	2,1E-02	5,5E-03	2,8E-03	1,1E-01	1,4E-03	5,7E-03	1,1E-02	9,3E-02	1,7E-03	3,5E-04	3,7E-02	1,8E-04	8,8E-05	3,0E-05	3,4E-04	2,9E-02	4,1E-03
Solution	Green waste compost	Z1	13-01-23	D	Interculture	mg L ⁻¹	7,3E-05	1,1E-03	2,0E-03	8,5E-04	7,2E-04	2,7E-04	6,2E-03	1,2E-02	3,8E-01	1,3E-03	5,1E-04	2,9E-02	4,7E-04	5,1E-05	8,3E-05	4,8E-04	2,1E-02	9,0E-05
Solution	Green waste compost	Z2	13-01-23	A	Interculture	mg L ⁻¹	3,0E-05	1,6E-03	9,9E-04	3,5E-04	1,3E-03	1,3E-04	2,7E-03	4,1E-03	8,1E-02	8,6E-04	1,5E-04	4,8E-02	2,4E-04	2,2E-05	5,0E-05	2,1E-04	1,6E-02	6,7E-05
Solution	Green waste compost	Z2	13-01-23	B	Interculture	mg L ⁻¹	4,5E-05	7,6E-04	1,8E-03	5,5E-04	1,2E-03	2,1E-04	4,6E-03	7,8E-03	2,4E-01	1,4E-03	4,0E-04	6,3E-02	8,5E-04	3,6E-05	3,6E-05	3,7E-04	2,2E-02	5,1E-05
Solution	Green waste compost	Z2	13-01-23	C	Interculture	mg L ⁻¹	4,7E-05	6,6E-04	1,5E-03	5,6E-04	1,0E-03	2,3E-04	4,6E-03	7,4E-03	1,3E-01	1,1E-03	2,3E-04	5,5E-02	6,2E-04	2,9E-05	3,7E-05	3,4E-04	1,8E-02	6,3E-05
Solution	Green waste compost	Z2	13-01-23	D	Interculture	mg L ⁻¹	3,4E-05	1,1E-03	1,0E-03	4,7E-04	6,5E-04	1,4E-04	4,2E-03	6,1E-03	9,0E-02	6,7E-04	2,5E-04	3,5E-02	3,0E-04	2,5E-05	3,8E-05	2,6E-04	2,1E-02	5,4E-05
Solution	Green waste compost	Z2	13-01-23	E	Interculture	mg L ⁻¹	5,1E-05	7,7E-04	1,3E-03	5,5E-04	9,1E-04	2,4E-04	4,7E-03	9,5E-03	6,7E-02	1,5E-03	2,8E-04	8,1E-02	5,6E-04	3,0E-05	4,3E-05	3,5E-04	3,0E-02	3,4E-05
Solution	Green waste compost	Z3	13-01-23	A	Interculture	mg L ⁻¹	2,9E-05	1,1E-03	2,9E-03	7,0E-04	3,1E-03	3,1E-04	3,2E-03	5,2E-03	1,0E+00	1,4E-03	1,8E-04	5,2E-02	8,9E-04	2,1E-05	7,9E-05	3,3E-04	2,2E-02	1,1E-04
Solution	Green waste compost	Z3	13-01-23	B	Interculture	mg L ⁻¹	3,0E-05	1,5E-03	2,2E-03	7,3E-04	3,5E-03	2,3E-04	2,9E-03	5,0E-03	5,9E-01	1,2E-03	1,7E-04	3,9E-02	5,4E-04	1,7E-05	5,1E-05	3,2E-04	1,7E-02	1,5E-04
Solution	Green waste compost	Z3	13-01-23	C	Interculture	mg L ⁻¹	4,4E-05	3,0E-03	2,8E-03	8,7E-04	6,7E-03	3,4E-04	4,9E-03	9,9E-03	3,3E-01	1,9E-03	3,7E-04	6,9E-02	2,4E-03	4,0E-05	7,7E-05	4,6E-04	1,9E-02	3,6E-04

Solution	Green waste compost	Z3	13-01-23	D	Interculture	mg L ⁻¹	5,1E-05	3,6E-04	2,3E-03	6,8E-04	2,0E-03	2,8E-04	3,8E-03	7,8E-03	5,1E-02	1,6E-03	2,0E-04	1,2E-01	1,5E-03	2,3E-05	4,2E-05	4,5E-04	1,8E-02	3,2E-05
Solution	Green waste compost	Z3	13-01-23	E	Interculture	mg L ⁻¹	4,1E-05	1,1E-03	3,0E-03	8,3E-04	1,7E-03	2,2E-04	3,6E-03	6,1E-03	5,5E-01	1,5E-03	3,4E-04	4,6E-02	1,2E-03	2,5E-05	7,2E-05	3,8E-04	1,8E-02	6,8E-05
Solution	Cattle manure	Z1	13-01-23	A	Interculture	mg L ⁻¹	5,8E-05	1,2E-03	2,2E-03	7,6E-04	2,5E-03	1,9E-04	5,3E-03	9,7E-03	1,2E-01	1,3E-03	3,6E-04	6,5E-02	2,6E-04	6,5E-05	8,9E-05	3,8E-04	4,4E-02	1,7E-04
Solution	Cattle manure	Z1	13-01-23	B	Interculture	mg L ⁻¹	5,6E-05	8,8E-04	1,9E-03	8,6E-04	9,4E-04	2,2E-04	6,0E-03	9,6E-03	3,2E-01	1,2E-03	4,2E-04	4,2E-02	3,7E-04	5,3E-05	4,1E-05	3,6E-04	2,5E-02	8,1E-05
Solution	Cattle manure	Z1	13-01-23	C	Interculture	mg L ⁻¹	4,5E-05	1,6E-03	1,5E-03	7,0E-04	1,8E-03	1,8E-04	4,1E-03	7,2E-03	2,8E-01	8,2E-04	2,4E-04	2,2E-02	1,3E-04	4,0E-05	3,0E-05	3,0E-04	1,9E-02	1,3E-04
Solution	Cattle manure	Z1	13-01-23	D	Interculture	mg L ⁻¹	7,6E-05	7,3E-04	1,6E-03	7,1E-04	1,4E-03	1,7E-04	5,3E-03	1,0E-02	7,2E-02	1,3E-03	2,9E-04	3,9E-02	2,4E-04	4,8E-05	3,0E-05	3,8E-04	1,9E-02	5,5E-05
Solution	Cattle manure	Z1	13-01-23	E	Interculture	mg L ⁻¹	3,3E-05	1,7E-03	2,2E-03	7,4E-04	1,6E-03	2,1E-04	4,9E-03	8,1E-03	6,4E-01	1,1E-03	2,0E-04	1,4E-02	4,9E-04	3,2E-05	3,4E-05	3,5E-04	1,5E-02	1,2E-04
Solution	Cattle manure	Z2	13-01-23	A	Interculture	mg L ⁻¹	3,8E-05	6,5E-04	1,7E-03	4,8E-04	1,1E-03	2,0E-04	3,5E-03	6,5E-03	8,3E-01	7,8E-04	2,2E-04	2,5E-02	1,5E-04	2,5E-05	3,3E-05	2,3E-04	2,5E-02	5,5E-05
Solution	Cattle manure	Z2	13-01-23	B	Interculture	mg L ⁻¹	6,0E-05	6,2E-04	1,6E-03	4,7E-04	1,2E-03	1,7E-04	4,4E-03	6,4E-03	3,9E-01	9,7E-04	1,8E-04	5,8E-02	2,0E-04	3,6E-05	5,3E-05	2,3E-04	5,1E-02	5,1E-05
Solution	Cattle manure	Z2	13-01-23	C	Interculture	mg L ⁻¹	4,0E-05	4,5E-03	2,3E-03	7,4E-04	1,3E-02	4,0E-04	4,9E-03	8,2E-03	9,3E-01	9,0E-04	2,3E-04	3,5E-02	1,7E-04	3,7E-05	3,2E-05	2,8E-04	3,3E-02	4,4E-04
Solution	Cattle manure	Z2	13-01-23	D	Interculture	mg L ⁻¹	3,5E-05	3,9E-04	1,0E-03	3,3E-04	7,3E-04	1,1E-04	2,7E-03	4,9E-03	1,6E-01	6,1E-04	1,1E-04	5,0E-02	1,5E-04	2,5E-05	2,4E-05	1,9E-04	2,0E-02	4,5E-05
Solution	Cattle manure	Z2	13-01-23	E	Interculture	mg L ⁻¹	5,6E-05	5,4E-04	1,2E-03	5,0E-04	9,5E-04	1,7E-04	5,2E-03	9,2E-03	7,2E-02	1,1E-03	2,3E-04	5,3E-02	1,8E-04	3,9E-05	6,1E-05	3,0E-04	3,2E-02	6,3E-05
Solution	Cattle manure	Z3	13-01-23	A	Interculture	mg L ⁻¹	4,4E-05	7,7E-04	1,9E-03	5,5E-04	1,2E-03	1,6E-04	4,0E-03	5,8E-03	2,2E-01	1,1E-03	3,0E-04	3,5E-02	2,2E-04	1,8E-05	6,8E-05	3,1E-04	2,8E-02	6,3E-05
Solution	Cattle manure	Z3	13-01-23	C	Interculture	mg L ⁻¹	3,6E-05	2,0E-03	2,3E-03	1,1E-03	2,7E-03	2,2E-04	4,8E-03	6,0E-03	6,6E-01	8,3E-04	2,1E-04	1,6E-02	2,3E-04	2,2E-05	4,4E-05	2,9E-04	2,1E-02	1,7E-04
Solution	Cattle manure	Z3	13-01-23	D	Interculture	mg L ⁻¹	2,8E-05	1,0E-03	2,3E-03	5,0E-04	1,9E-03	2,0E-04	3,7E-03	5,2E-03	4,6E-01	7,4E-04	2,4E-04	2,7E-02	1,5E-04	1,9E-05	4,6E-05	2,6E-04	1,5E-02	9,2E-05
Solution	Cattle manure	Z3	13-01-23	E	Interculture	mg L ⁻¹	5,3E-05	1,7E-03	2,0E-03	7,4E-04	2,9E-03	3,2E-04	6,6E-03	8,8E-03	4,6E-01	1,2E-03	3,6E-04	2,8E-02	3,5E-04	2,6E-05	5,0E-05	3,5E-04	1,8E-02	1,4E-04
Solution	Cover crop restitution	Z1	13-01-23	B	Interculture	mg L ⁻¹	6,5E-05	1,5E-03	7,4E-04	7,2E-04	2,7E-03	1,1E-04	5,5E-03	6,7E-03	4,3E-02	6,3E-04	2,7E-04	1,3E-02	1,1E-04	6,8E-05	2,9E-05	2,0E-04	1,0E-02	1,8E-04
Solution	Cover crop restitution	Z1	13-01-23	C	Interculture	mg L ⁻¹	5,2E-05	1,5E-03	8,2E-04	6,9E-04	3,6E-03	1,1E-04	5,2E-03	6,4E-03	5,0E-02	6,0E-04	3,1E-04	1,1E-02	5,4E-05	6,2E-05	2,2E-05	2,2E-04	1,1E-02	2,1E-04
Solution	Cover crop restitution	Z1	13-01-23	E	Interculture	mg L ⁻¹	9,2E-05	8,8E-04	9,1E-04	7,7E-04	1,9E-03	1,4E-04	6,9E-03	8,5E-03	9,5E-02	6,5E-04	2,8E-04	1,3E-02	5,9E-05	8,1E-05	5,6E-05	2,3E-04	1,2E-02	1,3E-04
Solution	Cover crop restitution	Z2	13-01-23	B	Interculture	mg L ⁻¹	3,7E-05	1,2E-03	8,9E-04	4,2E-04	4,4E-03	1,5E-04	2,9E-03	4,1E-03	1,3E-02	7,3E-04	1,9E-04	6,4E-02	1,1E-04	2,7E-05	2,4E-05	1,5E-04	2,2E-02	1,2E-04
Solution	Cover crop restitution	Z2	13-01-23	C	Interculture	mg L ⁻¹	2,8E-05	6,0E-04	1,1E-03	4,5E-04	1,1E-03	1,3E-04	4,2E-03	5,7E-03	4,9E-02	6,1E-04	2,0E-04	2,5E-02	9,7E-05	2,4E-05	2,3E-05	2,0E-04	1,2E-02	6,7E-05

Appendices

Solution	Cover crop restitution	Z2	13-01-23	D	Interculture	mg L ⁻¹	2,9E-05	4,7E-04	8,1E-04	4,7E-04	5,7E-04	1,1E-04	3,7E-03	6,3E-03	2,8E-02	6,1E-04	1,7E-04	2,1E-02	9,8E-05	1,8E-05	2,9E-05	1,9E-04	7,9E-03	2,8E-05
Solution	Cover crop restitution	Z2	13-01-23	E	Interculture	mg L ⁻¹	4,1E-05	4,6E-04	8,4E-04	4,3E-04	9,7E-04	1,2E-04	4,1E-03	6,0E-03	2,3E-02	6,0E-04	1,3E-04	2,9E-02	7,6E-05	3,4E-05	3,0E-05	1,7E-04	1,2E-02	6,2E-05
Solution	Cover crop restitution	Z3	13-01-23	A	Interculture	mg L ⁻¹	3,3E-05	5,9E-04	1,1E-03	4,6E-04	6,1E-04	9,1E-05	3,6E-03	4,9E-03	7,8E-02	5,7E-04	8,1E-05	2,9E-02	7,3E-05	1,6E-05	2,0E-05	2,1E-04	7,7E-03	5,0E-05
Solution	Cover crop restitution	Z3	13-01-23	C	Interculture	mg L ⁻¹	3,0E-05	9,5E-04	1,7E-03	4,3E-04	1,5E-03	1,7E-04	2,8E-03	4,3E-03	5,1E-01	6,1E-04	8,4E-05	2,9E-02	1,2E-04	1,7E-05	3,4E-05	2,1E-04	1,7E-02	9,7E-05
Solution	Cover crop restitution	Z3	13-01-23	D	Interculture	mg L ⁻¹	3,3E-05	5,5E-04	1,4E-03	5,4E-04	1,2E-03	1,4E-04	3,7E-03	5,8E-03	3,9E-02	7,2E-04	1,3E-04	3,5E-02	1,3E-04	2,1E-05	4,9E-05	2,1E-04	1,3E-02	6,1E-05
Solution	Cover crop restitution	Z3	13-01-23	E	Interculture	mg L ⁻¹	3,0E-05	7,6E-04	1,7E-03	5,4E-04	1,4E-03	1,8E-04	3,9E-03	5,6E-03	4,3E-02	9,6E-04	2,2E-04	3,9E-02	1,1E-04	1,7E-05	2,0E-05	2,3E-04	9,3E-03	6,1E-05
EOM	Cattle manure	/	08-05-23	/	Year 2	mg kg ⁻¹	4,2E-01	2,5E+02	4,6E+00	8,2E+00	1,0E+02	7,3E-01	4,1E+02	1,4E+01	6,9E+01	8,9E-01	5,9E-02	5,4E+01	2,9E+00	1,8E-01	2,8E-01	1,5E-01	4,9E+01	3,1E+00
EOM	Green waste compost	/	08-05-23	/	Year 2	mg kg ⁻¹	2,4E+00	8,9E+02	1,8E+01	2,2E+01	3,9E+02	1,2E+01	1,0E+01	2,6E+01	1,4E+02	3,2E+00	1,6E-01	8,7E+01	1,8E+00	5,2E-01	2,0E+00	7,0E-01	1,5E+02	2,7E+01
Solution	No application	Z1	26-07-23	B	Year 2	mg L ⁻¹	9,4E-04	2,0E-02	4,1E-03	2,0E-03	5,4E+00	2,6E-03	6,8E-02	3,8E-03	8,6E-01	1,0E-03	6,3E-04	2,5E+00	1,4E-04	5,6E-03	7,3E-05	1,9E-04	6,3E-01	9,1E-04
Solution	No application	Z1	26-07-23	C	Year 2	mg L ⁻¹	1,2E-04	1,3E-02	3,3E-03	1,9E-03	6,6E-02	8,9E-04	3,5E-03	6,7E-03	4,1E+00	9,4E-04	3,5E-04	1,7E-02	5,8E-05	1,1E-04	4,8E-05	2,6E-04	3,6E-02	2,2E-03
Solution	No application	Z1	26-07-23	DAE	Year 2	mg L ⁻¹	2,5E-04	4,2E-02	9,5E-03	6,2E-03	8,4E-01	3,3E-03	1,6E-02	2,2E-02	4,1E+00	2,7E-03	6,0E-04	2,9E-01	2,2E-04	9,3E-04	3,5E-04	4,0E-04	1,4E-01	8,4E-03
Solution	No application	Z2	26-07-23	C	Year 2	mg L ⁻¹	7,0E-05	8,3E-03	1,5E-03	1,2E-03	2,2E-02	4,3E-04	2,8E-03	4,4E-03	4,8E-01	6,6E-04	2,1E-04	1,6E-02	5,9E-05	4,6E-05	3,2E-05	2,4E-04	6,4E-02	8,4E-04
Solution	No application	Z2	26-07-23	AD	Year 2	mg L ⁻¹	5,8E-04	5,4E-02	1,3E-02	9,5E-03	6,1E-01	5,4E-03	3,1E-02	2,1E-01	5,4E+00	3,0E-03	6,3E-04	1,4E+00	1,2E-04	1,8E-03	2,1E-03	3,6E-04	3,8E-01	2,0E-02
Solution	No application	Z3	26-07-23	AE	Year 2	mg L ⁻¹	2,6E-04	2,5E-02	7,8E-03	4,6E-03	1,3E-01	2,1E-03	6,6E-03	1,6E-02	3,7E+00	2,3E-03	4,4E-04	2,8E-01	6,4E-04	1,3E-04	2,1E-04	5,0E-04	5,5E-02	4,4E-03
Solution	No application	Z3	26-07-23	C	Year 2	mg L ⁻¹	1,3E-04	1,5E-02	4,1E-03	2,2E-03	4,8E-02	8,9E-04	3,2E-03	4,1E-03	1,1E+00	1,1E-03	2,1E-04	1,3E-01	3,0E-04	6,0E-05	1,0E-04	3,8E-04	7,0E-02	1,8E-03
Solution	No application	Z3	26-07-23	D	Year 2	mg L ⁻¹	2,8E-04	2,6E-02	7,5E-03	4,8E-03	1,2E-01	2,0E-03	6,0E-03	6,8E-03	2,5E-01	2,4E-03	6,1E-04	3,3E-01	3,7E-04	9,2E-05	2,3E-04	5,0E-04	5,9E-02	3,6E-03
Solution	Green waste compost	Z1	26-07-23	C	Year 2	mg L ⁻¹	1,7E-04	1,8E-02	4,0E-03	1,8E-03	5,6E-02	1,1E-03	5,5E-03	1,0E-02	8,8E-01	1,8E-03	5,7E-04	5,2E-02	7,0E-04	6,7E-05	8,0E-05	3,9E-04	5,8E-02	2,2E-03
Solution	Green waste compost	Z1	26-07-23	A	Year 2	mg L ⁻¹	3,1E-04	3,7E-02	7,6E-03	4,8E-03	1,5E-01	3,0E-03	1,2E-02	3,9E-02	1,1E+00	3,9E-03	1,4E-03	9,5E-02	7,8E-04	2,2E-04	2,5E-04	6,6E-04	9,5E-02	5,3E-03
Solution	Green waste compost	Z2	26-07-23	C	Year 2	mg L ⁻¹	1,1E-04	7,7E-03	3,0E-03	1,3E-03	2,7E-02	6,3E-04	5,5E-03	8,6E-03	2,6E-01	2,4E-03	5,0E-04	6,9E-02	6,5E-04	6,2E-05	1,3E-04	4,1E-04	1,9E-02	9,8E-04
Solution	Green waste compost	Z2	26-07-23	D	Year 2	mg L ⁻¹	1,3E-04	1,4E-02	3,0E-03	1,6E-03	3,9E-02	9,5E-04	6,4E-03	9,1E-03	3,6E-01	1,7E-03	5,4E-04	8,8E-02	6,8E-04	7,2E-05	1,7E-04	3,9E-04	3,8E-02	1,2E-03

Solution	Green waste compost	Z3	26-07-23	AD	Year 2	mg L ⁻¹	2,4E-04	4,3E-02	1,4E-02	1,0E-02	1,9E-01	3,1E-03	1,2E-02	2,0E-02	1,7E+01	3,4E-03	1,1E-04	2,4E-01	1,5E-03	2,2E-04	4,3E-04	6,2E-04	7,2E-02	8,7E-03
Solution	Cattle manure	Z1	26-07-23	A	Year 2	mg L ⁻¹	4,0E-04	3,8E-02	8,5E-03	3,8E-03	1,3E-01	2,6E-03	1,3E-02	2,2E-02	3,5E+00	4,9E-03	8,6E-04	1,7E-01	1,0E-03	2,3E-04	3,0E-04	7,2E-04	9,1E-02	3,7E-03
Solution	Cattle manure	Z1	26-07-23	C	Year 2	mg L ⁻¹	1,1E-04	8,6E-03	4,6E-03	1,3E-03	2,8E-02	7,2E-04	6,4E-03	9,1E-03	2,7E+00	4,7E-03	2,4E-04	7,4E-02	1,5E-03	1,5E-04	2,1E-04	3,9E-04	2,9E-02	9,5E-04
Solution	Cattle manure	Z1	26-07-23	D	Year 2	mg L ⁻¹	2,4E-04	2,5E-02	6,0E-03	2,7E-03	8,9E-02	1,8E-03	1,1E-02	1,7E-02	7,1E-01	3,6E-03	8,0E-04	3,3E-01	1,1E-03	2,0E-04	7,9E-05	6,2E-04	1,0E-01	2,7E-03
Solution	Cattle manure	Z2	26-07-23	C	Year 2	mg L ⁻¹	8,3E-05	3,6E-03	1,8E-03	8,7E-04	9,1E-03	4,5E-04	8,0E-03	1,3E-02	3,6E-01	1,4E-03	4,6E-04	4,8E-02	6,9E-04	6,5E-05	1,3E-04	3,7E-04	3,8E-02	3,7E-04
Solution	Cattle manure	Z2	26-07-23	D	Year 2	mg L ⁻¹	1,1E-04	5,0E-03	3,0E-03	1,1E-03	3,8E-02	1,0E-03	9,6E-03	1,4E-02	6,0E+00	1,7E-03	5,6E-04	9,8E-02	5,6E-04	1,1E-04	2,2E-04	4,1E-04	4,3E-02	5,8E-04
Solution	Cattle manure	Z2	26-07-23	A	Year 2	mg L ⁻¹	4,8E-04	2,3E-02	8,8E-03	5,7E-03	2,3E-01	3,1E-03	1,8E-02	5,4E-01	5,9E+00	3,4E-03	1,0E-03	8,1E-01	6,3E-04	6,0E-04	5,0E-03	6,8E-04	3,2E-01	4,5E-02
Solution	Cattle manure	Z3	26-07-23	D	Year 2	mg L ⁻¹	1,9E-04	2,1E-02	5,6E-03	2,5E-03	6,8E-02	1,7E-03	1,1E-02	1,2E-02	4,9E-01	3,0E-03	8,6E-04	2,0E-01	1,8E-03	8,8E-05	2,3E-04	5,2E-04	6,2E-02	2,1E-03
Solution	Cattle manure	Z3	26-07-23	BA	Year 2	mg L ⁻¹	2,4E-04	3,3E-02	9,4E-03	2,5E-02	3,7E-01	5,3E-03	2,2E-02	8,6E-01	2,4E+00	3,1E-03	3,1E-04	2,2E-01	4,4E-04	6,7E-04	8,4E-03	8,4E-04	1,1E-01	6,2E-02
Solution	Cover crop restitution	Z1	26-07-23	DE	Year 2	mg L ⁻¹	3,7E-04	3,0E-02	6,3E-03	7,0E-03	2,4E+00	5,2E-03	4,0E-02	4,0E-02	1,1E+01	2,3E-03	6,6E-04	6,3E-01	2,2E-04	4,8E-03	5,7E-04	5,6E-04	3,2E-01	6,7E-03
Solution	Cover crop restitution	Z2	26-07-23	D	Year 2	mg L ⁻¹	4,0E-04	4,0E-02	7,7E-03	5,6E-03	5,2E-01	3,3E-03	3,0E-02	8,8E-01	2,6E+00	2,5E-03	4,0E-04	1,3E+00	1,2E-04	2,1E-03	9,6E-03	7,1E-04	3,7E-01	6,6E-02
Solution	Cover crop restitution	Z2	26-07-23	E	Year 2	mg L ⁻¹	2,9E-04	1,4E-02	4,3E-03	6,4E-03	3,0E+00	4,5E-03	4,7E-02	1,8E-01	1,9E+00	1,7E-03	9,2E-04	1,3E+00	3,9E-04	4,4E-03	2,6E-03	5,1E-04	6,5E-01	1,4E-02
Solution	Cover crop restitution	Z3	26-07-23	E	Year 2	mg L ⁻¹	1,6E-04	1,5E-02	5,5E-03	9,7E-03	9,7E-02	1,6E-03	1,1E-02	1,7E-02	1,1E+01	2,3E-03	2,9E-04	1,9E-01	1,1E-03	1,0E-04	4,3E-04	6,1E-04	1,1E-01	2,2E-03
Solution	No application	Z1	13-09-23	C	Year 2	mg L ⁻¹	3,0E-05	8,0E-04	7,9E-04	6,2E-04	8,4E-03	1,8E-04	2,4E-03	3,9E-03	4,6E+00	3,5E-04	9,0E-05	4,3E-02	8,0E-05	1,1E-04	7,5E-05	2,1E-04	2,5E-02	5,0E-05
Solution	Green waste compost	Z1	13-09-23	A	Year 2	mg L ⁻¹	1,1E-04	9,8E-03	3,0E-03	1,5E-03	5,2E-02	1,4E-03	4,6E-03	1,5E-02	1,0E+01	1,6E-03	3,7E-04	1,3E-01	2,8E-04	9,1E-05	7,2E-05	3,7E-04	5,8E-02	2,0E-03
Solution	Green waste compost	Z1	13-09-23	C	Year 2	mg L ⁻¹	5,6E-05	5,0E-03	2,1E-03	1,3E-03	1,4E-02	9,2E-04	4,1E-03	1,1E-02	4,7E+00	1,3E-03	3,4E-04	8,3E-02	9,2E-04	5,2E-05	1,0E-04	4,1E-04	3,4E-02	6,5E-04
Solution	Green waste compost	Z1	13-09-23	E	Year 2	mg L ⁻¹	6,7E-05	2,2E-03	3,1E-03	1,6E-03	7,1E-03	9,0E-04	7,2E-03	1,0E-01	3,6E+00	2,7E-03	5,2E-04	1,4E-01	3,1E-03	1,1E-04	1,1E-03	7,1E-04	5,8E-02	6,4E-03
Solution	Green waste compost	Z2	13-09-23	A	Year 2	mg L ⁻¹	1,1E-04	1,2E-02	4,0E-03	2,2E-03	4,8E-02	1,8E-03	5,7E-03	2,1E-02	1,3E+01	1,7E-03	3,3E-04	1,3E-01	6,7E-04	7,5E-05	1,4E-04	3,7E-04	4,9E-02	2,6E-03
Solution	Green waste compost	Z2	13-09-23	C	Year 2	mg L ⁻¹	5,2E-05	1,0E-03	1,9E-03	6,3E-04	3,6E-03	2,9E-04	3,4E-03	1,8E-02	1,5E+00	1,7E-03	2,7E-04	1,2E-01	6,1E-04	3,7E-05	2,0E-04	3,2E-04	3,9E-02	9,1E-04
Solution	Green waste compost	Z2	13-09-23	D	Year 2	mg L ⁻¹	5,2E-05	8,7E-04	1,8E-03	6,7E-04	4,6E-03	3,6E-04	3,9E-03	6,8E-03	2,1E+00	1,2E-03	4,0E-04	1,1E-01	6,4E-04	4,2E-05	9,4E-05	3,5E-04	3,3E-02	5,6E-05

Appendices

Solution	Green waste compost	Z3	13-09-23	A	Year 2	mg L ⁻¹	1,1E-04	3,3E-03	5,4E-03	2,8E-03	2,3E-02	1,1E-03	7,4E-02	1,1E-02	7,9E+01	1,3E-03	3,5E-04	2,2E-01	1,8E-03	6,1E-05	2,4E-04	5,9E-04	2,5E-02	7,1E-04
Solution	Green waste compost	Z3	13-09-23	C	Year 2	mg L ⁻¹	5,2E-05	3,1E-03	3,5E-03	1,4E-03	1,6E-02	1,0E-03	4,6E-03	8,4E-02	2,1E+01	1,6E-03	5,4E-05	1,8E-01	8,5E-04	5,5E-05	4,5E-04	4,4E-04	4,6E-02	5,3E-03
Solution	Cattle manure	Z1	13-09-23	C	Year 2	mg L ⁻¹	2,7E-05	6,5E-04	2,9E-03	4,3E-04	6,0E-03	2,5E-04	2,5E-03	6,4E-02	1,2E+01	1,6E-03	1,4E-04	6,7E-02	7,8E-04	7,3E-05	6,1E-04	2,3E-04	2,6E-02	4,1E-03
Solution	Cattle manure	Z1	13-09-23	D	Year 2	mg L ⁻¹	7,2E-05	1,4E-03	3,1E-03	1,1E-03	6,5E-03	6,6E-04	7,8E-03	2,0E-02	4,1E+00	2,7E-03	6,3E-04	1,8E-01	1,3E-03	9,8E-05	1,7E-04	6,5E-04	4,5E-02	5,1E-04
Solution	Cattle manure	Z1	13-09-23	E	Year 2	mg L ⁻¹	9,3E-05	2,0E-03	3,4E-03	4,1E-03	1,9E-02	2,2E-03	1,4E-02	4,8E-01	2,0E+01	1,7E-03	2,0E-04	3,5E-01	9,3E-04	4,4E-04	5,9E-03	8,3E-04	1,2E-01	4,5E-02
Solution	Cattle manure	Z2	13-09-23	C	Year 2	mg L ⁻¹	1,8E-04	7,0E-03	2,8E-03	1,8E-03	2,8E-02	9,5E-04	9,5E-03	4,4E-02	7,0E+00	1,3E-03	4,1E-04	1,2E-01	6,9E-04	1,2E-04	7,6E-04	5,6E-04	8,5E-02	2,5E-03
Solution	Cattle manure	Z2	13-09-23	D	Year 2	mg L ⁻¹	1,9E-04	2,3E-03	9,5E-03	5,8E-03	2,0E-02	1,1E-03	8,1E-03	1,0E-01	6,4E+01	1,3E-03	5,4E-05	2,1E-01	5,0E-04	1,3E-04	7,0E-04	4,4E-04	9,3E-02	6,3E-03
Solution	Cattle manure	Z3	13-09-23	B	Year 2	mg L ⁻¹	4,5E-05	2,6E-03	3,2E-03	8,7E-04	1,3E-02	6,5E-04	5,4E-03	8,2E-03	9,1E+00	2,0E-03	3,0E-04	9,7E-02	5,9E-04	4,0E-05	1,1E-04	3,0E-04	2,7E-02	4,6E-04
Solution	Cattle manure	Z3	13-09-23	E	Year 2	mg L ⁻¹	1,6E-04	1,4E-03	3,9E-03	9,7E-04	7,5E-03	7,6E-04	7,6E-03	9,8E-02	1,6E+01	1,8E-03	3,3E-04	2,9E-01	7,1E-04	1,0E-04	9,1E-04	4,4E-04	7,2E-02	5,8E-03
Solution	Cover crop restitution	Z3	13-09-23	A	Year 2	mg L ⁻¹	9,6E-04	1,3E-01	5,0E-02	3,3E-02	1,1E+00	1,9E-02	4,4E-02	6,9E-01	7,0E+01	7,5E-03	1,1E-04	2,6E-01	3,7E-04	1,3E-03	2,6E-03	7,4E-04	2,0E-01	9,3E-02
Solution	Cover crop restitution	Z3	13-09-23	E	Year 2	mg L ⁻¹	1,4E-04	1,3E-02	7,3E-03	5,2E-03	1,1E-01	2,1E-03	1,2E-02	6,5E-01	6,0E+01	2,1E-03	1,6E-04	1,4E-01	1,7E-04	3,5E-04	2,9E-03	5,4E-04	7,6E-02	4,5E-02
Maize roots	No application	Z1	20-09-23	/	Year 2	mg kg ⁻¹	1,8E+00	7,0E+02	1,1E+01	1,5E+01	1,1E+02	1,7E+00	3,2E+02	8,7E+00	2,3E+01	2,0E+00	2,3E-01	2,0E+01	2,1E-01	4,7E-01	4,1E-01	1,9E-01	7,1E+01	5,1E+00
Maize roots	No application	Z2	20-09-23	/	Year 2	mg kg ⁻¹	3,6E+00	1,5E+03	2,7E+01	3,1E+01	1,9E+02	3,5E+00	6,4E+02	1,1E+01	3,2E+01	4,4E+00	1,8E-01	3,7E+01	3,9E-01	3,7E-01	1,0E+00	3,5E-01	1,4E+02	9,8E+00
Maize roots	No application	Z3	20-09-23	/	Year 2	mg kg ⁻¹	2,6E+00	9,7E+02	1,8E+01	2,2E+01	1,3E+02	2,7E+00	3,9E+02	9,7E+00	2,5E+01	2,9E+00	1,6E-02	3,0E+01	3,3E-01	2,5E-01	5,9E-01	2,6E-01	9,2E+01	6,6E+00
Maize roots	Green waste compost	Z1	20-09-23	/	Year 2	mg kg ⁻¹	4,3E-01	1,2E+02	2,8E+00	4,3E+00	2,6E+01	5,7E-01	1,4E+02	5,0E+00	1,3E+01	5,9E-01	5,3E-02	7,9E+00	4,8E-01	2,3E-01	1,1E-01	5,8E-02	1,6E+01	2,0E+00
Maize roots	Green waste compost	Z2	20-09-23	/	Year 2	mg kg ⁻¹	4,4E-01	1,4E+02	2,8E+00	3,5E+00	2,2E+01	5,0E-01	6,3E+01	3,4E+00	9,3E+00	5,4E-01	4,1E-02	8,3E+00	4,3E-01	1,3E-01	9,9E-02	6,8E-02	1,8E+01	1,1E+00
Maize roots	Green waste compost	Z3	20-09-23	/	Year 2	mg kg ⁻¹	6,3E-01	1,9E+02	4,5E+00	5,2E+00	3,7E+01	8,7E-01	1,2E+02	4,5E+00	1,3E+01	8,4E-01	3,3E-02	9,9E+00	7,0E-01	1,4E-01	1,6E-01	7,4E-02	2,0E+01	1,7E+00
Maize roots	Cattle manure	Z1	20-09-23	/	Year 2	mg kg ⁻¹	8,3E-01	3,5E+02	6,3E+00	8,0E+00	5,3E+01	1,0E+00	1,7E+02	5,5E+00	1,6E+01	1,2E+00	1,3E-01	1,1E+01	7,7E-01	3,1E-01	2,0E-01	1,0E-01	2,9E+01	2,4E+00
Maize roots	Cattle manure	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,3E+00	4,6E+02	8,3E+00	9,7E+00	5,5E+01	1,2E+00	2,2E+02	6,4E+00	1,6E+01	1,5E+00	8,5E-02	1,4E+01	7,3E-01	3,3E-01	2,7E-01	1,2E-01	4,4E+01	2,9E+00
Maize roots	Cattle manure	Z3	20-09-23	/	Year 2	mg kg ⁻¹	3,4E+00	1,5E+03	2,9E+01	3,3E+01	2,2E+02	3,9E+00	4,9E+02	1,1E+01	3,4E+01	4,9E+00	2,0E-01	4,0E+01	8,9E-01	3,6E-01	1,0E+00	3,8E-01	1,5E+02	1,0E+01

Field experiments

Maize roots	Cover crop restitution	Z1	20-09-23	/	Year 2	mg kg ⁻¹	1,3E+00	4,8E+02	8,8E+00	1,1E+01	8,6E+01	1,3E+00	2,1E+02	1,8E+01	3,8E+01	1,6E+00	8,8E-02	1,8E+01	5,8E-01	9,1E-01	3,1E-01	1,6E-01	4,6E+01	4,0E+00
Maize roots	Cover crop restitution	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,1E+00	4,2E+02	7,8E+00	9,3E+00	6,7E+01	1,2E+00	1,7E+02	1,1E+01	3,6E+01	1,4E+00	1,6E-02	1,3E+01	6,5E-01	6,7E-01	2,4E-01	1,0E-01	3,2E+01	2,8E+00
Maize roots	Cover crop restitution	Z3	20-09-23	/	Year 2	mg kg ⁻¹	7,0E-01	2,0E+02	5,6E+00	6,9E+00	4,4E+01	9,1E-01	1,1E+02	8,1E+00	1,8E+01	9,8E-01	9,0E-02	1,2E+01	5,0E-01	4,0E-01	1,7E-01	9,6E-02	2,3E+01	2,0E+00
Maize stems	No application	Z1	20-09-23	/	Year 2	mg kg ⁻¹	7,5E-02	3,8E+01	6,6E-01	2,2E+00	6,6E+01	1,1E-01	1,8E+01	6,0E+00	5,5E+01	1,1E-01	1,6E-02	1,2E+01	5,4E-01	3,4E-01	5,2E-02	2,6E-02	6,8E+00	4,2E-01
Maize stems	No application	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,1E-01	5,3E+01	9,3E-01	3,9E+00	3,6E+01	1,8E-01	3,1E+01	9,3E+00	3,2E+01	1,6E-01	1,6E-02	8,3E+00	5,8E-01	1,7E-01	8,6E-02	2,9E-02	7,6E+00	6,3E-01
Maize stems	No application	Z3	20-09-23	/	Year 2	mg kg ⁻¹	6,6E-02	2,9E+01	4,7E-01	1,6E+00	5,1E+01	8,3E-02	1,1E+00	1,5E+01	6,8E+01	8,5E-02	1,6E-02	1,1E+01	6,8E-01	1,1E-01	6,9E-02	3,0E-02	9,3E+00	6,7E-01
Maize stems	Green waste compost	Z1	20-09-23	/	Year 2	mg kg ⁻¹	4,4E-02	1,5E+01	2,3E-01	1,2E+00	3,0E+01	4,8E-02	5,9E+00	4,2E+00	1,9E+01	5,8E-02	1,6E-02	1,1E+01	1,0E+00	1,5E-01	5,6E-02	3,7E-02	5,5E+00	2,5E-01
Maize stems	Green waste compost	Z2	20-09-23	/	Year 2	mg kg ⁻¹	6,2E-02	2,4E+01	4,1E-01	1,3E+00	2,8E+01	1,3E-01	1,2E+01	3,8E+00	1,6E+01	7,4E-02	1,6E-02	1,1E+01	2,8E-01	1,3E-01	7,5E-02	4,7E-02	6,4E+00	2,9E-01
Maize stems	Green waste compost	Z3	20-09-23	/	Year 2	mg kg ⁻¹	6,0E-02	3,2E+01	5,3E-01	1,7E+00	2,7E+01	9,8E-02	2,3E+01	6,2E+00	1,9E+01	9,8E-02	1,6E-02	9,0E+00	5,4E-01	7,5E-02	8,5E-02	3,9E-02	3,8E+00	3,1E-01
Maize stems	Cattle manure	Z1	20-09-23	/	Year 2	mg kg ⁻¹	5,6E-02	3,8E+01	7,5E-01	1,4E+00	3,2E+01	1,2E-01	2,0E+01	4,2E+00	1,7E+01	9,4E-02	1,6E-02	1,1E+01	1,2E+00	2,8E-01	6,3E-02	3,6E-02	8,4E+00	3,2E-01
Maize stems	Cattle manure	Z2	20-09-23	/	Year 2	mg kg ⁻¹	8,6E-02	5,4E+01	8,6E-01	1,9E+00	2,3E+01	1,4E-01	3,2E+01	4,4E+00	1,3E+01	1,3E-01	4,0E-02	1,3E+01	2,1E+00	1,8E-01	6,7E-02	3,6E-02	8,4E+00	4,0E-01
Maize stems	Cattle manure	Z3	20-09-23	/	Year 2	mg kg ⁻¹	5,1E-02	2,8E+01	4,9E-01	1,3E+00	2,2E+01	8,3E-02	2,2E+01	5,3E+00	1,2E+01	9,0E-02	1,6E-02	1,2E+01	2,2E+00	1,6E-01	5,5E-02	2,6E-02	5,7E+00	2,6E-01
Maize stems	Cover crop restitution	Z1	20-09-23	/	Year 2	mg kg ⁻¹	5,2E-02	2,7E+01	4,8E-01	1,1E+00	5,1E+01	8,3E-02	2,2E+01	5,2E+00	6,5E+01	9,6E-02	1,6E-02	1,1E+01	1,6E+00	2,9E-01	4,6E-02	2,7E-02	7,5E+00	2,6E-01
Maize stems	Cover crop restitution	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,7E-01	8,5E+01	1,2E+00	3,1E+00	5,7E+01	1,8E-01	4,5E+01	8,2E+00	9,2E+01	2,4E-01	1,5E-02	1,3E+01	1,6E+00	3,0E-01	1,8E-01	7,7E-02	1,5E+01	7,3E-01
Maize stems	Cover crop restitution	Z3	20-09-23	/	Year 2	mg kg ⁻¹	4,5E-02	2,1E+01	3,2E-01	1,5E+00	4,6E+01	6,6E-02	1,5E+01	6,8E+00	4,2E+01	7,4E-02	3,5E-02	1,3E+01	9,1E-01	1,8E-01	5,9E-02	2,5E-02	5,7E+00	2,6E-01
Maize leaves	No application	Z1	20-09-23	/	Year 2	mg kg ⁻¹	3,1E-02	1,5E+01	2,3E-01	7,4E-01	1,1E+02	1,0E-01	1,4E+01	1,2E+01	4,5E+01	7,1E-02	1,6E-02	1,6E+01	1,1E+00	1,5E-01	9,7E-02	4,2E-02	3,4E+00	3,0E-01
Maize leaves	No application	Z2	20-09-23	/	Year 2	mg kg ⁻¹	3,2E-02	1,2E+01	2,0E-01	7,5E-01	7,8E+01	3,6E-02	1,3E+01	1,8E+01	6,3E+01	7,9E-02	5,6E-02	1,6E+01	1,1E+00	1,3E-01	9,0E-02	3,4E-02	2,5E+00	2,5E-01
Maize leaves	No application	Z3	20-09-23	/	Year 2	mg kg ⁻¹	7,4E-02	2,9E+01	5,0E-01	1,0E+00	7,3E+01	8,2E-02	3,6E+01	2,1E+01	5,0E+01	1,3E-01	1,6E-02	2,7E+01	2,3E+00	6,5E-02	1,0E-01	4,6E-02	3,3E+00	3,6E-01
Maize leaves	Green waste compost	Z1	20-09-23	/	Year 2	mg kg ⁻¹	6,4E-02	2,1E+01	3,2E-01	9,8E-01	4,4E+01	5,1E-02	1,4E+01	1,2E+01	4,1E+01	1,3E-01	1,6E-02	1,5E+01	1,4E+00	7,8E-02	1,2E-01	4,3E-02	4,1E+00	3,8E-01
Maize leaves	Green waste compost	Z2	20-09-23	/	Year 2	mg kg ⁻¹	3,1E-02	8,1E+00	1,7E-01	7,1E-01	2,7E+01	2,7E-02	6,9E+00	7,0E+00	2,2E+01	6,8E-02	1,6E-02	1,2E+01	1,0E+00	4,7E-02	5,3E-02	2,7E-02	2,4E+00	2,1E-01

Appendices

Maize leaves	Green waste compost	Z3	20-09-23	/	Year 2	mg kg ⁻¹	4,6E-02	1,6E+01	3,0E-01	7,3E-01	5,7E+01	5,4E-02	2,7E+01	1,4E+01	4,6E+01	1,1E-01	1,6E-02	1,7E+01	1,7E+00	5,4E-02	9,6E-02	3,9E-02	2,6E+00	3,1E-01
Maize leaves	Cattle manure	Z1	20-09-23	/	Year 2	mg kg ⁻¹	9,5E-02	4,0E+01	7,1E-01	1,2E+00	6,8E+01	1,2E-01	2,0E+01	1,4E+01	4,7E+01	2,5E-01	1,5E-02	1,8E+01	1,5E+00	1,9E-01	1,6E-01	6,8E-02	8,0E+00	5,9E-01
Maize leaves	Cattle manure	Z2	20-09-23	/	Year 2	mg kg ⁻¹	3,6E-02	9,9E+00	1,8E-01	5,9E-01	3,0E+01	3,3E-02	1,2E+01	8,7E+00	2,8E+01	9,6E-02	1,5E-02	1,1E+01	1,3E+00	8,1E-02	1,1E-01	3,8E-02	3,1E+00	2,3E-01
Maize leaves	Cattle manure	Z3	20-09-23	/	Year 2	mg kg ⁻¹	3,0E-02	9,0E+00	1,6E-01	5,3E-01	4,4E+01	3,5E-02	7,8E+00	1,1E+01	3,0E+01	7,7E-02	4,7E-02	1,4E+01	1,5E+00	6,5E-02	7,9E-02	2,7E-02	2,8E+00	2,3E-01
Maize leaves	Cover crop restitution	Z1	20-09-23	/	Year 2	mg kg ⁻¹	2,1E-01	5,4E+01	8,6E-01	1,5E+00	1,6E+02	1,2E-01	1,9E+01	8,4E+00	5,0E+01	2,2E-01	1,6E-02	1,6E+01	6,7E-01	1,7E-01	1,1E-01	6,6E-02	9,9E+00	6,2E-01
Maize leaves	Cover crop restitution	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,3E-01	4,9E+01	8,8E-01	1,6E+00	9,2E+01	1,2E-01	2,3E+01	1,2E+01	4,4E+01	2,2E-01	1,6E-02	1,3E+01	9,7E-01	1,4E-01	2,0E-01	7,0E-02	7,3E+00	6,7E-01
Maize leaves	Cover crop restitution	Z3	20-09-23	/	Year 2	mg kg ⁻¹	1,1E-01	5,2E+01	8,8E-01	1,6E+00	8,9E+01	1,3E-01	2,4E+01	1,3E+01	3,8E+01	1,9E-01	5,0E-02	1,8E+01	1,0E+00	1,1E-01	1,4E-01	4,6E-02	6,1E+00	5,2E-01

Table. VI-20 – Rare earth element contents/concentrations in soil, exogenous organic matter, plant parts, and soil solution samples for the 2 years field experiment (plot n°3).

Sample	Modality	Sub-area	Date	Replicate	Year	Units	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Soil	Cover crop restitution	Z1	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,4E+01	7,2E+01	8,3E+00	3,2E+01	6,1E+00	1,0E+00	4,9E+00	6,6E-01	3,7E+00	6,9E-01	2,0E+00	2,9E-01	1,9E+00	2,9E-01
Soil	Cover crop restitution	Z1	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,7E+01	7,6E+01	8,7E+00	3,3E+01	6,4E+00	1,1E+00	5,1E+00	6,7E-01	3,9E+00	7,1E-01	2,0E+00	2,9E-01	1,9E+00	2,9E-01
Soil	Cover crop restitution	Z2	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,6E+01	7,5E+01	8,8E+00	3,4E+01	6,5E+00	1,2E+00	5,5E+00	7,3E-01	4,2E+00	7,7E-01	2,2E+00	3,1E-01	2,1E+00	3,1E-01
Soil	Cover crop restitution	Z2	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,9E+01	8,0E+01	9,5E+00	3,7E+01	7,1E+00	1,2E+00	5,9E+00	7,7E-01	4,5E+00	8,2E-01	2,3E+00	3,3E-01	2,2E+00	3,3E-01
Soil	Cover crop restitution	Z3	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,9E+01	7,9E+01	9,3E+00	3,6E+01	6,9E+00	1,2E+00	5,6E+00	7,4E-01	4,2E+00	7,6E-01	2,1E+00	3,2E-01	2,1E+00	3,1E-01
Soil	Cover crop restitution	Z3	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,9E+01	8,1E+01	9,4E+00	3,6E+01	7,0E+00	1,2E+00	5,7E+00	7,6E-01	4,4E+00	8,1E-01	2,2E+00	3,3E-01	2,2E+00	3,3E-01
Soil	Cattle manure	Z1	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,5E+01	7,3E+01	8,4E+00	3,2E+01	6,1E+00	1,0E+00	4,9E+00	6,6E-01	3,7E+00	6,9E-01	1,9E+00	2,9E-01	1,9E+00	2,9E-01
Soil	Cattle manure	Z1	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,5E+01	7,3E+01	8,2E+00	3,1E+01	5,8E+00	9,7E-01	4,7E+00	6,3E-01	3,5E+00	6,3E-01	1,8E+00	2,7E-01	1,7E+00	2,7E-01
Soil	Cattle manure	Z2	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,5E+01	7,1E+01	8,3E+00	3,2E+01	6,2E+00	1,1E+00	5,2E+00	7,0E-01	4,0E+00	7,5E-01	2,1E+00	3,1E-01	2,1E+00	3,1E-01
Soil	Cattle manure	Z2	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,7E+01	7,7E+01	9,0E+00	3,5E+01	6,8E+00	1,2E+00	5,7E+00	7,8E-01	4,5E+00	8,1E-01	2,3E+00	3,4E-01	2,2E+00	3,4E-01
Soil	Cattle manure	Z3	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,6E+01	7,4E+01	8,7E+00	3,3E+01	6,4E+00	1,2E+00	5,3E+00	7,2E-01	4,2E+00	7,6E-01	2,2E+00	3,2E-01	2,1E+00	3,1E-01
Soil	Cattle manure	Z3	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	4,0E+01	8,1E+01	9,5E+00	3,6E+01	6,9E+00	1,2E+00	5,6E+00	7,8E-01	4,4E+00	8,0E-01	2,2E+00	3,2E-01	2,1E+00	3,3E-01
Soil	Green waste compost	Z1	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,5E+01	7,2E+01	8,2E+00	3,1E+01	5,9E+00	1,0E+00	4,9E+00	6,6E-01	3,8E+00	7,0E-01	2,0E+00	3,0E-01	2,0E+00	3,0E-01
Soil	Green waste compost	Z1	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,7E+01	7,7E+01	8,6E+00	3,3E+01	6,3E+00	1,1E+00	5,1E+00	6,8E-01	4,0E+00	7,3E-01	2,1E+00	3,1E-01	2,1E+00	3,2E-01
Soil	Green waste compost	Z2	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,6E+01	7,6E+01	8,7E+00	3,3E+01	6,4E+00	1,2E+00	5,5E+00	7,4E-01	4,3E+00	7,8E-01	2,2E+00	3,2E-01	2,3E+00	3,2E-01
Soil	Green waste compost	Z2	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	4,0E+01	8,2E+01	9,7E+00	3,7E+01	7,1E+00	1,3E+00	6,0E+00	8,1E-01	4,8E+00	8,7E-01	2,4E+00	3,7E-01	2,4E+00	3,6E-01
Soil	Green waste compost	Z3	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,6E+01	7,5E+01	8,6E+00	3,3E+01	6,3E+00	1,1E+00	5,4E+00	7,2E-01	4,1E+00	7,5E-01	2,1E+00	3,1E-01	2,0E+00	3,1E-01
Soil	Green waste compost	Z3	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,6E+01	7,5E+01	8,6E+00	3,3E+01	6,4E+00	1,1E+00	5,2E+00	7,0E-01	4,0E+00	7,3E-01	2,2E+00	3,0E-01	2,0E+00	3,0E-01
Soil	No application	Z1	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,2E+01	6,6E+01	7,4E+00	2,8E+01	5,4E+00	9,4E-01	4,4E+00	6,1E-01	3,4E+00	6,4E-01	1,9E+00	2,7E-01	1,8E+00	2,8E-01
Soil	No application	Z1	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,2E+01	6,8E+01	7,6E+00	2,9E+01	5,4E+00	9,4E-01	4,5E+00	5,9E-01	3,6E+00	6,3E-01	1,8E+00	2,6E-01	1,9E+00	2,8E-01
Soil	No application	Z2	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,5E+01	7,2E+01	8,4E+00	3,3E+01	6,2E+00	1,1E+00	5,3E+00	7,1E-01	4,1E+00	7,6E-01	2,2E+00	3,2E-01	2,1E+00	3,2E-01
Soil	No application	Z2	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,8E+01	8,0E+01	9,2E+00	3,5E+01	6,8E+00	1,2E+00	5,7E+00	7,7E-01	4,5E+00	8,2E-01	2,1E+00	3,4E-01	2,3E+00	3,5E-01
Soil	No application	Z3	23-03-22	0-30 cm	Year 1	mg kg ⁻¹	3,5E+01	7,3E+01	8,5E+00	3,3E+01	6,3E+00	1,1E+00	5,2E+00	7,1E-01	4,1E+00	7,5E-01	2,1E+00	3,2E-01	2,1E+00	3,1E-01
Soil	No application	Z3	23-03-22	30-50 cm	Year 1	mg kg ⁻¹	3,6E+01	7,6E+01	8,8E+00	3,4E+01	6,5E+00	1,2E+00	5,2E+00	7,1E-01	4,1E+00	7,5E-01	2,1E+00	3,1E-01	2,0E+00	3,1E-01
EOM	Cover crop restitution	/	24-03-22	A	Year 1	mg kg ⁻¹	1,6E-01	2,2E-01	2,8E-02	9,9E-02	1,4E-02	4,2E-03	1,8E-02	2,8E-03	1,3E-02	2,2E-03	8,3E-03	1,1E-03	7,6E-03	1,1E-03
EOM	Cover crop restitution	/	24-03-22	B	Year 1	mg kg ⁻¹	1,6E-01	2,3E-01	2,4E-02	8,8E-02	1,3E-02	3,5E-03	1,4E-02	2,3E-03	7,9E-03	3,2E-03	3,5E-03	9,3E-04	5,5E-03	7,9E-04
EOM	Cattle manure	/	24-03-22	A	Year 1	mg kg ⁻¹	2,1E+00	4,0E+00	4,6E-01	1,8E+00	3,2E-01	6,3E-02	2,7E-01	4,0E-02	2,3E-01	4,3E-02	1,3E-01	2,1E-02	1,3E-01	1,9E-02
EOM	Cattle manure	/	24-03-22	B	Year 1	mg kg ⁻¹	1,9E+00	3,7E+00	4,2E-01	1,6E+00	2,8E-01	5,7E-02	2,6E-01	3,6E-02	2,3E-01	4,3E-02	1,2E-01	1,9E-02	1,2E-01	2,1E-02
EOM	Green waste compost	/	24-03-22	A	Year 1	mg kg ⁻¹	1,5E+01	3,0E+01	3,3E+00	1,3E+01	2,5E+00	4,3E-01	2,0E+00	2,9E-01	1,7E+00	3,2E-01	9,2E-01	1,3E-01	8,9E-01	1,4E-01
EOM	Green waste compost	/	24-03-22	B	Year 1	mg kg ⁻¹	1,3E+01	2,6E+01	2,9E+00	1,1E+01	2,2E+00	4,2E-01	1,9E+00	2,6E-01	1,6E+00	2,8E-01	8,5E-01	1,3E-01	8,1E-01	1,2E-01
Solution	No application	Z1	23-05-22	A	Year 1	mg L ⁻¹	5,0E-04	8,7E-04	1,6E-04	7,5E-04	1,7E-04	3,5E-05	1,7E-04	2,0E-05	1,2E-04	2,6E-05	7,6E-05	1,1E-05	6,9E-05	1,1E-05
Solution	No application	Z1	23-05-22	BC	Year 1	mg L ⁻¹	3,6E-04	5,0E-04	9,4E-05	4,4E-04	9,3E-05	2,0E-05	9,9E-05	1,1E-05	6,6E-05	1,4E-05	4,2E-05	6,1E-06	3,9E-05	6,7E-06
Solution	No application	Z1	23-05-22	DE	Year 1	mg L ⁻¹	7,2E-04	9,6E-04	1,6E-04	7,2E-04	1,5E-04	3,3E-05	1,5E-04	1,9E-05	1,1E-04	2,3E-05	6,6E-05	9,4E-06	5,9E-05	1,0E-05
Solution	No application	Z2	23-05-22	ACD	Year 1	mg L ⁻¹	5,1E-04	8,0E-04	1,4E-04	6,8E-04	1,4E-04	2,9E-05	1,4E-04	1,7E-05	1,0E-04	2,0E-05	5,4E-05	7,5E-06	4,8E-05	7,5E-06

Appendices

Solution	No application	Z2	23-05-22	B	Year 1	mg L ⁻¹	4,0E-04	5,3E-04	1,3E-04	6,5E-04	1,4E-04	3,0E-05	1,4E-04	1,7E-05	1,1E-04	2,4E-05	7,0E-05	1,0E-05	6,8E-05	1,1E-05
Solution	No application	Z2	23-05-22	E	Year 1	mg L ⁻¹	2,9E-04	4,0E-04	8,3E-05	3,9E-04	8,4E-05	1,7E-05	8,8E-05	1,1E-05	6,7E-05	1,5E-05	4,3E-05	6,4E-06	4,1E-05	6,5E-06
Solution	No application	Z3	23-05-22	ACE	Year 1	mg L ⁻¹	1,8E-04	2,7E-04	5,0E-05	2,4E-04	5,3E-05	1,2E-05	5,7E-05	7,2E-06	4,4E-05	9,9E-06	3,2E-05	4,5E-06	3,2E-05	5,4E-06
Solution	Green waste compost	Z1	23-05-22	A	Year 1	mg L ⁻¹	6,9E-04	9,2E-04	2,4E-04	1,2E-03	2,6E-04	5,6E-05	2,6E-04	3,1E-05	1,8E-04	3,9E-05	1,1E-04	1,6E-05	1,1E-04	1,8E-05
Solution	Green waste compost	Z1	23-05-22	BCE	Year 1	mg L ⁻¹	1,2E-03	1,9E-03	4,0E-04	1,9E-03	4,4E-04	9,3E-05	4,4E-04	5,3E-05	3,2E-04	6,6E-05	1,9E-04	2,7E-05	1,8E-04	2,9E-05
Solution	Green waste compost	Z1	23-05-22	D	Year 1	mg L ⁻¹	1,2E-03	1,9E-03	4,3E-04	2,1E-03	4,8E-04	1,0E-04	4,7E-04	5,6E-05	3,4E-04	7,0E-05	2,0E-04	2,9E-05	1,9E-04	3,1E-05
Solution	Green waste compost	Z2	23-05-22	A	Year 1	mg L ⁻¹	9,3E-04	9,8E-04	3,2E-04	1,6E-03	3,6E-04	7,7E-05	3,6E-04	4,2E-05	2,5E-04	5,2E-05	1,5E-04	2,1E-05	1,4E-04	2,3E-05
Solution	Green waste compost	Z2	23-05-22	BC	Year 1	mg L ⁻¹	1,4E-03	1,9E-03	4,6E-04	2,3E-03	5,1E-04	1,1E-04	5,1E-04	6,0E-05	3,6E-04	7,4E-05	2,2E-04	3,1E-05	2,1E-04	3,5E-05
Solution	Green waste compost	Z2	23-05-22	D	Year 1	mg L ⁻¹	1,2E-03	1,5E-03	4,3E-04	2,2E-03	4,9E-04	1,0E-04	4,9E-04	5,7E-05	3,4E-04	6,9E-05	2,0E-04	2,9E-05	1,9E-04	3,1E-05
Solution	Green waste compost	Z3	23-05-22	AD	Year 1	mg L ⁻¹	6,1E-04	8,1E-04	2,0E-04	9,5E-04	2,2E-04	4,9E-05	2,4E-04	3,0E-05	1,9E-04	3,9E-05	1,1E-04	1,6E-05	9,9E-05	1,6E-05
Solution	Green waste compost	Z3	23-05-22	E	Year 1	mg L ⁻¹	5,7E-04	6,9E-04	2,0E-04	1,0E-03	2,3E-04	5,1E-05	2,3E-04	2,9E-05	1,7E-04	3,7E-05	1,1E-04	1,6E-05	1,0E-04	1,7E-05
Solution	Cattle manure	Z1	23-05-22	ABC	Year 1	mg L ⁻¹	9,1E-04	1,6E-03	3,0E-04	1,5E-03	3,3E-04	6,9E-05	3,2E-04	3,9E-05	2,4E-04	4,9E-05	1,4E-04	2,0E-05	1,3E-04	2,2E-05
Solution	Cattle manure	Z1	23-05-22	D	Year 1	mg L ⁻¹	8,4E-04	1,5E-03	2,9E-04	1,4E-03	3,2E-04	6,7E-05	3,1E-04	3,7E-05	2,2E-04	4,6E-05	1,4E-04	2,0E-05	1,4E-04	2,2E-05
Solution	Cattle manure	Z1	23-05-22	E	Year 1	mg L ⁻¹	1,2E-03	1,8E-03	3,7E-04	1,8E-03	4,1E-04	8,7E-05	4,0E-04	5,0E-05	3,1E-04	6,3E-05	1,8E-04	2,4E-05	1,6E-04	2,6E-05
Solution	Cattle manure	Z2	23-05-22	AB	Year 1	mg L ⁻¹	7,3E-04	1,2E-03	2,3E-04	1,1E-03	2,5E-04	6,3E-05	2,7E-04	3,5E-05	2,1E-04	4,3E-05	1,2E-04	1,6E-05	9,7E-05	1,6E-05
Solution	Cattle manure	Z2	23-05-22	C	Year 1	mg L ⁻¹	7,6E-04	9,7E-04	2,4E-04	1,2E-03	2,7E-04	5,7E-05	2,8E-04	3,6E-05	2,2E-04	4,6E-05	1,3E-04	1,8E-05	1,2E-04	1,9E-05
Solution	Cattle manure	Z2	23-05-22	E	Year 1	mg L ⁻¹	9,0E-04	1,0E-03	3,0E-04	1,5E-03	3,3E-04	7,2E-05	3,3E-04	4,1E-05	2,4E-04	5,0E-05	1,4E-04	2,0E-05	1,2E-04	1,9E-05
Solution	Cattle manure	Z3	23-05-22	AB	Year 1	mg L ⁻¹	4,5E-04	5,5E-04	1,4E-04	6,8E-04	1,5E-04	3,2E-05	1,5E-04	1,9E-05	1,1E-04	2,3E-05	6,6E-05	9,1E-06	5,5E-05	8,8E-06
Solution	Cattle manure	Z3	23-05-22	C	Year 1	mg L ⁻¹	2,4E-04	3,5E-04	7,5E-05	3,5E-04	8,0E-05	1,8E-05	8,2E-05	1,1E-05	6,7E-05	1,4E-05	3,9E-05	5,3E-06	3,4E-05	5,5E-06
Solution	Cattle manure	Z3	23-05-22	DE	Year 1	mg L ⁻¹	4,7E-04	5,2E-04	1,5E-04	7,5E-04	1,7E-04	3,7E-05	1,7E-04	2,0E-05	1,3E-04	2,6E-05	7,5E-05	1,0E-05	6,5E-05	1,0E-05
Solution	Cover crop restitution	Z1	23-05-22	AB	Year 1	mg L ⁻¹	1,3E-03	2,4E-03	4,3E-04	2,1E-03	4,5E-04	9,9E-05	4,6E-04	6,0E-05	3,6E-04	7,3E-05	2,1E-04	2,9E-05	1,9E-04	3,0E-05
Solution	Cover crop restitution	Z1	23-05-22	C	Year 1	mg L ⁻¹	8,3E-04	1,5E-03	2,9E-04	1,4E-03	3,2E-04	6,7E-05	3,1E-04	3,9E-05	2,4E-04	5,0E-05	1,5E-04	2,1E-05	1,4E-04	2,2E-05
Solution	Cover crop restitution	Z1	23-05-22	DE	Year 1	mg L ⁻¹	9,8E-04	1,8E-03	3,5E-04	1,7E-03	4,0E-04	8,5E-05	4,0E-04	5,2E-05	3,1E-04	6,4E-05	1,9E-04	2,7E-05	1,7E-04	2,8E-05
Solution	Cover crop restitution	Z2	23-05-22	A	Year 1	mg L ⁻¹	7,4E-04	9,6E-04	2,1E-04	1,0E-03	2,2E-04	4,9E-05	2,2E-04	2,7E-05	1,6E-04	3,4E-05	9,7E-05	1,3E-05	8,5E-05	1,4E-05
Solution	Cover crop restitution	Z2	23-05-22	BC	Year 1	mg L ⁻¹	6,1E-04	8,4E-04	1,8E-04	8,8E-04	1,9E-04	4,1E-05	1,9E-04	2,3E-05	1,4E-04	2,8E-05	8,1E-05	1,1E-05	7,1E-05	1,1E-05
Solution	Cover crop restitution	Z2	23-05-22	DE	Year 1	mg L ⁻¹	4,4E-04	5,5E-04	1,5E-04	7,3E-04	1,7E-04	3,4E-05	1,7E-04	2,0E-05	1,2E-04	2,5E-05	7,3E-05	1,0E-05	6,5E-05	1,1E-05
Solution	Cover crop restitution	Z3	23-05-22	ABC	Year 1	mg L ⁻¹	6,3E-04	1,2E-03	1,9E-04	8,3E-04	1,9E-04	4,2E-05	1,9E-04	2,4E-05	1,4E-04	2,8E-05	7,4E-05	1,0E-05	6,0E-05	9,4E-06
Solution	Cover crop restitution	Z3	23-05-22	D	Year 1	mg L ⁻¹	4,9E-04	8,4E-04	1,4E-04	6,6E-04	1,5E-04	3,4E-05	1,6E-04	2,1E-05	1,2E-04	3,3E-05	6,8E-05	9,0E-06	5,6E-05	8,4E-06
Solution	Cover crop restitution	Z3	23-05-22	E	Year 1	mg L ⁻¹	1,3E-03	3,2E-03	3,8E-04	1,6E-03	3,7E-04	9,3E-05	3,6E-04	4,9E-05	2,8E-04	5,1E-05	1,4E-04	1,8E-05	1,0E-04	1,6E-05
Barley roots	No application	Z1	25-05-22	/	Year 1	mg kg ⁻¹	2,4E+01	5,0E+01	6,4E+00	2,6E+01	5,0E+00	8,2E-01	4,1E+00	5,4E-01	3,2E+00	5,8E-01	1,7E+00	2,6E-01	1,7E+00	2,6E-01
Barley roots	No application	Z2	25-05-22	/	Year 1	mg kg ⁻¹	2,0E+01	4,2E+01	5,5E+00	2,3E+01	4,4E+00	7,5E-01	3,8E+00	5,0E-01	2,9E+00	5,4E-01	1,6E+00	2,2E-01	1,4E+00	2,1E-01
Barley roots	No application	Z3	25-05-22	/	Year 1	mg kg ⁻¹	2,1E+01	4,5E+01	6,0E+00	2,3E+01	4,5E+00	8,0E-01	3,9E+00	5,2E-01	3,1E+00	5,8E-01	1,6E+00	2,4E-01	1,6E+00	2,5E-01
Barley roots	Green waste compost	Z1	25-05-22	/	Year 1	mg kg ⁻¹	2,1E+01	4,4E+01	6,0E+00	2,3E+01	4,3E+00	7,0E-01	3,5E+00	5,1E-01	2,7E+00	5,0E-01	1,5E+00	2,2E-01	1,4E+00	2,2E-01
Barley roots	Green waste compost	Z2	25-05-22	/	Year 1	mg kg ⁻¹	1,9E+01	3,9E+01	5,4E+00	2,1E+01	4,2E+00	7,4E-01	3,5E+00	5,0E-01	2,9E+00	5,3E-01	1,5E+00	2,2E-01	1,4E+00	2,2E-01
Barley roots	Green waste compost	Z3	25-05-22	/	Year 1	mg kg ⁻¹	2,3E+01	4,7E+01	6,3E+00	2,5E+01	4,7E+00	7,8E-01	4,0E+00	5,3E-01	3,1E+00	5,8E-01	1,6E+00	2,4E-01	1,6E+00	2,5E-01
Barley roots	Cattle manure	Z1	25-05-22	/	Year 1	mg kg ⁻¹	1,9E+01	4,2E+01	5,7E+00	2,2E+01	4,3E+00	7,2E-01	3,5E+00	4,7E-01	2,7E+00	5,1E-01	1,4E+00	2,1E-01	1,3E+00	2,1E-01
Barley roots	Cattle manure	Z2	25-05-22	/	Year 1	mg kg ⁻¹	1,9E+01	3,9E+01	5,5E+00	2,2E+01	4,1E+00	7,1E-01	3,4E+00	4,5E-01	2,6E+00	4,8E-01	1,4E+00	1,9E-01	1,2E+00	1,9E-01
Barley roots	Cattle manure	Z3	25-05-22	/	Year 1	mg kg ⁻¹	1,9E+01	4,0E+01	5,6E+00	2,2E+01	4,2E+00	7,3E-01	3,6E+00	4,8E-01	2,8E+00	5,1E-01	1,5E+00	2,1E-01	1,3E+00	2,1E-01

Field experiments

Barley roots	Cover crop restitution	Z1	25-05-22	/	Year 1	mg kg ⁻¹	2,2E+01	4,7E+01	6,0E+00	2,4E+01	4,7E+00	7,8E-01	3,9E+00	5,3E-01	3,1E+00	5,6E-01	1,6E+00	2,4E-01	1,5E+00	2,5E-01
Barley roots	Cover crop restitution	Z2	25-05-22	/	Year 1	mg kg ⁻¹	1,7E+01	3,5E+01	4,9E+00	1,9E+01	3,7E+00	6,4E-01	3,1E+00	4,2E-01	2,4E+00	4,6E-01	1,3E+00	1,9E-01	1,2E+00	1,9E-01
Barley roots	Cover crop restitution	Z3	25-05-22	/	Year 1	mg kg ⁻¹	1,8E+01	3,8E+01	5,2E+00	1,9E+01	3,8E+00	6,7E-01	3,3E+00	4,3E-01	2,5E+00	4,6E-01	1,3E+00	1,8E-01	1,2E+00	1,8E-01
Barley shoots	No application	Z1	25-05-22	/	Year 1	mg kg ⁻¹	5,9E-01	1,2E+00	1,3E-01	5,2E-01	9,8E-02	1,7E-02	8,6E-02	1,2E-02	7,1E-02	1,3E-02	3,8E-02	5,6E-03	3,6E-02	5,5E-03
Barley shoots	No application	Z2	25-05-22	/	Year 1	mg kg ⁻¹	1,0E+00	2,1E+00	2,5E-01	9,6E-01	1,9E-01	3,3E-02	1,6E-01	2,2E-02	1,3E-01	2,3E-02	6,5E-02	9,3E-03	5,9E-02	9,1E-03
Barley shoots	No application	Z3	25-05-22	/	Year 1	mg kg ⁻¹	1,7E+00	3,5E+00	4,1E-01	1,6E+00	3,1E-01	5,5E-02	2,6E-01	3,4E-02	4,3E-01	3,7E-02	1,0E-01	1,5E-02	9,7E-02	1,5E-02
Barley shoots	Green waste compost	Z1	25-05-22	/	Year 1	mg kg ⁻¹	7,0E-01	1,5E+00	1,7E-01	6,6E-01	1,2E-01	2,4E-02	1,1E-01	1,5E-02	8,9E-02	1,7E-02	4,7E-02	7,1E-03	4,6E-02	7,2E-03
Barley shoots	Green waste compost	Z2	25-05-22	/	Year 1	mg kg ⁻¹	1,6E+00	3,2E+00	3,7E-01	1,5E+00	2,9E-01	5,0E-02	2,4E-01	3,3E-02	2,0E-01	3,5E-02	1,0E-01	1,4E-02	9,4E-02	1,4E-02
Barley shoots	Green waste compost	Z3	25-05-22	/	Year 1	mg kg ⁻¹	2,0E+00	4,1E+00	4,6E-01	1,8E+00	3,4E-01	6,3E-02	3,0E-01	4,0E-02	2,3E-01	4,1E-02	1,2E-01	1,8E-02	1,1E-01	1,7E-02
Barley shoots	Cattle manure	Z1	25-05-22	/	Year 1	mg kg ⁻¹	5,7E-01	1,1E+00	1,3E-01	5,1E-01	1,0E-01	1,9E-02	9,5E-02	1,3E-02	7,5E-02	1,5E-02	4,3E-02	6,2E-03	4,1E-02	6,3E-03
Barley shoots	Cattle manure	Z2	25-05-22	/	Year 1	mg kg ⁻¹	8,2E-01	1,7E+00	2,0E-01	7,8E-01	1,5E-01	2,8E-02	1,3E-01	1,9E-02	1,0E-01	2,0E-02	5,9E-02	8,7E-03	5,4E-02	8,6E-03
Barley shoots	Cattle manure	Z3	25-05-22	/	Year 1	mg kg ⁻¹	4,1E-01	8,2E-01	9,5E-02	3,6E-01	6,7E-02	1,2E-02	5,7E-02	7,7E-03	4,5E-02	8,0E-03	2,4E-02	3,4E-03	2,2E-02	3,5E-03
Barley shoots	Cover crop restitution	Z1	25-05-22	/	Year 1	mg kg ⁻¹	6,0E-01	1,2E+00	1,4E-01	5,3E-01	1,0E-01	1,7E-02	9,0E-02	1,1E-02	6,5E-02	1,2E-02	3,4E-02	5,0E-03	3,3E-02	5,0E-03
Barley shoots	Cover crop restitution	Z2	25-05-22	/	Year 1	mg kg ⁻¹	1,3E+00	2,6E+00	3,0E-01	1,2E+00	2,2E-01	3,4E-02	1,9E-01	2,5E-02	1,4E-01	2,4E-02	6,8E-02	1,0E-02	6,4E-02	9,7E-03
Barley shoots	Cover crop restitution	Z3	25-05-22	/	Year 1	mg kg ⁻¹	2,1E+00	4,3E+00	5,1E-01	2,0E+00	3,9E-01	7,4E-02	3,4E-01	4,8E-02	3,1E-01	5,6E-02	1,6E-01	2,3E-02	1,5E-01	2,2E-02
Barley roots	No application	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,9E+01	4,0E+01	5,2E+00	2,0E+01	3,8E+00	6,3E-01	3,3E+00	4,3E-01	2,5E+00	4,6E-01	1,3E+00	1,9E-01	1,2E+00	2,0E-01
Barley roots	No application	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,8E+01	3,7E+01	4,9E+00	1,9E+01	3,7E+00	6,4E-01	3,3E+00	4,2E-01	2,5E+00	4,6E-01	1,3E+00	1,9E-01	1,3E+00	2,0E-01
Barley roots	No application	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,9E+01	3,8E+01	5,0E+00	1,9E+01	3,8E+00	6,5E-01	3,3E+00	4,4E-01	2,6E+00	4,6E-01	1,4E+00	2,0E-01	1,3E+00	2,1E-01
Barley roots	Green waste compost	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,1E+01	1,8E+01	2,4E+00	9,5E+00	1,8E+00	3,2E-01	1,6E+00	2,2E-01	1,3E+00	2,3E-01	6,8E-01	1,0E-01	6,4E-01	1,0E-01
Barley roots	Green waste compost	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,3E+01	2,4E+01	3,3E+00	1,2E+01	2,5E+00	4,3E-01	2,1E+00	2,8E-01	1,7E+00	3,1E-01	8,8E-01	1,3E-01	8,3E-01	1,3E-01
Barley roots	Green waste compost	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,7E+01	3,1E+01	4,1E+00	1,6E+01	3,0E+00	5,2E-01	2,7E+00	3,5E-01	2,0E+00	3,7E-01	1,0E+00	1,5E-01	1,0E+00	1,6E-01
Barley roots	Cattle manure	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,8E+01	3,7E+01	4,9E+00	1,9E+01	3,6E+00	5,7E-01	3,1E+00	4,0E-01	2,3E+00	4,2E-01	1,2E+00	1,8E-01	1,2E+00	1,9E-01
Barley roots	Cattle manure	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,7E+01	3,4E+01	4,5E+00	1,7E+01	3,3E+00	5,8E-01	2,9E+00	3,8E-01	2,3E+00	4,1E-01	1,2E+00	1,7E-01	1,1E+00	1,8E-01
Barley roots	Cattle manure	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,9E+01	3,9E+01	5,2E+00	1,9E+01	3,9E+00	6,6E-01	3,4E+00	4,4E-01	2,5E+00	4,6E-01	1,3E+00	1,9E-01	1,2E+00	2,0E-01
Barley roots	Cover crop restitution	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,9E+01	3,9E+01	4,9E+00	2,0E+01	3,7E+00	6,2E-01	3,3E+00	4,2E-01	2,5E+00	4,4E-01	1,2E+00	1,8E-01	1,2E+00	2,0E-01
Barley roots	Cover crop restitution	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,8E+01	3,1E+01	4,2E+00	1,6E+01	3,1E+00	5,3E-01	2,7E+00	3,6E-01	2,1E+00	3,7E-01	1,1E+00	1,6E-01	1,0E+00	1,6E-01
Barley roots	Cover crop restitution	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,7E+01	3,3E+01	4,5E+00	1,7E+01	3,3E+00	5,6E-01	2,8E+00	3,6E-01	2,1E+00	3,6E-01	1,0E+00	1,5E-01	9,8E-01	1,5E-01
Barley shoots	No application	Z1	25-07-22	/	Year 1	mg kg ⁻¹	5,7E-01	1,1E+00	1,2E-01	4,9E-01	9,4E-02	1,9E-02	8,1E-02	1,3E-02	7,6E-02	1,4E-02	4,3E-02	6,7E-03	4,3E-02	6,7E-03
Barley shoots	No application	Z2	25-07-22	/	Year 1	mg kg ⁻¹	6,2E-01	1,1E+00	1,3E-01	5,3E-01	1,0E-01	2,1E-02	9,8E-02	1,3E-02	7,7E-02	1,5E-02	4,4E-02	6,7E-03	4,6E-02	7,1E-03
Barley shoots	No application	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,3E+00	2,6E+00	2,9E-01	1,1E+00	2,0E-01	2,8E-02	1,7E-01	2,1E-02	1,2E-01	2,1E-02	6,0E-02	8,9E-03	5,5E-02	8,7E-03
Barley shoots	Green waste compost	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,1E+00	2,2E+00	2,4E-01	9,3E-01	1,7E-01	3,1E-02	1,6E-01	2,0E-02	1,2E-01	2,1E-02	6,3E-02	8,8E-03	6,0E-02	9,6E-03
Barley shoots	Green waste compost	Z2	25-07-22	/	Year 1	mg kg ⁻¹	7,0E-01	1,4E+00	1,6E-01	6,0E-01	1,2E-01	2,2E-02	1,1E-01	1,4E-02	8,7E-02	1,5E-02	4,6E-02	6,6E-03	4,6E-02	7,3E-03
Barley shoots	Green waste compost	Z3	25-07-22	/	Year 1	mg kg ⁻¹	8,0E-01	1,6E+00	1,8E-01	7,3E-01	1,3E-01	2,1E-02	1,2E-01	1,5E-02	8,5E-02	1,5E-02	4,4E-02	6,3E-03	4,1E-02	6,6E-03
Barley shoots	Cattle manure	Z1	25-07-22	/	Year 1	mg kg ⁻¹	7,6E-01	1,5E+00	1,7E-01	6,7E-01	1,3E-01	2,0E-02	1,2E-01	1,5E-02	8,9E-02	1,7E-02	5,1E-02	7,2E-03	5,0E-02	7,7E-03
Barley shoots	Cattle manure	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,0E+00	2,0E+00	2,3E-01	9,0E-01	1,6E-01	2,6E-02	1,4E-01	1,7E-02	9,4E-02	1,8E-02	4,9E-02	7,4E-03	4,6E-02	7,6E-03
Barley shoots	Cattle manure	Z3	25-07-22	/	Year 1	mg kg ⁻¹	5,6E-01	1,1E+00	1,3E-01	5,2E-01	9,8E-02	1,6E-02	8,4E-02	1,1E-02	6,6E-02	1,2E-02	3,4E-02	4,8E-03	3,4E-02	5,4E-03
Barley shoots	Cover crop restitution	Z1	25-07-22	/	Year 1	mg kg ⁻¹	4,5E-01	8,5E-01	9,5E-02	3,7E-01	6,5E-02	1,2E-02	6,0E-02	8,1E-03	4,5E-02	8,5E-03	2,4E-02	3,5E-03	2,4E-02	3,6E-03
Barley shoots	Cover crop restitution	Z2	25-07-22	/	Year 1	mg kg ⁻¹	7,4E-01	1,4E+00	1,6E-01	6,3E-01	1,1E-01	1,6E-02	9,5E-02	1,2E-02	6,8E-02	1,2E-02	3,4E-02	4,9E-03	3,0E-02	4,7E-03

Appendices

Barley shoots	Cover crop restitution	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,4E+00	2,7E+00	3,2E-01	1,2E+00	2,4E-01	3,9E-02	2,1E-01	2,7E-02	1,6E-01	2,8E-02	8,1E-02	1,2E-02	7,7E-02	1,2E-02
Barley heads	No application	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,9E-02	3,7E-02	3,4E-03	1,4E-02	2,8E-03	8,1E-04	2,6E-03	4,0E-04	2,1E-03	3,6E-04	1,2E-03	1,3E-03	1,2E-03	2,0E-04
Barley heads	No application	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,6E-02	3,2E-02	3,2E-03	1,2E-02	1,7E-03	4,6E-04	2,4E-03	3,3E-04	1,6E-03	4,0E-04	1,1E-03	2,1E-04	1,1E-03	1,6E-04
Barley heads	No application	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,1E-02	2,3E-02	2,4E-03	9,0E-03	1,8E-03	4,8E-04	2,0E-03	2,2E-04	1,4E-03	3,5E-04	1,0E-03	1,6E-04	1,2E-03	1,4E-04
Barley heads	Green waste compost	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,2E-02	2,5E-02	2,6E-03	1,0E-02	1,8E-03	5,1E-04	2,1E-03	2,4E-04	1,8E-03	2,8E-04	1,0E-03	1,3E-04	8,1E-04	1,5E-04
Barley heads	Green waste compost	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,5E-02	2,6E-02	3,1E-03	1,1E-02	2,4E-03	3,6E-04	2,2E-03	3,3E-04	2,1E-03	5,5E-04	1,1E-03	1,6E-04	1,3E-03	1,3E-04
Barley heads	Green waste compost	Z3	25-07-22	/	Year 1	mg kg ⁻¹	1,0E-02	2,0E-02	2,1E-03	7,3E-03	1,9E-03	2,9E-04	2,0E-03	2,5E-04	1,5E-03	4,1E-04	9,2E-04	9,6E-05	8,9E-04	1,4E-04
Barley heads	Cattle manure	Z1	25-07-22	/	Year 1	mg kg ⁻¹	1,6E-02	3,1E-02	3,2E-03	1,2E-02	2,0E-03	4,1E-04	2,5E-03	3,1E-04	2,0E-03	3,5E-04	9,3E-04	2,3E-04	9,0E-04	1,9E-04
Barley heads	Cattle manure	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,4E-02	2,6E-02	3,0E-03	1,1E-02	1,8E-03	3,6E-04	2,4E-03	3,6E-04	2,1E-03	4,4E-04	9,2E-04	1,5E-04	9,3E-04	1,2E-04
Barley heads	Cattle manure	Z3	25-07-22	/	Year 1	mg kg ⁻¹	2,2E-02	4,6E-02	5,0E-03	1,8E-02	2,8E-03	6,3E-04	3,6E-03	3,8E-04	2,3E-03	6,1E-04	1,6E-03	2,4E-04	1,2E-03	2,6E-04
Barley heads	Cover crop restitution	Z1	25-07-22	/	Year 1	mg kg ⁻¹	2,5E-02	4,8E-02	5,5E-03	2,1E-02	3,9E-03	8,7E-04	3,7E-03	4,4E-04	3,2E-03	6,0E-04	1,3E-03	2,0E-04	1,0E-03	1,3E-04
Barley heads	Cover crop restitution	Z2	25-07-22	/	Year 1	mg kg ⁻¹	1,5E-02	2,9E-02	3,2E-03	1,2E-02	2,8E-03	6,1E-04	3,1E-03	4,3E-04	2,8E-03	5,3E-04	1,4E-03	2,4E-04	1,4E-03	2,4E-04
Barley heads	Cover crop restitution	Z3	25-07-22	/	Year 1	mg kg ⁻¹	5,2E-02	1,2E-01	1,2E-02	4,7E-02	7,3E-03	1,4E-03	8,4E-03	9,7E-04	6,4E-03	1,1E-03	3,4E-03	4,3E-04	3,1E-03	3,8E-04
Solution	Cover crop restitution	Z2	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	6,7E-04	9,2E-04	2,2E-04	1,1E-03	2,4E-04	5,3E-05	2,5E-04	3,1E-05	2,0E-04	4,1E-05	1,2E-04	1,7E-05	1,1E-04	1,9E-05
Solution	Cover crop restitution	Z3	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	9,5E-04	1,2E-03	3,2E-04	1,5E-03	3,3E-04	7,1E-05	3,2E-04	4,0E-05	2,2E-04	4,1E-05	1,2E-04	1,6E-05	1,0E-04	1,7E-05
Solution	Cattle manure	Z1	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	1,3E-03	1,9E-03	4,5E-04	2,2E-03	4,9E-04	1,1E-04	5,1E-04	6,6E-05	4,0E-04	8,3E-05	2,4E-04	3,3E-05	2,1E-04	3,4E-05
Solution	Cattle manure	Z2	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	5,5E-04	6,0E-04	1,8E-04	9,0E-04	1,9E-04	4,3E-05	2,0E-04	2,5E-05	1,6E-04	3,0E-05	8,8E-05	1,3E-05	7,7E-05	1,1E-05
Solution	Cattle manure	Z3	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	8,7E-04	1,2E-03	2,7E-04	1,3E-03	2,9E-04	6,5E-05	2,9E-04	3,8E-05	2,2E-04	4,4E-05	1,2E-04	1,7E-05	1,0E-04	1,7E-05
Solution	Green waste compost	Z1	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	1,2E-03	1,4E-03	3,9E-04	1,9E-03	4,4E-04	9,7E-05	4,6E-04	5,7E-05	3,4E-04	6,9E-05	2,0E-04	2,9E-05	1,8E-04	2,9E-05
Solution	Green waste compost	Z2	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	9,0E-04	8,0E-04	2,9E-04	1,5E-03	3,3E-04	7,2E-05	3,4E-04	4,0E-05	2,4E-04	5,1E-05	1,4E-04	2,0E-05	1,2E-04	2,1E-05
Solution	Green waste compost	Z3	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	1,0E-03	2,1E-03	3,1E-04	1,3E-03	3,0E-04	6,7E-05	3,3E-04	4,2E-05	2,6E-04	4,7E-05	1,3E-04	1,9E-05	1,1E-04	1,9E-05
Solution	No application	Z1	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	5,2E-04	8,9E-04	2,0E-04	9,8E-04	2,2E-04	4,8E-05	2,2E-04	2,6E-05	1,6E-04	3,3E-05	9,8E-05	1,4E-05	9,4E-05	1,6E-05
Solution	No application	Z2	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	6,8E-04	8,9E-04	2,4E-04	1,2E-03	2,5E-04	5,5E-05	2,5E-04	3,0E-05	1,8E-04	3,7E-05	1,0E-04	1,5E-05	9,9E-05	1,6E-05
Solution	No application	Z3	09-11-22	Mix 5 rhizons	Interculture	mg L ⁻¹	5,8E-04	1,3E-03	1,7E-04	7,4E-04	1,6E-04	3,3E-05	1,6E-04	2,2E-05	1,3E-04	2,4E-05	6,9E-05	9,8E-06	6,4E-05	9,9E-06
Solution	No application	Z1	13-01-23	B	Interculture	mg L ⁻¹	4,8E-04	7,7E-04	1,8E-04	8,7E-04	2,0E-04	4,2E-05	1,9E-04	2,3E-05	1,4E-04	2,9E-05	8,5E-05	1,2E-05	8,0E-05	1,3E-05
Solution	No application	Z1	13-01-23	C	Interculture	mg L ⁻¹	3,9E-04	5,8E-04	1,5E-04	7,4E-04	1,7E-04	3,6E-05	1,6E-04	2,0E-05	1,3E-04	2,4E-05	7,3E-05	1,0E-05	6,8E-05	1,2E-05
Solution	No application	Z1	13-01-23	D	Interculture	mg L ⁻¹	6,0E-04	1,1E-03	2,3E-04	1,1E-03	2,5E-04	5,6E-05	2,4E-04	3,0E-05	1,8E-04	3,7E-05	1,1E-04	1,6E-05	1,1E-04	1,7E-05
Solution	No application	Z1	13-01-23	E	Interculture	mg L ⁻¹	4,7E-04	7,0E-04	1,6E-04	7,7E-04	1,7E-04	3,7E-05	1,7E-04	2,0E-05	1,2E-04	2,5E-05	7,4E-05	1,0E-05	6,9E-05	1,2E-05
Solution	No application	Z2	13-01-23	A	Interculture	mg L ⁻¹	5,2E-04	8,2E-04	1,7E-04	8,1E-04	1,8E-04	3,9E-05	1,7E-04	2,1E-05	1,3E-04	2,6E-05	7,3E-05	1,0E-05	6,4E-05	1,1E-05
Solution	No application	Z2	13-01-23	C	Interculture	mg L ⁻¹	5,2E-04	5,7E-04	1,8E-04	9,0E-04	1,9E-04	4,3E-05	1,9E-04	2,4E-05	1,4E-04	2,9E-05	8,3E-05	1,1E-05	7,6E-05	1,3E-05
Solution	No application	Z2	13-01-23	D	Interculture	mg L ⁻¹	7,4E-04	1,1E-03	2,5E-04	1,2E-03	2,5E-04	5,4E-05	2,5E-04	3,1E-05	1,8E-04	3,7E-05	1,0E-04	1,4E-05	9,3E-05	1,5E-05
Solution	No application	Z2	13-01-23	E	Interculture	mg L ⁻¹	4,9E-04	5,8E-04	1,7E-04	8,3E-04	1,8E-04	4,0E-05	1,8E-04	2,2E-05	1,3E-04	2,7E-05	7,8E-05	1,1E-05	7,0E-05	1,2E-05
Solution	No application	Z3	13-01-23	A	Interculture	mg L ⁻¹	5,0E-05	4,2E-05	1,5E-05	7,6E-05	1,9E-05	4,3E-06	2,1E-05	2,9E-06	2,0E-05	4,4E-06	1,4E-05	2,2E-06	1,4E-05	2,4E-06
Solution	No application	Z3	13-01-23	B	Interculture	mg L ⁻¹	4,6E-05	4,3E-05	1,4E-05	7,2E-05	1,8E-05	5,1E-06	2,1E-05	2,6E-06	1,8E-05	4,2E-06	1,3E-05	1,9E-06	1,3E-05	2,0E-06
Solution	No application	Z3	13-01-23	D	Interculture	mg L ⁻¹	2,8E-05	1,6E-05	8,2E-06	4,3E-05	1,1E-05	2,6E-06	1,2E-05	1,5E-06	1,0E-05	2,5E-06	1,0E-05	1,4E-06	1,1E-05	2,0E-06
Solution	No application	Z3	13-01-23	E	Interculture	mg L ⁻¹	4,5E-05	3,8E-05	1,3E-05	1,6E-05	6,9E-05	1,6E-05	4,2E-06	1,8E-05	1,6E-05	3,5E-06	1,1E-05	1,6E-06	9,5E-06	1,6E-06
Solution	Green waste compost	Z1	13-01-23	A	Interculture	mg L ⁻¹	4,6E-04	4,9E-04	1,6E-04	7,8E-04	1,7E-04	3,7E-05	1,7E-04	2,1E-05	1,2E-04	2,6E-05	7,5E-05	1,1E-05	6,8E-05	1,1E-05
Solution	Green waste compost	Z1	13-01-23	B	Interculture	mg L ⁻¹	9,4E-04	1,4E-03	2,8E-04	1,3E-03	2,9E-04	6,2E-05	2,8E-04	3,6E-05	2,1E-04	4,1E-05	1,1E-04	1,6E-05	9,9E-05	1,6E-05

Field experiments

Solution	Green waste compost	Z1	13-01-23	C	Interculture	mg L ⁻¹	2,3E-03	4,9E-03	6,9E-04	3,0E-03	6,6E-04	1,4E-04	6,5E-04	8,8E-05	5,1E-04	9,5E-05	2,6E-04	3,5E-05	2,1E-04	3,1E-05
Solution	Green waste compost	Z1	13-01-23	D	Interculture	mg L ⁻¹	8,2E-04	8,5E-04	2,8E-04	1,3E-03	3,0E-04	6,6E-05	3,1E-04	3,8E-05	2,3E-04	4,7E-05	1,4E-04	1,9E-05	1,2E-04	2,0E-05
Solution	Green waste compost	Z2	13-01-23	A	Interculture	mg L ⁻¹	2,8E-04	2,8E-04	9,0E-05	4,3E-04	9,4E-05	2,1E-05	9,9E-05	1,2E-05	7,1E-05	1,5E-05	4,3E-05	6,0E-06	3,9E-05	6,3E-06
Solution	Green waste compost	Z2	13-01-23	B	Interculture	mg L ⁻¹	4,0E-04	2,6E-04	1,3E-04	6,6E-04	1,5E-04	3,4E-05	1,5E-04	1,9E-05	1,1E-04	2,4E-05	6,6E-05	9,6E-06	6,1E-05	1,0E-05
Solution	Green waste compost	Z2	13-01-23	C	Interculture	mg L ⁻¹	4,4E-04	3,3E-04	1,4E-04	7,2E-04	1,6E-04	3,5E-05	1,7E-04	2,0E-05	1,2E-04	2,5E-05	7,2E-05	9,9E-06	6,3E-05	1,0E-05
Solution	Green waste compost	Z2	13-01-23	D	Interculture	mg L ⁻¹	5,4E-04	4,6E-04	1,8E-04	8,7E-04	1,8E-04	4,0E-05	1,9E-04	2,2E-05	1,3E-04	2,8E-05	8,0E-05	1,1E-05	7,3E-05	1,2E-05
Solution	Green waste compost	Z2	13-01-23	E	Interculture	mg L ⁻¹	3,6E-04	2,2E-04	1,2E-04	5,9E-04	1,3E-04	3,0E-05	1,4E-04	1,7E-05	1,1E-04	2,2E-05	6,5E-05	9,3E-06	5,9E-05	9,6E-06
Solution	Green waste compost	Z3	13-01-23	A	Interculture	mg L ⁻¹	1,6E-04	1,5E-04	5,0E-05	2,5E-04	5,6E-05	1,3E-05	6,2E-05	7,2E-06	4,8E-05	1,0E-05	3,0E-05	4,5E-06	2,8E-05	4,5E-06
Solution	Green waste compost	Z3	13-01-23	B	Interculture	mg L ⁻¹	2,3E-04	2,1E-04	6,9E-05	3,4E-04	7,5E-05	1,6E-05	7,9E-05	9,6E-06	5,9E-05	1,2E-05	3,4E-05	4,9E-06	3,0E-05	5,2E-06
Solution	Green waste compost	Z3	13-01-23	C	Interculture	mg L ⁻¹	3,1E-04	3,8E-04	9,5E-05	4,7E-04	1,1E-04	2,4E-05	1,1E-04	1,5E-05	9,1E-05	1,9E-05	5,6E-05	7,6E-06	4,6E-05	7,6E-06
Solution	Green waste compost	Z3	13-01-23	D	Interculture	mg L ⁻¹	1,1E-04	4,7E-05	3,5E-05	1,9E-04	4,5E-05	1,0E-05	4,9E-05	6,6E-06	4,1E-05	9,2E-06	2,9E-05	4,2E-06	2,8E-05	4,4E-06
Solution	Green waste compost	Z3	13-01-23	E	Interculture	mg L ⁻¹	1,6E-04	8,0E-05	5,1E-05	2,6E-04	6,0E-05	1,5E-05	6,8E-05	7,8E-06	5,1E-05	1,0E-05	3,1E-05	4,5E-06	2,8E-05	4,6E-06
Solution	Cattle manure	Z1	13-01-23	A	Interculture	mg L ⁻¹	7,8E-04	1,0E-03	2,6E-04	1,3E-03	2,7E-04	6,0E-05	2,8E-04	3,4E-05	2,0E-04	4,1E-05	1,2E-04	1,7E-05	1,1E-04	1,8E-05
Solution	Cattle manure	Z1	13-01-23	B	Interculture	mg L ⁻¹	8,2E-04	9,0E-04	2,6E-04	1,3E-03	2,8E-04	6,3E-05	2,9E-04	3,6E-05	2,1E-04	4,3E-05	1,2E-04	1,7E-05	1,1E-04	1,7E-05
Solution	Cattle manure	Z1	13-01-23	C	Interculture	mg L ⁻¹	6,8E-04	9,7E-04	2,3E-04	1,1E-03	2,5E-04	5,3E-05	2,6E-04	3,1E-05	1,8E-04	3,7E-05	1,1E-04	1,5E-05	1,0E-04	1,6E-05
Solution	Cattle manure	Z1	13-01-23	D	Interculture	mg L ⁻¹	8,5E-04	1,1E-03	2,9E-04	1,4E-03	3,1E-04	6,8E-05	3,1E-04	3,9E-05	2,3E-04	4,7E-05	1,4E-04	1,9E-05	1,2E-04	2,0E-05
Solution	Cattle manure	Z1	13-01-23	E	Interculture	mg L ⁻¹	7,1E-04	8,8E-04	2,3E-04	1,1E-03	2,4E-04	5,4E-05	2,5E-04	3,1E-05	1,9E-04	3,8E-05	1,1E-04	1,5E-05	9,4E-05	1,5E-05
Solution	Cattle manure	Z2	13-01-23	A	Interculture	mg L ⁻¹	4,3E-04	4,9E-04	1,5E-04	7,4E-04	1,6E-04	3,5E-05	1,6E-04	2,0E-05	1,2E-04	2,4E-05	7,0E-05	9,9E-06	6,3E-05	1,1E-05
Solution	Cattle manure	Z2	13-01-23	B	Interculture	mg L ⁻¹	4,7E-04	4,7E-04	1,6E-04	7,7E-04	1,6E-04	3,7E-05	1,7E-04	2,0E-05	1,2E-04	2,5E-05	7,4E-05	1,1E-05	6,6E-05	1,1E-05
Solution	Cattle manure	Z2	13-01-23	C	Interculture	mg L ⁻¹	7,9E-04	1,2E-03	2,7E-04	1,3E-03	2,8E-04	6,1E-05	2,8E-04	3,4E-05	2,0E-04	3,9E-05	1,1E-04	1,5E-05	1,0E-04	1,6E-05
Solution	Cattle manure	Z2	13-01-23	D	Interculture	mg L ⁻¹	3,0E-04	2,6E-04	9,7E-05	4,8E-04	1,0E-04	2,3E-05	1,1E-04	1,2E-05	7,4E-05	1,5E-05	4,5E-05	6,3E-06	4,0E-05	6,8E-06
Solution	Cattle manure	Z2	13-01-23	E	Interculture	mg L ⁻¹	6,5E-04	6,0E-04	2,1E-04	1,1E-03	2,3E-04	4,9E-05	2,3E-04	2,7E-05	1,6E-04	3,3E-05	9,5E-05	1,3E-05	8,4E-05	1,3E-05
Solution	Cattle manure	Z3	13-01-23	A	Interculture	mg L ⁻¹	3,7E-04	2,4E-04	1,2E-04	5,8E-04	1,3E-04	3,0E-05	1,3E-04	1,6E-05	9,9E-05	2,0E-05	5,7E-05	7,8E-06	5,0E-05	7,8E-06
Solution	Cattle manure	Z3	13-01-23	C	Interculture	mg L ⁻¹	6,8E-04	8,1E-04	2,2E-04	1,0E-03	2,3E-04	5,0E-05	2,2E-04	2,7E-05	1,5E-04	3,1E-05	8,6E-05	1,2E-05	7,5E-05	1,2E-05
Solution	Cattle manure	Z3	13-01-23	D	Interculture	mg L ⁻¹	3,4E-04	3,1E-04	1,1E-04	5,4E-04	1,2E-04	2,6E-05	1,2E-04	1,4E-05	8,5E-05	1,7E-05	4,9E-05	6,8E-06	4,3E-05	7,3E-06
Solution	Cattle manure	Z3	13-01-23	E	Interculture	mg L ⁻¹	7,2E-04	6,0E-04	2,2E-04	1,1E-03	2,3E-04	5,2E-05	2,4E-04	2,8E-05	1,6E-04	3,3E-05	9,2E-05	1,3E-05	8,2E-05	1,3E-05
Solution	Cover crop restitution	Z1	13-01-23	B	Interculture	mg L ⁻¹	7,6E-04	1,5E-03	3,0E-04	1,5E-03	3,3E-04	7,1E-05	3,3E-04	4,2E-05	2,6E-04	5,1E-05	1,6E-04	2,2E-05	1,5E-04	2,4E-05
Solution	Cover crop restitution	Z1	13-01-23	C	Interculture	mg L ⁻¹	7,7E-04	1,5E-03	3,0E-04	1,5E-03	3,3E-04	7,2E-05	3,4E-04	4,3E-05	2,6E-04	5,2E-05	1,6E-04	2,3E-05	1,5E-04	2,3E-05
Solution	Cover crop restitution	Z1	13-01-23	E	Interculture	mg L ⁻¹	1,0E-03	2,0E-03	4,0E-04	1,9E-03	4,4E-04	9,7E-05	4,4E-04	5,6E-05	3,4E-04	6,8E-05	2,0E-04	3,0E-05	2,0E-04	3,2E-05
Solution	Cover crop restitution	Z2	13-01-23	B	Interculture	mg L ⁻¹	2,1E-04	2,7E-04	6,5E-05	3,1E-04	6,8E-05	1,5E-05	6,6E-05	8,7E-06	5,0E-05	1,0E-05	3,0E-05	4,1E-06	2,6E-05	4,4E-06
Solution	Cover crop restitution	Z2	13-01-23	C	Interculture	mg L ⁻¹	4,4E-04	4,4E-04	1,5E-04	7,1E-04	1,6E-04	3,4E-05	1,6E-04	1,9E-05	1,1E-04	2,3E-05	6,7E-05	9,1E-06	5,9E-05	9,9E-06
Solution	Cover crop restitution	Z2	13-01-23	D	Interculture	mg L ⁻¹	3,6E-04	3,6E-04	1,2E-04	6,0E-04	1,3E-04	2,8E-05	1,3E-04	1,6E-05	9,8E-05	2,0E-05	5,7E-05	7,7E-06	5,2E-05	8,6E-06
Solution	Cover crop restitution	Z2	13-01-23	E	Interculture	mg L ⁻¹	4,0E-04	4,5E-04	1,4E-04	6,7E-04	1,4E-04	3,2E-05	1,4E-04	1,7E-05	1,0E-04	2,1E-05	6,2E-05	8,8E-06	5,7E-05	9,5E-06
Solution	Cover crop restitution	Z3	13-01-23	A	Interculture	mg L ⁻¹	3,6E-04	2,7E-04	1,2E-04	5,8E-04	1,2E-04	2,8E-05	1,3E-04	1,5E-05	9,0E-05	1,8E-05	5,1E-05	7,3E-06	4,6E-05	7,3E-06
Solution	Cover crop restitution	Z3	13-01-23	C	Interculture	mg L ⁻¹	2,6E-04	2,2E-04	8,1E-05	4,0E-04	8,6E-05	1,9E-05	8,6E-05	1,1E-05	6,0E-05	1,3E-05	3,6E-05	4,9E-06	3,1E-05	5,1E-06
Solution	Cover crop restitution	Z3	13-01-23	D	Interculture	mg L ⁻¹	2,8E-04	2,1E-04	8,8E-05	4,3E-04	9,3E-05	2,1E-05	9,5E-05	1,1E-05	7,1E-05	1,5E-05	4,3E-05	5,8E-06	3,7E-05	6,0E-06
Solution	Cover crop restitution	Z3	13-01-23	E	Interculture	mg L ⁻¹	3,0E-04	2,4E-04	9,4E-05	4,5E-04	9,9E-05	2,2E-05	1,0E-04	1,2E-05	7,4E-05	1,5E-05	4,1E-05	5,9E-06	3,7E-05	5,9E-06
EOM	Cattle manure	/	08-05-23	/	Year 2	mg kg ⁻¹	2,1E+00	4,2E+00	5,1E-01	2,0E+00	3,7E-01	7,2E-02	3,3E-01	4,5E-02	2,8E-01	5,2E-02	1,5E-01	2,2E-02	1,4E-01	2,3E-02

Appendices

EOM	Green waste compost	/	08-05-23	/	Year 2	mg kg ⁻¹	8,0E+00	1,7E+01	1,9E+00	7,7E+00	1,5E+00	2,9E-01	1,3E+00	1,8E-01	1,2E+00	2,0E-01	5,9E-01	8,6E-02	5,5E-01	8,6E-02
Solution	No application	Z1	26-07-23	B	Year 2	mg L ⁻¹	6,2E-03	6,3E-03	7,7E-04	3,0E-03	5,2E-04	1,2E-04	6,3E-04	7,6E-05	4,4E-04	8,5E-05	2,3E-04	2,6E-05	1,4E-04	2,2E-05
Solution	No application	Z1	26-07-23	C	Year 2	mg L ⁻¹	1,4E-03	3,2E-03	4,1E-04	1,8E-03	3,9E-04	8,2E-05	3,7E-04	5,1E-05	2,9E-04	5,7E-05	1,5E-04	2,1E-05	1,3E-04	2,0E-05
Solution	No application	Z1	26-07-23	DAE	Year 2	mg L ⁻¹	3,5E-03	8,3E-03	9,8E-04	4,1E-03	8,8E-04	1,9E-04	8,6E-04	1,2E-04	7,0E-04	1,3E-04	3,4E-04	4,5E-05	2,8E-04	3,9E-05
Solution	No application	Z2	26-07-23	C	Year 2	mg L ⁻¹	7,0E-04	1,5E-03	2,2E-04	9,7E-04	2,1E-04	4,6E-05	2,1E-04	2,7E-05	1,6E-04	3,0E-05	8,9E-05	1,2E-05	7,4E-05	1,1E-05
Solution	No application	Z2	26-07-23	AD	Year 2	mg L ⁻¹	7,1E-03	1,4E-02	1,8E-03	7,4E-03	1,6E-03	3,4E-04	1,6E-03	2,1E-04	1,2E-03	2,2E-04	5,9E-04	7,9E-05	4,6E-04	7,1E-05
Solution	No application	Z3	26-07-23	AE	Year 2	mg L ⁻¹	3,1E-03	6,1E-03	8,4E-04	3,4E-03	7,4E-04	1,5E-04	7,0E-04	9,8E-05	5,6E-04	1,0E-04	2,7E-04	3,6E-05	2,1E-04	3,2E-05
Solution	No application	Z3	26-07-23	C	Year 2	mg L ⁻¹	1,2E-03	2,7E-03	3,2E-04	1,3E-03	3,0E-04	6,1E-05	2,9E-04	4,0E-05	2,2E-04	4,2E-05	1,1E-04	1,5E-05	9,0E-05	1,3E-05
Solution	No application	Z3	26-07-23	D	Year 2	mg L ⁻¹	2,3E-03	5,4E-03	6,4E-04	2,7E-03	6,0E-04	1,3E-04	5,8E-04	8,1E-05	4,7E-04	8,6E-05	2,3E-04	3,1E-05	1,8E-04	2,8E-05
Solution	Green waste compost	Z1	26-07-23	C	Year 2	mg L ⁻¹	1,2E-03	2,7E-03	3,6E-04	1,5E-03	3,4E-04	6,9E-05	3,2E-04	4,4E-05	2,6E-04	4,8E-05	1,3E-04	1,8E-05	1,1E-04	1,7E-05
Solution	Green waste compost	Z1	26-07-23	A	Year 2	mg L ⁻¹	2,5E-03	5,9E-03	7,3E-04	3,2E-03	7,0E-04	1,5E-04	6,7E-04	9,4E-05	5,4E-04	1,0E-04	2,8E-04	3,8E-05	2,5E-04	3,7E-05
Solution	Green waste compost	Z2	26-07-23	C	Year 2	mg L ⁻¹	8,6E-04	1,7E-03	2,6E-04	1,2E-03	2,8E-04	6,0E-05	2,7E-04	3,7E-05	2,2E-04	4,3E-05	1,2E-04	1,6E-05	1,0E-04	1,6E-05
Solution	Green waste compost	Z2	26-07-23	D	Year 2	mg L ⁻¹	1,0E-03	2,1E-03	3,1E-04	1,4E-03	3,0E-04	6,4E-05	3,0E-04	4,0E-05	2,4E-04	4,5E-05	1,3E-04	1,7E-05	1,1E-04	1,7E-05
Solution	Green waste compost	Z3	26-07-23	AD	Year 2	mg L ⁻¹	4,5E-03	1,0E-02	1,3E-03	5,6E-03	1,2E-03	2,5E-04	1,2E-03	1,7E-04	9,6E-04	1,7E-04	4,7E-04	6,4E-05	3,8E-04	5,8E-05
Solution	Cattle manure	Z1	26-07-23	A	Year 2	mg L ⁻¹	2,2E-03	5,4E-03	6,7E-04	2,9E-03	6,5E-04	1,4E-04	6,3E-04	8,7E-05	5,1E-04	9,6E-05	2,6E-04	3,5E-05	2,1E-04	3,2E-05
Solution	Cattle manure	Z1	26-07-23	C	Year 2	mg L ⁻¹	7,3E-04	1,4E-03	2,3E-04	1,0E-03	2,4E-04	5,3E-05	2,5E-04	3,4E-05	2,0E-04	4,0E-05	1,1E-04	1,4E-05	8,9E-05	1,3E-05
Solution	Cattle manure	Z1	26-07-23	D	Year 2	mg L ⁻¹	1,6E-03	3,4E-03	4,5E-04	2,0E-03	4,4E-04	9,4E-05	4,3E-04	5,8E-05	3,3E-04	6,5E-05	1,8E-04	2,3E-05	1,5E-04	2,3E-05
Solution	Cattle manure	Z2	26-07-23	C	Year 2	mg L ⁻¹	4,3E-04	7,2E-04	1,4E-04	6,5E-04	1,5E-04	3,1E-05	1,5E-04	1,9E-05	1,1E-04	2,3E-05	6,8E-05	9,7E-06	6,1E-05	1,0E-05
Solution	Cattle manure	Z2	26-07-23	D	Year 2	mg L ⁻¹	8,0E-04	1,7E-03	2,7E-04	1,3E-03	2,8E-04	5,8E-05	2,8E-04	3,4E-05	2,1E-04	4,1E-05	1,2E-04	1,7E-05	1,0E-04	1,7E-05
Solution	Cattle manure	Z2	26-07-23	A	Year 2	mg L ⁻¹	3,6E-03	8,3E-03	1,0E-03	4,5E-03	1,0E-03	2,1E-04	9,8E-04	1,3E-04	7,7E-04	1,4E-04	3,9E-04	5,2E-05	3,1E-04	4,6E-05
Solution	Cattle manure	Z3	26-07-23	D	Year 2	mg L ⁻¹	1,3E-03	3,1E-03	3,8E-04	1,6E-03	3,7E-04	8,1E-05	3,6E-04	5,5E-05	2,9E-04	5,4E-05	1,5E-04	2,0E-05	1,2E-04	1,9E-05
Solution	Cattle manure	Z3	26-07-23	BA	Year 2	mg L ⁻¹	3,9E-03	1,2E-02	1,1E-03	5,0E-03	1,1E-03	2,4E-04	1,1E-03	1,4E-04	8,5E-04	1,6E-04	4,2E-04	5,8E-05	3,3E-04	5,0E-05
Solution	Cover crop restitution	Z1	26-07-23	DE	Year 2	mg L ⁻¹	2,7E-03	5,9E-03	7,6E-04	3,4E-03	7,9E-04	1,6E-04	6,9E-04	9,1E-05	5,5E-04	1,1E-04	2,9E-04	4,1E-05	2,5E-04	4,0E-05
Solution	Cover crop restitution	Z2	26-07-23	D	Year 2	mg L ⁻¹	3,7E-03	7,8E-03	9,7E-04	4,1E-03	9,0E-04	1,9E-04	9,0E-04	1,2E-04	7,0E-04	1,3E-04	3,4E-04	4,8E-05	2,7E-04	4,1E-05
Solution	Cover crop restitution	Z2	26-07-23	E	Year 2	mg L ⁻¹	3,3E-03	5,4E-03	7,3E-04	3,2E-03	6,5E-04	1,5E-04	6,8E-04	8,7E-05	5,0E-04	9,6E-05	2,7E-04	3,4E-05	2,2E-04	3,4E-05
Solution	Cover crop restitution	Z3	26-07-23	E	Year 2	mg L ⁻¹	1,2E-03	2,7E-03	3,8E-04	1,7E-03	3,7E-04	8,2E-05	3,9E-04	5,2E-05	3,1E-04	5,6E-05	1,5E-04	2,0E-05	1,2E-04	1,9E-05
Solution	No application	Z1	13-09-23	C	Year 2	mg L ⁻¹	2,0E-04	3,9E-04	7,4E-05	3,6E-04	8,0E-05	1,8E-05	8,0E-05	9,7E-06	6,2E-05	1,3E-05	3,9E-05	5,5E-06	3,8E-05	6,2E-06
Solution	Green waste compost	Z1	13-09-23	A	Year 2	mg L ⁻¹	9,5E-04	2,0E-03	2,7E-04	1,2E-03	2,6E-04	5,5E-05	2,5E-04	3,6E-05	2,1E-04	4,1E-05	1,2E-04	1,9E-05	1,3E-04	2,1E-05
Solution	Green waste compost	Z1	13-09-23	C	Year 2	mg L ⁻¹	4,1E-04	7,0E-04	1,2E-04	5,5E-04	1,2E-04	2,7E-05	1,2E-04	1,6E-05	9,4E-05	1,9E-05	5,3E-05	7,2E-06	4,5E-05	7,7E-06
Solution	Green waste compost	Z1	13-09-23	E	Year 2	mg L ⁻¹	2,4E-04	3,3E-04	7,3E-05	3,7E-04	8,6E-05	1,8E-05	8,7E-05	1,1E-05	7,1E-05	1,5E-05	4,4E-05	6,0E-06	4,0E-05	7,0E-06
Solution	Green waste compost	Z2	13-09-23	A	Year 2	mg L ⁻¹	1,3E-03	2,7E-03	3,9E-04	1,7E-03	3,7E-04	7,7E-05	3,6E-04	4,8E-05	2,8E-04	5,1E-05	1,4E-04	1,9E-05	1,1E-04	1,8E-05
Solution	Green waste compost	Z2	13-09-23	C	Year 2	mg L ⁻¹	2,5E-04	3,2E-04	7,8E-05	3,8E-04	8,4E-05	1,8E-05	8,8E-05	1,1E-05	6,4E-05	1,3E-05	3,7E-05	5,1E-06	3,3E-05	5,6E-06
Solution	Green waste compost	Z2	13-09-23	D	Year 2	mg L ⁻¹	2,9E-04	3,4E-04	8,9E-05	4,3E-04	9,0E-05	2,0E-05	9,5E-05	1,2E-05	6,9E-05	1,4E-05	4,1E-05	5,5E-06	3,7E-05	6,1E-06
Solution	Green waste compost	Z3	13-09-23	A	Year 2	mg L ⁻¹	3,6E-04	8,2E-04	1,2E-04	5,5E-04	1,1E-04	2,2E-05	1,2E-04	1,5E-05	8,0E-05	1,5E-05	4,2E-05	5,6E-06	3,7E-05	6,5E-06
Solution	Green waste compost	Z3	13-09-23	C	Year 2	mg L ⁻¹	3,3E-04	6,9E-04	9,6E-05	4,4E-04	1,0E-04	2,2E-05	1,0E-04	1,4E-05	8,0E-05	1,5E-05	4,1E-05	5,6E-06	3,4E-05	5,1E-06
Solution	Cattle manure	Z1	13-09-23	C	Year 2	mg L ⁻¹	1,9E-04	2,6E-04	5,6E-05	2,7E-04	6,3E-05	1,3E-05	6,2E-05	8,1E-06	4,9E-05	9,6E-06	2,6E-05	3,6E-06	2,1E-05	3,5E-06
Solution	Cattle manure	Z1	13-09-23	D	Year 2	mg L ⁻¹	2,8E-04	2,9E-04	8,1E-05	4,1E-04	8,6E-05	1,9E-05	9,5E-05	1,1E-05	6,9E-05	1,5E-05	4,3E-05	6,3E-06	4,2E-05	7,0E-06
Solution	Cattle manure	Z1	13-09-23	E	Year 2	mg L ⁻¹	4,9E-04	6,6E-04	1,3E-04	6,4E-04	1,3E-04	2,8E-05	1,4E-04	1,7E-05	1,0E-04	2,2E-05	6,5E-05	9,3E-06	5,7E-05	9,5E-06

Field experiments

Solution	Cattle manure	Z2	13-09-23	C	Year 2	mg L ⁻¹	9,8E-04	1,8E-03	2,8E-04	1,3E-03	2,6E-04	5,9E-05	2,6E-04	3,4E-05	1,9E-04	3,6E-05	9,5E-05	1,3E-05	7,6E-05	1,2E-05
Solution	Cattle manure	Z2	13-09-23	D	Year 2	mg L ⁻¹	5,4E-04	1,2E-03	2,3E-04	1,1E-03	2,1E-04	4,1E-05	2,1E-04	2,5E-05	1,4E-04	2,7E-05	7,1E-05	9,0E-06	5,7E-05	9,9E-06
Solution	Cattle manure	Z3	13-09-23	B	Year 2	mg L ⁻¹	4,6E-04	7,0E-04	1,4E-04	6,5E-04	1,4E-04	3,0E-05	1,4E-04	1,8E-05	1,0E-04	2,0E-05	5,5E-05	7,8E-06	4,5E-05	7,4E-06
Solution	Cattle manure	Z3	13-09-23	E	Year 2	mg L ⁻¹	2,8E-04	4,7E-04	9,5E-05	4,5E-04	9,5E-05	1,9E-05	9,5E-05	1,2E-05	7,2E-05	1,4E-05	3,9E-05	5,5E-06	3,2E-05	5,4E-06
Solution	Cover crop restitution	Z3	13-09-23	A	Year 2	mg L ⁻¹	2,4E-02	5,8E-02	7,1E-03	3,0E-02	6,6E-03	1,4E-03	6,4E-03	8,8E-04	5,1E-03	9,3E-04	2,4E-03	3,2E-04	1,9E-03	2,8E-04
Solution	Cover crop restitution	Z3	13-09-23	E	Year 2	mg L ⁻¹	3,5E-03	7,8E-03	9,7E-04	3,9E-03	7,9E-04	1,6E-04	7,1E-04	9,7E-05	5,3E-04	9,6E-05	2,4E-04	3,1E-05	1,8E-04	2,7E-05
Maize roots	No application	Z1	20-09-23	/	Year 2	mg kg ⁻¹	7,5E+00	1,5E+01	1,8E+00	7,1E+00	1,3E+00	2,4E-01	1,1E+00	1,5E-01	1,1E+00	1,7E-01	4,9E-01	7,3E-02	4,9E-01	7,7E-02
Maize roots	No application	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,4E+01	3,1E+01	3,5E+00	1,4E+01	2,6E+00	4,6E-01	2,2E+00	3,1E-01	1,8E+00	3,4E-01	9,6E-01	1,4E-01	9,4E-01	1,4E-01
Maize roots	No application	Z3	20-09-23	/	Year 2	mg kg ⁻¹	1,1E+01	2,2E+01	2,6E+00	1,0E+01	1,9E+00	3,4E-01	1,6E+00	2,2E-01	1,3E+00	2,4E-01	6,8E-01	9,9E-02	6,7E-01	1,0E-01
Maize roots	Green waste compost	Z1	20-09-23	/	Year 2	mg kg ⁻¹	2,3E+00	3,5E+00	4,8E-01	1,9E+00	3,9E-01	8,1E-02	3,7E-01	5,1E-02	2,8E-01	5,5E-02	1,4E-01	1,9E-02	1,2E-01	1,7E-02
Maize roots	Green waste compost	Z2	20-09-23	/	Year 2	mg kg ⁻¹	2,3E+00	4,5E+00	5,6E-01	2,2E+00	4,2E-01	7,1E-02	3,5E-01	4,8E-02	2,8E-01	5,1E-02	1,4E-01	2,1E-02	1,4E-01	2,0E-02
Maize roots	Green waste compost	Z3	20-09-23	/	Year 2	mg kg ⁻¹	2,3E+00	4,7E+00	5,7E-01	2,2E+00	4,4E-01	8,4E-02	3,8E-01	5,2E-02	3,1E-01	5,8E-02	1,6E-01	2,3E-02	1,6E-01	2,3E-02
Maize roots	Cattle manure	Z1	20-09-23	/	Year 2	mg kg ⁻¹	3,2E+00	6,5E+00	7,5E-01	2,9E+00	5,7E-01	9,5E-02	5,0E-01	6,8E-02	3,9E-01	7,3E-02	2,1E-01	3,0E-02	2,0E-01	3,0E-02
Maize roots	Cattle manure	Z2	20-09-23	/	Year 2	mg kg ⁻¹	4,7E+00	9,3E+00	1,1E+00	4,4E+00	8,6E-01	7,6E-01	1,0E-01	1,0E-01	5,9E-01	1,1E-01	3,1E-01	4,7E-02	3,1E-01	4,6E-02
Maize roots	Cattle manure	Z3	20-09-23	/	Year 2	mg kg ⁻¹	1,4E+01	3,1E+01	3,5E+00	1,4E+01	2,7E+00	4,8E-01	2,2E+00	3,0E-01	1,8E+00	3,4E-01	9,5E-01	1,4E-01	9,2E-01	1,4E-01
Maize roots	Cover crop restitution	Z1	20-09-23	/	Year 2	mg kg ⁻¹	5,2E+00	1,1E+01	1,2E+00	4,9E+00	9,5E-01	1,7E-01	8,1E-01	1,1E-01	6,5E-01	1,2E-01	3,4E-01	5,0E-02	3,2E-01	4,9E-02
Maize roots	Cover crop restitution	Z2	20-09-23	/	Year 2	mg kg ⁻¹	3,3E+00	6,8E+00	8,2E-01	3,2E+00	6,4E-01	1,2E-01	5,6E-01	8,1E-02	4,7E-01	8,8E-02	2,5E-01	3,8E-02	2,4E-01	3,6E-02
Maize roots	Cover crop restitution	Z3	20-09-23	/	Year 2	mg kg ⁻¹	2,4E+00	4,9E+00	5,9E-01	2,4E+00	4,7E-01	8,9E-02	4,2E-01	5,9E-02	3,4E-01	6,5E-02	1,8E-01	2,7E-02	1,7E-01	2,5E-02
Maize stems	No application	Z1	20-09-23	/	Year 2	mg kg ⁻¹	2,2E-01	5,0E-01	5,9E-02	2,4E-01	4,5E-02	6,5E-03	3,3E-02	4,7E-03	2,7E-02	4,2E-03	1,2E-02	1,7E-03	1,2E-02	2,0E-03
Maize stems	No application	Z2	20-09-23	/	Year 2	mg kg ⁻¹	4,4E-01	8,9E-01	1,1E-01	4,3E-01	8,4E-02	1,5E-02	7,2E-02	9,0E-03	5,2E-02	9,9E-03	2,8E-02	4,1E-03	2,7E-02	3,9E-03
Maize stems	No application	Z3	20-09-23	/	Year 2	mg kg ⁻¹	2,4E-01	4,8E-01	5,5E-02	2,1E-01	3,7E-02	6,9E-03	3,4E-02	4,3E-03	2,8E-02	5,2E-03	1,5E-02	2,3E-03	1,5E-02	2,1E-03
Maize stems	Green waste compost	Z1	20-09-23	/	Year 2	mg kg ⁻¹	1,6E-01	3,2E-01	3,7E-02	1,4E-01	2,4E-02	4,2E-03	2,1E-02	2,6E-03	1,5E-02	2,6E-03	8,3E-03	1,1E-03	7,3E-03	1,2E-03
Maize stems	Green waste compost	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,8E-01	3,7E-01	4,3E-02	1,7E-01	3,2E-02	6,2E-03	2,7E-02	3,6E-03	2,3E-02	4,3E-03	1,2E-02	2,0E-03	1,2E-02	2,2E-03
Maize stems	Green waste compost	Z3	20-09-23	/	Year 2	mg kg ⁻¹	2,0E-01	4,1E-01	4,8E-02	1,9E-01	3,4E-02	6,3E-03	3,1E-02	4,3E-03	2,4E-02	4,5E-03	1,2E-02	1,7E-03	1,2E-02	1,8E-03
Maize stems	Cattle manure	Z1	20-09-23	/	Year 2	mg kg ⁻¹	1,8E-01	3,8E-01	4,5E-02	1,8E-01	3,1E-02	5,8E-03	2,7E-02	3,5E-03	2,1E-02	4,0E-03	1,2E-02	1,6E-03	1,7E-02	1,5E-03
Maize stems	Cattle manure	Z2	20-09-23	/	Year 2	mg kg ⁻¹	3,0E-01	6,2E-01	7,2E-02	2,9E-01	5,5E-02	1,0E-02	4,8E-02	6,2E-03	3,7E-02	7,4E-03	2,2E-02	3,3E-03	2,1E-02	3,1E-03
Maize stems	Cattle manure	Z3	20-09-23	/	Year 2	mg kg ⁻¹	1,2E-01	2,6E-01	3,2E-02	1,3E-01	2,6E-02	4,7E-03	2,3E-02	3,1E-03	1,9E-02	3,4E-03	1,0E-02	1,6E-03	1,1E-02	1,5E-03
Maize stems	Cover crop restitution	Z1	20-09-23	/	Year 2	mg kg ⁻¹	1,9E-01	3,7E-01	4,4E-02	1,8E-01	3,2E-02	6,2E-03	3,1E-02	4,3E-03	2,7E-02	4,7E-03	1,5E-02	2,2E-03	1,5E-02	2,2E-03
Maize stems	Cover crop restitution	Z2	20-09-23	/	Year 2	mg kg ⁻¹	6,9E-01	1,4E+00	1,7E-01	6,5E-01	1,2E-01	2,1E-02	1,0E-01	1,3E-02	7,3E-02	1,4E-02	3,9E-02	5,7E-03	3,8E-02	6,1E-03
Maize stems	Cover crop restitution	Z3	20-09-23	/	Year 2	mg kg ⁻¹	1,5E-01	2,9E-01	3,5E-02	1,3E-01	2,6E-02	5,1E-03	2,2E-02	3,2E-03	2,0E-02	3,9E-03	1,1E-02	1,5E-03	1,0E-02	1,6E-03
Maize leaves	No application	Z1	20-09-23	/	Year 2	mg kg ⁻¹	2,1E-01	3,5E-01	4,1E-02	1,7E-01	3,2E-02	5,8E-03	2,9E-02	3,9E-03	2,1E-02	4,2E-03	1,1E-02	1,7E-03	9,3E-03	1,3E-03
Maize leaves	No application	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,5E-01	2,0E-01	2,7E-02	1,1E-01	2,1E-02	3,8E-03	1,8E-02	2,4E-03	1,5E-02	2,7E-03	7,3E-03	9,8E-04	6,4E-03	1,0E-03
Maize leaves	No application	Z3	20-09-23	/	Year 2	mg kg ⁻¹	2,4E-01	4,7E-01	5,5E-02	2,2E-01	4,3E-02	8,0E-03	3,8E-02	5,6E-03	3,0E-02	5,7E-03	1,6E-02	2,2E-03	1,5E-02	2,2E-03
Maize leaves	Green waste compost	Z1	20-09-23	/	Year 2	mg kg ⁻¹	3,0E-01	5,7E-01	6,6E-02	2,5E-01	4,7E-02	8,8E-03	3,9E-02	5,1E-03	3,0E-02	5,5E-03	1,4E-02	2,4E-03	1,4E-02	2,0E-03
Maize leaves	Green waste compost	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,5E-01	2,2E-01	3,0E-02	1,2E-01	2,2E-02	5,0E-03	2,2E-02	2,6E-03	1,5E-02	3,0E-03	8,5E-03	1,1E-03	7,1E-03	1,1E-03
Maize leaves	Green waste compost	Z3	20-09-23	/	Year 2	mg kg ⁻¹	1,7E-01	3,2E-01	3,9E-02	1,5E-01	2,8E-02	4,8E-03	2,4E-02	3,3E-03	1,9E-02	3,4E-03	9,9E-03	1,5E-03	9,8E-03	1,5E-03
Maize leaves	Cattle manure	Z1	20-09-23	/	Year 2	mg kg ⁻¹	3,6E-01	7,2E-01	8,3E-02	3,2E-01	6,2E-02	1,2E-02	5,3E-02	8,0E-03	4,6E-02	8,6E-03	2,3E-02	3,7E-03	2,4E-02	4,0E-03
Maize leaves	Cattle manure	Z2	20-09-23	/	Year 2	mg kg ⁻¹	1,4E-01	2,4E-01	3,0E-02	1,2E-01	2,4E-02	4,6E-03	2,1E-02	3,1E-03	1,8E-02	3,1E-03	9,1E-03	1,6E-03	8,7E-03	1,4E-03

Appendices

Maize leaves	Cattle manure	Z3	20-09-23	/	Year 2	mg kg ⁻¹	8,1E-02	1,4E-01	1,7E-02	6,9E-02	1,2E-02	2,6E-03	1,3E-02	1,7E-03	9,5E-03	2,0E-03	5,3E-03	9,5E-04	5,5E-03	8,9E-04
Maize leaves	Cover crop restitution	Z1	20-09-23	/	Year 2	mg kg ⁻¹	1,3E+00	2,5E+00	3,0E-01	1,1E+00	2,1E-01	3,3E-02	1,8E-01	2,2E-02	1,2E-01	2,3E-02	5,9E-02	8,7E-03	5,5E-02	8,4E-03
Maize leaves	Cover crop restitution	Z2	20-09-23	/	Year 2	mg kg ⁻¹	5,1E-01	1,1E+00	1,2E-01	4,7E-01	8,9E-02	1,5E-02	7,2E-02	9,6E-03	5,7E-02	1,1E-02	3,1E-02	4,7E-03	3,1E-02	4,4E-03
Maize leaves	Cover crop restitution	Z3	20-09-23	/	Year 2	mg kg ⁻¹	4,8E-01	9,1E-01	1,1E-01	4,2E-01	8,2E-02	1,5E-02	7,2E-02	9,8E-03	5,7E-02	1,1E-02	3,1E-02	4,7E-03	3,1E-02	4,7E-03