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Coffee trees intercropped with common beans: An opportunity to regulate the aphid *Toxoptera aurantii* (Boyer de Fonscolombe) (Hemiptera: Aphididae) in coffee agroecosystems

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Abstract

The coffee aphid *Toxoptera aurantii* (Boyer de Fonscolombe) (Hemiptera: Aphididae) causes direct feeding injuries and vectors the *coffee ringspot virus* (CoRSV) (Mononegavirales: Rhabdoviridae), which is more damaging to coffee plants. Coffee farmers have controlled this pest using synthetic pesticides. However, chemical control is ineffective and sometimes associated with resistance, environmental pollution, and pest resurgence, leading to the deterioration of agricultural ecosystem services. Therefore, there is a need to find more effective and safe biocontrol agents to keep this pest under the economic threshold. In that context, we installed six plots to compare the dynamics of aphid populations in coffee trees intercropped with common beans (*Phaseolus vulgaris* L., Fabales: Fabaceae) to coffee monoculture farming systems in open fields in the Southern Province of Rwanda. Results show a significant difference in infestations of coffee aphids. The population of aphids is higher in coffee monocultures than in intercropping systems. Our results also indicate that beneficial insects respond positively to the intercropping system with more species of natural enemies, mostly ladybird beetles (Coccinellidae), hoverflies (Syrphidae), and wasps (Vespidae) than in monocultures. No Hymenoptera were observed in coffee monoculture plots, indicating that common beans attract diverse natural enemies. Therefore, coffee trees intercropped with beans can help to maintain and diversify indigenous natural enemies in agroecosystems and regulate the aphid *T. aurantii*. We recommend future researchers use the Land Equivalent Ratio (LER) and compare these coffee farming systems to help people decide exactly what intercropping crops yield should be.

Keywords Interaction · Intercropping · Parasitoid · Predator · Monoculture

Introduction

Coffee arabica L. (Gentianales: Rubiaceae) is the dominant coffee species cultivated in Rwanda, with a share of more than 99% of the national coffee area (Mukashema et al. 2014). It represents, besides tea, the major export crop and around 400,000 farm families rely on its production, farming about 42,000 ha of coffee plantations (Gather and Wollni 2022). Agriculture increased the Gross Domestic Product (GDP) from USD 362 in 2006 to 493 million in 2019, accounting for 26% of the overall GDP in 2020, and Coffee contribution was USD 62,7617 (Nsengimana et al. 2023).

However, coffee farmers face several challenges, including poor soil fertility and insufficient access to fertilizers, old and less productive coffee trees, low prices compared to competing crops, and pests and diseases reducing production by as much as 50% per year at the farm level (Gather and Wollni 2022). There are many serious pests of coffee

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for example, *Hypothebemus hampei (*Ferrari) (Coleoptera: Curculionidae), *Leucoptera coffeella* (Guérin-Méneville) (Lepidoptera: Lyonitiidae), *Toxoptera aurantii* (Boyer de Fonscolombe) (Hemiptera: Aphididae), *Antestiopsis thunbergii* (Gmelin) (Hemiptera: Pentatomidae) (Bigirimana et al. 2019), *Xylosandrus compactus* (Eichhoff) (Coleoptera: Curculionidae) and *Monochamus leuconotus* (Hunt & Breuning (1956) (Coleoptera: Cerambycidae) (Kuyah et al. 2017). Among diseases, there is coffee berry disease caused by *Colletotrichum kahawae* (Waller and Bridge) (Ascomycota: Glomerellaceae) (Batista et al. 2017) and coffee yellow rust caused by *Hemileia vastatrix* (Berk and Br.) (Basidiomycota: Pucciniaceae) (Daba et al. 2019).

However, some of these organisms were not serious pests; but due to different environmental factors and poor agricultural practices that make them thrive, they become abundant and affect coffee yields. Empirical studies indicate that several applications of insecticides enabled pests to become more serious (Dantas et al. 2021). For instance, in 2017 in Tanzania, the population of *T. aurantii* was higher and doubled in coffee trees managed with insecticides than in untreated trees (Lyimo et al. 2017). Poor agricultural practices like low levels of diversified agroforestry systems in coffee trees in favor of monocultures reduce ecosystem services (Perfecto and Vandermeer 2015) some of which regulate pest problems. Furthermore, the effect of climate change favored the reproduction of insects; that is the case of *H. hampei* which is more serious when temperatures rise (Jaramillo et al. 2011).

The aphid *T. aurantii* is characterized by a globoid, dark green, or black body and is easily excited having stridulatory organs producing a characteristic noise that is audible when colonies are very large (Firempong 1977). An apterous female can produce 50 female nymphs in 6 days (Firempong 1977). It sucks sap from coffee trees (Gaitán et al. 2015) and vectors the *coffee ringspot virus* (CoRSV) (Waller et al. 2007), which is now a severe problem in tropical and subtropical regions (Ramalho et al. 2014). *T. aurantii* excretes a considerable quantity of honeydew, upon which the sooty moulds develop, interfering with photosynthesis and decreasing production. They are often more serious pests in young plantations and coffee nurseries (Barrera 2008).

Despite diseases and pests, farmers in Rwanda produce coffee under two main farming systems; monoculture and polyculture (Harelimana et al. 2018) in which farmers intercrop coffee trees with food crops, fodder, and fruit trees simultaneously (Balasubramanian and Egli 1986). Under the polyculture system, farmers in Rwanda primarily associate coffee with food crops such as beans, tomatoes, sweet potatoes, yams, cassava, and soya beans (Harelimana et al. 2018). There are several varieties of coffee under production, most of them being Mibilizi, Jackson 2/1257, MB71, MB 139, POP 3303/21, Harrar, Baraka, Catimor, Caturra and Catuaii (Nzeyimana et al. 2013). However, extension services in Rwanda recommend growing the varieties BM71, BM139, Jackson2/1257, and Pop3303/21 which produce high yields throughout the territory (Mukashema et al. 2014).

Intercropping can provide income and ensure food security for rural communities whose land is limited and can help farmers reduce the risk associated with changing environmental conditions (Perfecto and Vandermeer 1996; Siles et al. 2010) and coffee price volatility (Jassogne et al. 2013). Furthermore, intercropping exhibits more yield stability and less productivity decline during a drought than in the case of a single crop. It also regulates the problem of water stress by keeping humidity within crops (Altieri and Koohafkan 2008). For example, in El Salvador, shade trees in coffee plantations provide firewood for smallholder households for an equivalent value of one month of income generated by all household members (Bacon 2005). Similarly, in Nicaragua, where small-scale farmers usually practice intercropping, 60% of the farmers grow half or more of their food crops in coffee trees (Bacon 2008), while in Rwanda, intercropping of banana with avocados, pawpaw, banana, cassava, sugarcane, beans, soy, peas, and potatoes contribute to the food security for smallholder farmers who often produce for family consumption (Harelimana et al. 2018) and guarantee farm stability during the period of the re-establishment of coffee production (Souza et al. 2012a, b).

Intercropping is also effective in reinforcing ecosystem services. For instance, the nitrogen-fixing perennial *Inga densiflora* (Benth) (Fabales: Mumosaceae) and annual crops *Glycine max* (L.) Merr (Fabales: Fabaceae) intercropped with coffee can restore soil fertility (Romero-Alvarado et al. 2002) and generate a diversity of agricultural products like fruits, firewood, timber, and mulch (Dawson et al. 2008; Souza et al. 2010, 2012a, b; Bucagu et al. 2013). Furthermore, intercropping improves biological diversity and controls pest outbreaks (Avelino et al. 2011; De Souza et al. 2012a, b; Jassogne et al. 2013; Jha et al. 2014). For example, *P. vulgaris* mixed with the winter wheat *Triticum aestivum* L. (Poales: Poaceae) reduced *Aphis fabae* Scopoli (Hemiptera: Aphididae) populations (Altieri and Letourneau 1982), while brassica crops mixed with beans controlled the cabbage aphid *Brevicoryne brassicae* L. (Hemiptera: Aphididae) (Tukahirwa and Coaker 1982). Another intercropping example includes cassava and cowpeas which is reported to be effective in managing populations of *Aleurotrachelus socialis* Bondar (Hemiptera: Aleyrodidae) (Gold et al. 1989) while intercropping of corns and beans has controlled *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) (Altieri et al. 1978). Concerning shaded coffee by agroforestry trees, the system can suppress the coffee berry borer for *H. hampei* (Soto-Pinto et al. 2002) while coffee intercropped with the neem tree

Azadirachta indica (A. Juss) (Sapindales: Meliaceae) mitigated *L. coffeella* (Venzon et al. 2005). Moreover, coffee trees intercropped with weed complex(w eed diversities in the form of weed borders or alternate rows) in controlled *Antesiopsis intricate* (Ghesquière & Carayon) (Hemiptera: Pentatomidae) (Altieri and Letourneau 1982). Therefore, keeping non-cultivated areas as reservoirs in a highly cultivated environment ensures a diversity of native natural enemy species that can persist spatially and temporally within agricultural landscapes (Schmitz and Barton 2014; Harelimana et al. 2022).

Smallholder farmers in Rwanda often intercrop coffee trees with beans (Harelimana et al. 2018). However, nothing has been published about whether this cropping system can diversify natural enemies and reduce populations of the aphid *T. aurantii* in coffee plantations. The system of combining coffee plants with beans in the same field simultaneously is expected to manage the aphid *T. aurantii* because there are examples showing the role of leguminous plants in managing weeds and insects when they are intercropped with coffee plants (Kiseve 2012). Studies have shown that for example, *Inga edulis* (Mart.) (Fabales: Fabaceae) (Rezende et al. 2021), *Crotalaria juncea* (L.) (Fabales: Fabaceae) (Rosado et al. 2021) and *Mucuna pruriens* (L.) (Fabales: Fabaceae) (Carvalho et al. 2019) can manage population dynamics of insects in coffee trees, for instance, phytophagous mites. Furthermore, beans are seriously attacked by aphids especially *A. fabae* (Scopoli 1763) (Hemiptera: Aphididae) and can be an opportunity to promote and rear natural enemies that can feed on coffee aphids when they are established (the logic of apparent competition). In this study, we conducted experiments in natural environment conditions to compare *T.aurantii* infestations in coffee trees intercropped with common beans to coffee monocultures. During previous laboratory studies and field experiments, we evaluated the infestations of *T. aurantii* on four coffee varieties: BM71, BM139, Pop3303/21, and Jackson2/1257, which are under extension in Rwanda. Laboratory and field experiments indicated that BM71 is less susceptible to *T. aurantii* (Harelimana 2018). The main objective of this work is to integrate this less sensitive variety into polyculture systems to avoid insects that can overcome resistance over time. This study is based on the following scientific questions. (a) Can the coffee-bean intercropping system reduce aphid infestations compared to the coffee monocultures? and (b) can natural enemies of *T. aurantii* in intercropped coffee plantations with common beans be abundant and diversified? We hypothesize that coffee trees intercropped with *P.vulgaris* can reduce aphid (*T. aurantii*) infestations by augmenting and diversifying predators and parasitoids. Finally, we monitored aphid infestations and natural enemies's variation in situ to confirm the abovementioned research hypothesis.

Materials and methods

We set up experimental plots in the Rwanda Agriculture and Animal Resources Development Board (RAB) (2^0 06′ S 29^0 48′ E) in the Southern Province, Huye District. The climate is tropical, with an alternation of rain and dry seasons. The site elevation is around 1800 m above sea level and an average of 2500 mm yearly rainfall. The coffee production system in this area varies between polyculture and monoculture. The field site had a recent history of sorghum cultivation.

We established three randomized plots of coffee trees (variety BM71) with no ground cover except a dried mulch of *Cenchrus purpureus* Schumach (Poales: Poaceae) for 5 months to control splash soil erosion. Each plot had 16 plants with 2 m intra- and inter-row spacing. The area of each field is 36m^2. The distance between plots was 15 m grass buffer zones. We planted seedlings of *C. arabica* aged 13 months on September 15th, 2015. Each seedling received 20 kg of organic compost only during planting. Five months later, we intercropped coffee trees with common beans (Variety: Kiryumukwe). We installed three other plots of the same dimensions of coffee monocultures following spacing guidelines (2×2 m) as recommended by the Rwanda Agriculture and Animal Resources board in that area (generally, the spacing depends on soil fertility, slopes and the cover crop to avoid competition especially competition for light) but treated them as intercrop plots for different management practices. The three plots of coffee monocultures served as control. After harvesting (mi-June 2016), intercrop plots remained with coffee monocultures from July 2016 to February 2017, allowing senescent bean leaves to decompose. On March 15th, 2017, with the same coffee plots, we replicated the intercropping system with the same species of beans and control plots. In total, we followed six plots that were randomly spatially distributed. The sowing density of beans was 1.5 kg, that is, 0.5 kg per plot, the quantity recommended by RAB. We apply neither chemical fertilizers, pesticides nor irrigation to allow trees to grow in their normal conditions. We regularly removed weeds from experimental plots. We investigated aphid infestations on coffee trees (96 plants) intercropped with common beans to monocultures for two consecutive years.

After the germination of beans (at the stage of 3 leaves), the infestation of *T. aurantii* and its associated natural enemies were monitored and followed at weekly intervals. We follow up on plots every Wednesday between 8:30 a.m. and 11:30 a.m. (when insects are supposed to be active) from April 1st to July 15th, 2016, and April 1st up to July 15th, 2017, for the second experiment. These dates (July 15th, 2016, and July 15th, 2017) corresponded to the bean harvesting period. As coffee trees were young, we counted aphids on the whole plant.

The abundance of predatory insects was assessed (all visible stages: larva, and adults were collected). In this study, the population quantities of predatory natural enemies were observed once per week for two consecutive years by both visual observation and hand collection. At each plot, five randomly selected points were used for natural enemies sampling in the two coffee farming systems. A net was used to capture flying insects on coffee trees. When there were no moving insects, coffee plants were shaken, and falling arthropods were collected in a bag, counted in situ, and kept in a bottle containing ethanol 70% to preserve them for later laboratory identification.

For parasitoid wasps, we used coloured plastic basins (blue, white, and yellow) to attract them (Nuttman et al. 2011). We placed three traps at 0.5 m above ground level in each plot (Abrahamczyk et al. 2010). Traps were placed in the experimental plots once per week for 5 h (8:30 a.m. to 1:30 p.m.). Each trap contained l liter of the solution composed of soapy (10 ml of soap) water (to reduce water tension and inhibit their flight) and 15 ml of honey (to attract parasitoid wasps) (Pak et al. 2015).

We morphologically identified insects under a binocular magnifier in the Earth and Life Institute Laboratory of the Catholique University of Louvain (Carnoy 4–5, 1348 Louvain-La- Neuve/ Belgium). We used the identification key for African and South American insects (Delvare and Aberlenc 1989) and Rwanda's coccinellids (Fürsch 1997) to determine ladybird beetles. Nevertheless, we did not calculate Shannon's diversity index because natural enemies did not appear in all experimental plots. Moreover, as coffee took more than three years to get the first harvest of coffee berries, we did not collect data on the production during the two years of experiments.

Data analysis

We tested the effect of treatments on the number of aphids counted every week on six plots using a Generalized Linear Mixed Model with a linked function of Poisson distribution (Poisson-GLMM) but discarded the latter due to substantial overdispersion of aphid counts. Instead, we adopted the negative binomial (error distribution: negative binomial (NB-GLMM) with a log-link function for those comparisons. We included in the model cropping systems (treatments), dates of data collection, and years as fixed factors while we considered plots as random factors and the number of aphid populations counted in each plot as response variables. All GLMM analyses were performed using R version 4.2.3 Copyright (C) 2023 The R Foundation for Statistical Computing for Mac. If the treatment type was found to be statistically significant, post hoc analyses of the effects of treatments were then performed to know which treatment was different from others. In addition, the natural enemies abundance was analyzed by analysis of variance (ANOVA), and the means were compared with Tukey's test at $P<0.05$. All the analyses were performed using Graph Pad Prism 5.1 software (Dennis Radushev, San Diego, USA).

Results

There is a variation of *T. aurantii* populations in the two coffee farming systems over time and syrphids, coccinellids, mummified aphids, and wasps (Figs. 1 and 2). The results indicated that coffee trees intercropped with beans reduced aphid infestations after one season of beans cropping in coffee trees. The effect of the treatments on *T.aurantii* infestations is the same, especially in 2016 (Fig. 1; NB-GLMM:$\chi 2$ = 2.435; df = 1; p = 0.11865). However, there is a strong interaction between treatments, weeks, and years (Table 1; NB-GLMM:$\chi 2$ = 35.66; df = 11; p < 0.001 ;$\chi 2$ = 34.823; df = 1p < 0.0001). For the intercropping system, the infestations of *T. aurantii* are predicted to decrease over time compared to coffee monocultures. However, when infestations are low in monocultures, they increase over weeks during the two years of experimentation (Table 1; NB-GLMM:$\chi 2$ = 35.66; df = 11; p < 0.001). The infestations are statistically different among weeks and appeared as aphid populations grew (NB-GLMM:$\chi 2$ = 60.114; df = 11p < 0.0001). The population of *T. aurantii* reached critical levels in fields without intercropping (Mean: 120 ± 16.1 aphids /plot, (Fig. 1). The results also reveal a significant difference in infestations between years of experiments (NB-GLMM:$\chi 2$ = 66.629; df = 1p < 0.0001). The interaction between crop systems and the period (years) influenced aphid dynamics on coffee trees (NB-GLMM:$\chi 2$ = 38.495; df = 1p < 0.0001). When maintained over time, the intercropping systems can reduce thus infestations of *T. aurantii* in a second year (Fig. 1).

In the first year of the experiments, the population of *T. aurantii* remained at low levels and stable with an average of 40 individuals per plot in coffee trees intercropped with beans and 38 individuals per plot in coffee monoculture (Fig. 1). However, The population of *T.aurantii* showed a significant difference between treatments (Poisson- GLMM: $\chi^2 = 3993.6$, $Df = 1$, $P < 0.001$). The infestations were more important in coffee monocultures (Fig. 1.; Mean: 120 ± 16.1 aphids /plot) than in intercropping treatments (Mean: 30 ± 8 aphids/plot). We observed a high infestation in week 11 and then after that period, infestations began to decrease.

The variation of targeted natural enemies in treatments was significantly different ($F = 6.22$; $df = 3$; $p < 0.0001$). Syriphids were more abundant than Coccinellids, and

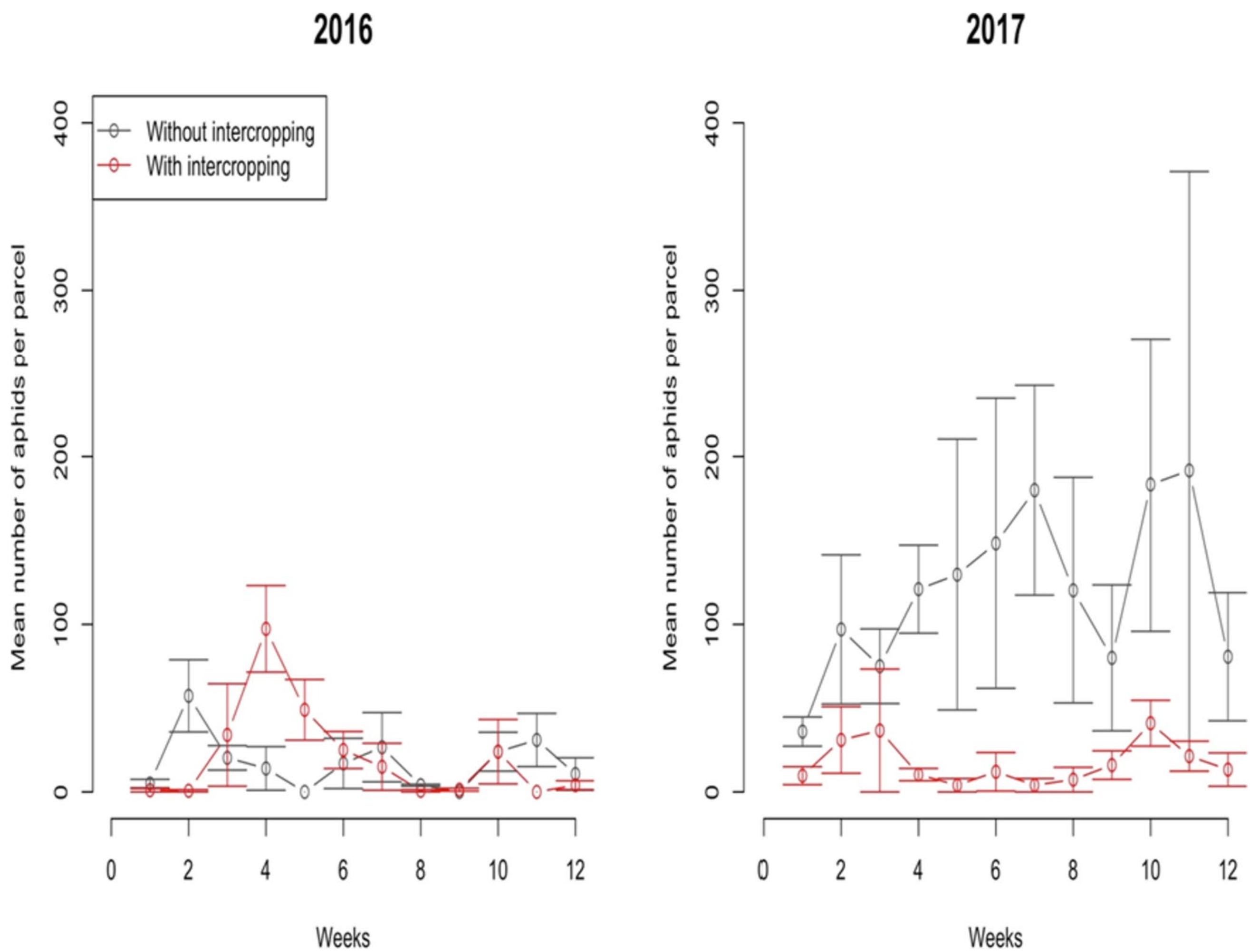

Fig. 1 The variation of aphid populations in coffee with (**a**) and without (**b**) intercropping. We collected data for 12 weeks each year, once weekly. In 2016, aphid populations were the same, and the mean number of aphids per plot was below 100 individuals, while in 2017, aphids remained rare in the intercropping system

Fig. 2 Variation of natural enemy populations (Mean ± Standard Error) on two coffee cropping systems during the experimental period

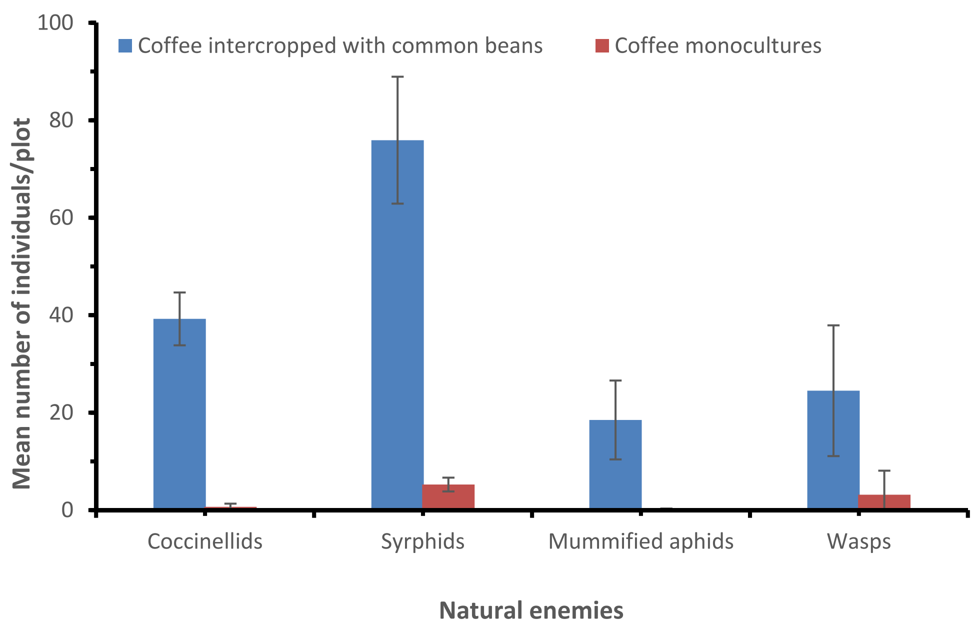

Table 1 Statistical results of the two experimental periods

Main effects and interactions	chisq	df	P	Level of significance
Intercropping	2.435	1	0.11865	NS
Week	60.114	11	$8.831e^{-9}$	***
Year	66.269	1	$3.934e^{-16}$	***
Intercropping*Week	35.662	11	0.0001926	**
Intercropping*Year	34.823	1	$3.611e^{-9}$	***
Week*Year	38.495	11	$6.454e^{-05}$	***

We tested the aphid infestations in intercrop vs. monocultures, infestation overtime (variation in weeks), and period (in years) (Table 1). We also tested the interactions (intercropping vs. week, intercropping vs. year, and week vs. year). They are all significant, as this table shows

wasps. In coffee trees- common bean cropping systems, there is a diverse fauna of insects belonging to families of Coccinellidae, Mantidae, Syrphidae, Formicidae, and Noctuidae. We collected 429 individuals of ladybird beetles in all three coffee-bean intercropping plots representing at least 13 species against 73 individuals belonging to only four species in the coffee monoculture. However, in coffee tree monocultures, the natural enemies are rare and sometimes absent. The findings also reveal that *Cheilomenes sulphurea* (Fabricius) and *C. sulphurea* (Olivier) (Coleoptera: Coccinelidae) species of ladybird beetles and 386 hoverflies (Syriphidae) in our experiments are abundant. (Fig. 2). We observed larvae of coccinellids feeding on aphids. We counted 189 larvae, but it was not easy to identify them at the species level. We also watched many hoverflies (syrphids) moving around in the intercropping systems.

The wasps collected from the three traps are diversified. We collected 110 individuals of Hymenoptera in cropping systems representing seven insect families (Table 2). Among them, there were Vespidae (73), Ormyridae (25), Trichogramidae (5), Evaniidae (3), Braconidae (2) and mummified aphids (214). However, in coffee monocultures, we observed Hymenoptera of the Vespidae family but did not find micro-wasps. We observed mummified aphids but found only eight mummies indicating low parasitisms in coffee trees. During the study, we came to gather almost 222 parasitized aphids, and some of them that we kept in a bottle for future identification emerged into adult micro-wasps (Ormyridae). The results indicated that aphids are more mummified in intercropping systems than in coffee monocultures. We observed three species of ants. We found *Pheidole megacephala* (Fabricius) (Hymenoptera: Formicidae) feeding on honeydew and protecting aphids from predators. Moreover, giant and biting ants, probably decomposers, were found in monocultures and mixed cropping systems.

Discussion

In this research, we aimed at studying agroecological strategies that help farmers deal with the potential aphid pest *T. aurantii* in coffee agroecosystems. Specifically, our research questions were (a) Can the coffee-bean intercropping system manage aphid infestations compared to the coffee monocultures? (b) can natural enemies of *T. aurantii* in the coffee-common bean agroecosystems be abundant and diversified? All two questions aimed to integrate the coffee variety BM71 into polyculture systems to avoid insects that can overcome resistance over time and rescue ecosystem services under pressure from synthetic pesticides. The intercropping and monoculture coffee management systems we tested indicate that aphid infestations are similar in the first year of experiments. In the same context, in France, cereal aphid populations were reduced in one year by intercropping wheat cultivars with winter wheat and white clover (Mansion-Vaquié et al. 2019). It was probably because, during that time, coffee trees were not well-established enough to attract aphids. The infestation can be low in plots with coffee tree-beans intercropping systems which can mitigate virus spread and prevent yield losses. For instance, empirical studies revealed that intercropping lettuce with alyssum controlled aphids in Salinas's USDA-ARS Organic Research farm (Brennan 2013). In the same way, at Miyagi Prefectural Agriculture and Horticulture Research Center in Natori-Japan, intercropping with leafy daikon in cabbage fields controlled pests by interfering with visual or olfactory host plant-finding cues or repelling insects (Sekine et al. 2021). This could be the case for intercropping with beans in coffee trees. Moreover, in Tanzania, experimental studies indicated that aphid populations on coffee trees in intercropping tend to be lower than on sole coffee plants (Lyimo et al. 2017).

The intercropping system diversified and increased natural enemies in coffee trees mixed with beans intercropping techniques (Table 2), with the dominance of *C. aurora*, *C. sulphurea, Declivitata* spp, and wasps of the Vespidae family. The abundance of ladybeetle density was also reported in intercropping peanuts with maize in China and significantly reduced the number of peanut aphids (Ju et al. 2019). Therefore, the abundance and diversification of Coccinelidis in Rwanda's coffee-common beans intercropping system can regulate coffee aphid populations and mitigate pathogens spread. These three ladybird species feed on *A. fabae* (Scopoli 1763) (Hemiptera: Aphididae) on beans (Latigo-Ogenga et al. 1993) and *A. gossypii* (Glover) (Hemiptera: Aphididae) on cotton (Mrosso et al. 2013), while *C. aurora* seems to be able to prey on *Helicoverpa armigera* (Hubner) (Lepidoptera: Noctuidae)

Table 2 Predatory and parasitoid insects identified during experimental plots

Order	Family	Identified species	Intercropping	Monocultures	Reported as
Arachnids	(spiders): Family not identified	-	1 case	–	Predator
Coleoptera	Coccinellidae	*Chilocorus distigma* (Say, 1835)	2	–	Predator
		Chilocorus nigripes (Mader, 1954)	–	1	Predator
		Cheilomenes aurora (Gerstäcker, 1871)	266	41	Pretator
		C. lunata (Fabricius)	20	12	Predator
		C. propinqua (Mulsant,1850)	2	–	Predator
		C. sulphurea (Olivier, 1795)	115	23	Predator
		Declivitata spp	51	–	Predator
		Epilachna spp	34	–	-
		Hyperaspis sp	2	–	Predator
		Hippodamia variegate (Goeze,1777)	3	–	Predator
		Exochomus troberti (Mulsant)	1	–	Predator
		Psyllobora spp	1	–	Predator
		Larvae: unidentified	189	–	Predator
Dictyoptera	Mantidae	*Mantis religiosa* (Linnaeus,1758)	2	–	Predator
Diptera	Syriphidae	*Allograpta* spp	46	–	Predator
		Ocyptamus spp	11	–	Predator
		Unidentified individuals	329		Predator
Lepidoptera	Erebidae	*Eublemma scitula* (Rambur)	1	–	Predator
Hymenoptera	Formicidae	*Macromischoides aculaetus* (Pulchellu)	+	–	-
		Crematogaster spp	+	+	-
		Pheidole megacephala (Fabricius)	+	–	-
	Braconidae	-	2	–	Parasitoid
	Ceraphronidae	-	1	–	Parasitoid
	Evaniidae	-	3	–	Parasitoid
	Mymaridae	-	1	–	Parasitoid
	Ormyridae	-	25	–	Parasitoid
	Trichogrammatidae	-	5	–	Parasitoid
	-	Mummified aphids	222	–	-
	Vespidae	-	73	–	Honeydew collectors and/and predators

We found various beneficial insects: Arachnids, Coleoptera, Dictyoptera, Diptera, Lepidoptera, and Hymenoptera (two species of ants: *P. megacephala* and *Crematogaster* spp were found feeding on honeydew and protecting aphid colonies. We found no co-infestations (more than two pest species on coffee trees)

+: present (it is not easy to count populations of ants); – : absence

larvae in the laboratory (Van den Berg et al. 1993)**.** Altieri and Nicholls (2004) found that plant species, both weeds and non-weeds, are a reservoir of natural enemies of plant pests. Therefore, the diversity of natural enemies of aphids we observed in the intercropping system can be related to the food availability, refuge, and microclimate that intercropping can offer.

These species, *C. stigma*; and *C. lunata* can feed on *Toxoptera spp*. (Michaud 1998), while *Hyperaspis* sp and spiders may feed on *T. aurantii* (Ye et al. 2014). However, the species *Declivitata spp, Epilachna* spp*, and Micraspis sp* found in intercropping systems have not yet been reported as predators of *T. aurantii* at the time of writing this paper. During the experiments, we found ladybird beetles feeding on populations of aphids of beans. It reveals that bean aphids can promote interactions between plants and insects and serve as the food source of natural enemies before *T. aurantii* colonizes coffee trees. In addition, to this assumption of apparent competition, common beans in coffee trees can keep soil moisture and enhance favorable micro-climate, which can explain the diversification of natural enemies we find in the intercropping system (Harelimana et al. 2022)**.** Furthermore, leguminous ground cover suppresses weeds that can harbor pests (Khan et al. 2016), fix atmospheric nitrogen which increases plants's vigor, and provide food, green manure and fodder for domestic animals (Beaupré et al. 2021). In addition to the compost we used, beans as leguminous ground cover enriched soil in nitrogen, possibly impacting the life history traits of coffee aphids. For example, the fecundity of the cereal aphid *Metopolophium dirhodum* (Walker 1849) (Hemiptera: Aphididae) was negatively affected by high nitrogen fertilization in England (Gash 2012). However, the nitrogen and water content were not a limiting factor to the history traits of the walnut aphid *Chromaphis juglandicola* (Kaltenbach) (Hemiptera: Aphididae) (Mace and Mills 2015) or *Myzus persicae* (Hemiptera: Aphididae) (Rousselin et al. 2016). Soil fertility may explain the low aphid infestations we observed on coffee trees intercropped with beans; thus a specific study on responses of *T. aurantii* on nitrogen content can reveal useful information on the management of this aphid species.

The families Braconidae, Ceraphronidae, Evanidae, Myrmaridae, Ormyridae, and Trichogramidae that we collected and identified feed on aphids (Han and Chen 2002; Engel 2013; Reznik et al. 2020). They may also feed on *T. aurantii* and reduce infestations. A diversity of wasps in coffee intercropping approaches was also documented by Pak et al. 2015 who showed that natural enemies were more abundant in complex than in simplified systems in Mexico.

Although it is not the study's primary objective, we harvested 37 kg of beans which is the source of proteins for rural communities unable to acquire animal proteins. Alternatively, the harvest could generate a revenue of RWF 17,500 ($18) (Katungi et al. 2018). For instance, with this amount of money, smallholder farmers can pay their National Health Insurance ($ 3/person/year) (Makaka et al. 2012).The pulses of *P.vulgaris* were so economically important as they can be used for mulching, substrates for mushroom multiplication and the source of energy (firewood) for smallholder farmers.

Conclusions and perspectives

This study can be crucial for developing countries where arable land is scarce and over-exploited due to the exponential population growth and where methods usually applied to control coffee pests rely on insecticide use which is expensive and unaffordable to smallholder farmers. The mixed farming system that rural communities have practiced for many years in maximizing profit on small plots indicates that aphid infestations can be managed in coffee trees mixed with beans. The approach can easily regulate aphid populations in young coffee trees and help farmers get diversified products on the same land simultaneously. There is also a wide diversity of beneficial insects in intercrop experimental parcels. These traditional practices are thus encouraged, but they need regular follow-up to ensure their application is improved. More data should be collected on such systems to understand the mechanisms better and to determine their resilience in the long term under changing environmental conditions. The insect-plant interaction is complex and indicates the need for further research to assess the effect of intercropping systems on beneficial soil arthropods and soil fertility. In the future, it should be of particular interest to focus on the parasitoids we found in intercropping systems and to identify them to species. Finally, a comparative study to clarify the cost–benefit analysis in terms of biodiversity conservation between monoculture and intercropping systems is essential to help farmers choose a promising and sustainable approach. As crops in intercropping systems compete for resources for example light and nutrients, it is very important to use the Land Equivalent Ratio (LER) to compare the two coffee farming systems.

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Declarations

Competing interest The authors have no conflicts of interest directly or indirectly related to this work.

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