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Intercropping on French farms: reducing pesticide and N fertiliser use while maintaining gross margins

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Abstract

Experimental studies to date have demonstrated the agronomic and environmental benefits of intercropping, making it a key diversification method for reducing chemical inputs in agriculture. However, intercropping is still a niche practice in European cropping systems, particularly for arable crops. Few studies have focused on farmers' perspectives or used farm data to assess the on-farm performances of intercropping. Here, we present an analysis of data collected from farms of the DEPHY network, a demonstration farm network that aims to show that pesticide reduction is possible through changes in farming practices. We focused our study on four main species in France: winter wheat (*Triticum aestivum L.*), winter barley (*Hordeum vulgare L.*), pea (*Pisum sativum L.*) and rapeseed (*Brassica napus L.*). We carried out paired comparison tests between sole crops and intercrops for each species to compare the use of pesticides (herbicides, fungicides, insecticides and all pesticides combined), mineral nitrogen fertiliser and the gross margin between the sole crop and the intercrop. We showed that pesticide use was reduced on average by 50% in the case of wheat- and barley-based intercrops compared with sole wheat and barley crops, respectively. Pesticide use for peas was reduced by 83% on average. Nitrogen fertiliser use was also reduced by up to 50% for wheat. On the other hand, in the case of rapeseed, which is mainly intercropped with unharvested companion plants, we found no significant differences in pesticide or fertiliser use between the sole crops and intercrops. This suggests that farmers must choose companion plants carefully depending on their objectives and desired services. Finally, our results show that crop mixtures do not negatively affect gross margins and can even improve them; intercropped peas in particular showed an average 16-fold increase in gross margins.

Keywords: crop mixtures; crop diversification; arable crops; cropping systems; agricultural practices; Treatment Frequency Index

1 Introduction

Intensive and specialised agriculture primarily uses chemical inputs that harm human health (Tudi et al., 2021; WHO, 1990) and the environment, e.g., by eroding biodiversity and degrading water and soil quality (Matson et al., 1997; Tilman et al., 2002). Meeting the global demand for food and feed while reducing the negative impact of agriculture on the environment is a major present-day challenge. Diversifying agricultural systems is a suitable strategy to achieve these objectives as it enables the restoration of ecosystem services (Beillouin et al., 2021; Lin, 2011; Raseduzzaman & Jensen, 2017) and reduces dependence on chemical inputs, such as fertilisers and pesticides.

Intercropping, which consists of growing two or more crop species simultaneously on the same field (Willey, 1979), is a promising diversification practice. Experimental studies have shown that intercropping can improve weed control in arable farming by improving soil cover and competition (Corre-Hellou et al., 2011; Hauggaard-Nielsen & Jensen, 2005). The morphological and physiological differences between the cultivated species can create barriers that limit the spread of diseases and pests (Boudreau, 2013; Finckh et al., 2000). Intercropping further improves crop quality, particularly in the case of cereal–legume associations, by increasing the amount of mineral nitrogen available in the soil and, therefore, the protein content in cereal seeds (Bedoussac et al., 2015; Li et al., 2023). In some cases, intercropping can stabilise or even increase yields (Lithourgidis et al., 2011; Malézieux et al., 2009). According to experimental results, intercropping is a relevant lever for reducing the use of chemical inputs while maintaining a certain quality and quantity of production (Bedoussac et al., 2015; Lithourgidis et al., 2011). Intercropping could also substantially contribute to achieving the goals of Ecophyto, the French National plan to reduce pesticide use by 50% by 2025. This plan was developed under the framework of the European Directive 2009/128/EC and encourages the demonstration of good farming practices to reduce dependence on pesticides.

Despite all its advantages, intercropping is still a niche practice in France as well as in Europe (Mamine & Farès, 2020; Timaeus et al., 2022), particularly in non-organic farming (Verret et al., 2020). According to Land Parcel Identification System data (IGN, 2023), intercropping accounted for only 3% of French arable land in 2020. Several factors seem to limit the spread of intercropping, including technical difficulties linked to sowing, harvesting and sorting crops on farms (Mamine & Farès, 2020; Timaeus et al., 2022; Verret et al., 2020); economic issues due to limited outlets when cooperatives do not collect grain mixtures because they are not equipped to sort grains (Bedoussac et al., 2015; Mamine & Farès, 2020); and farmers' psycho-social reluctance to adopt such an innovation (Bonke et al., 2021; Bonke & Musshoff, 2020).

Though addressing these obstacles to the broader adoption of intercropping is necessary, it is also crucial to understand how farmers manage crop mixtures in practice and whether on-farm intercropping actually delivers the advantages demonstrated by field or plot experiments. Recent research based on farmer interviews, such as Enjalbert et al. (2019) and Verret et al. (2020) in France and Timaeus et al. (2022) in Germany, has moved towards understanding farmers' satisfaction with intercropping. These qualitative studies aimed to show the diversity of intercrops effectively grown and highlight the obstacles to their adoption but included only small samples of farmers.

To our knowledge, apart from field trials, no study has yet verified the performance of crop mixtures on farms, looking at both inputs (pesticides and fertilisers) and production factors. This paper presents a quantitative study of the effects of intercropping on pesticide use, nitrogen fertilisation and gross margins of major crops in France based on data collected from farms across the country. Our analysis aimed to show the effects of intercropping under actual farming conditions and highlight this practice's agronomic and environmental benefits.

2 Material and methods

2.1 Data from a demonstration farm network: The DEPHY network

The DEPHY network is a French nationwide demonstration farm network created in 2010 as part of the Ecophyto National Plan. The DEPHY network aims to demonstrate that reducing the use of pesticides is possible through changes in agricultural practices. The network started with 178 farmers at its inception, and by 2016, more than 3000 farmers had joined and committed to reducing their pesticide use. The network covers seven major French production sectors (i.e., arable field crop, crop–livestock mixed farming, vegetables [both outdoor and protected], ornamental crops, tropical crops, viticulture and arboriculture). Participating farmers are gathered into local groups of 10 to 15 and regularly share their experiences with each other. One cropping system per farm is monitored and described year after year. Information on crops grown and management details, such as fertilisation, pesticide use, tillage and economic performance, is collected and entered into a database (the AGROSYST Information System). The database used for this study included 27,711 farm–years between 2010 and 2023.

2.2 Crop species

We focused our study on four of the most cultivated crops in France that may also be grown as intercrops: winter wheat (*Triticum aestivum L.*), winter barley (*Hordeum vulgare L.*), peas (*Pisum sativum L.*) and rapeseed (*Brassica napus L.*). According to the French annual agricultural statistics (Agreste, 2020), winter wheat (referred to as "wheat" hereafter) was the most cultivated crop in France in 2020, covering approximately 34% of the country's total arable crop area. Winter barley (referred to as "barley" hereafter) was the third most cultivated (behind maize) with approximately 10% of the arable crop area. Rapeseed was the most cultivated oilseed crop and peas were the most cultivated protein crop, with 9% and 2% of the arable crop area, respectively.

Because the DEPHY network aims at reducing pesticide use, farmers belonging to the network are likely to implement multiple practices to this end. Therefore, reductions in pesticide use cannot be easily attributed to a single practice – in our case, intercropping. To ensure that any differences in pesticide use, nitrogen fertiliser use, and gross margin actually resulted from intercropping, we compared the intercrops involving wheat, barley, peas or rapeseed with their corresponding sole crop (i.e., sole wheat, barley, peas or rapeseed) grown in cropping systems in which we noted similar characteristics.

2.3 Selection and characterisation of the cropping systems

We focused our analysis on two production sectors out of the seven available in the DEPHY database: the arable field crop and crop–livestock mixed farming, as these production sectors included wheat, barley, peas and rapeseed. Inspired by the work of Lechenet et al. (2016), we selected cropping systems with wheat, barley, peas and rapeseed either intercropped or as sole crops and, from the database, computed 36 agronomic variables that may affect the use of pesticides. These variables concern diversity in the crop sequence (e.g., proportion and number of different crops), length of the crop sequence, sowing periods, tillage and irrigation and are detailed in Table S1.

Organic farms were excluded due to the restricted use of chemical pesticides, which would have introduced bias in our analysis. Moreover, we excluded farms with incomplete information on crop succession and sowing operations. Finally, our dataset was narrowed down to n=2252 cropping system–years (1067 for arable field crops, 1185 for crop–livestock mixed farming) fully described by the 36 selected agronomic variables.

2.4 Paired comparison and statistical analysis

The intercrop–sole crop pairs were selected using the Euclidean distance between cropping systems. First, we calculated a matrix of Euclidean distances (function “dist”, R package “stats”, R-software version 4.1.3) between cropping systems based on the 36 agronomic variables (Table S1). In the DEPHY database, pesticide use for wheat, barley and rapeseed is generally lower in crop–livestock mixed farming than in arable field crop farming (Figure S1). Therefore, we paired each cropping system that included an intercrop with the closest cropping system that included the corresponding sole crop based on the minimal distance within the same production sector (arable field crop or crop–livestock mixed farming). For example, each wheat-based intercrop grown in a crop–livestock mixed farm was compared with the sole wheat crop from the least-distant cropping system in another crop–livestock mixed farm.

Some intercrops had several corresponding sole crops with the same minimal distance. Considering all the possible couples in our analysis would have biased the results as it would have multiplied the observations from the same intercrop, thus over-estimating the effects of the intercrop. To avoid such biases, we chose to perform the analysis on each possible combination and evaluate the deviation between these combinations. For example, if an intercrop had two possible corresponding sole crops (i.e., with the same minimal distance to the intercrop), we created a dataset for each and performed the analysis (i.e., the paired comparisons for pesticide use, nitrogen fertilisation and gross margin, detailed hereafter) on each dataset. Then, we calculated the coefficient of variation between the results of each of the two analyses to test the variability of the datasets. Figure 1 illustrates this methodology using an example with three intercrops: intercrop A is paired with sole crop A1, and intercrops B and C both have two possible sole crops to pair with (sole crops B1 and B2, and sole crops C1 and C2, respectively). In this example, there are four possible combinations, leading to four datasets on which the analyses would be performed.

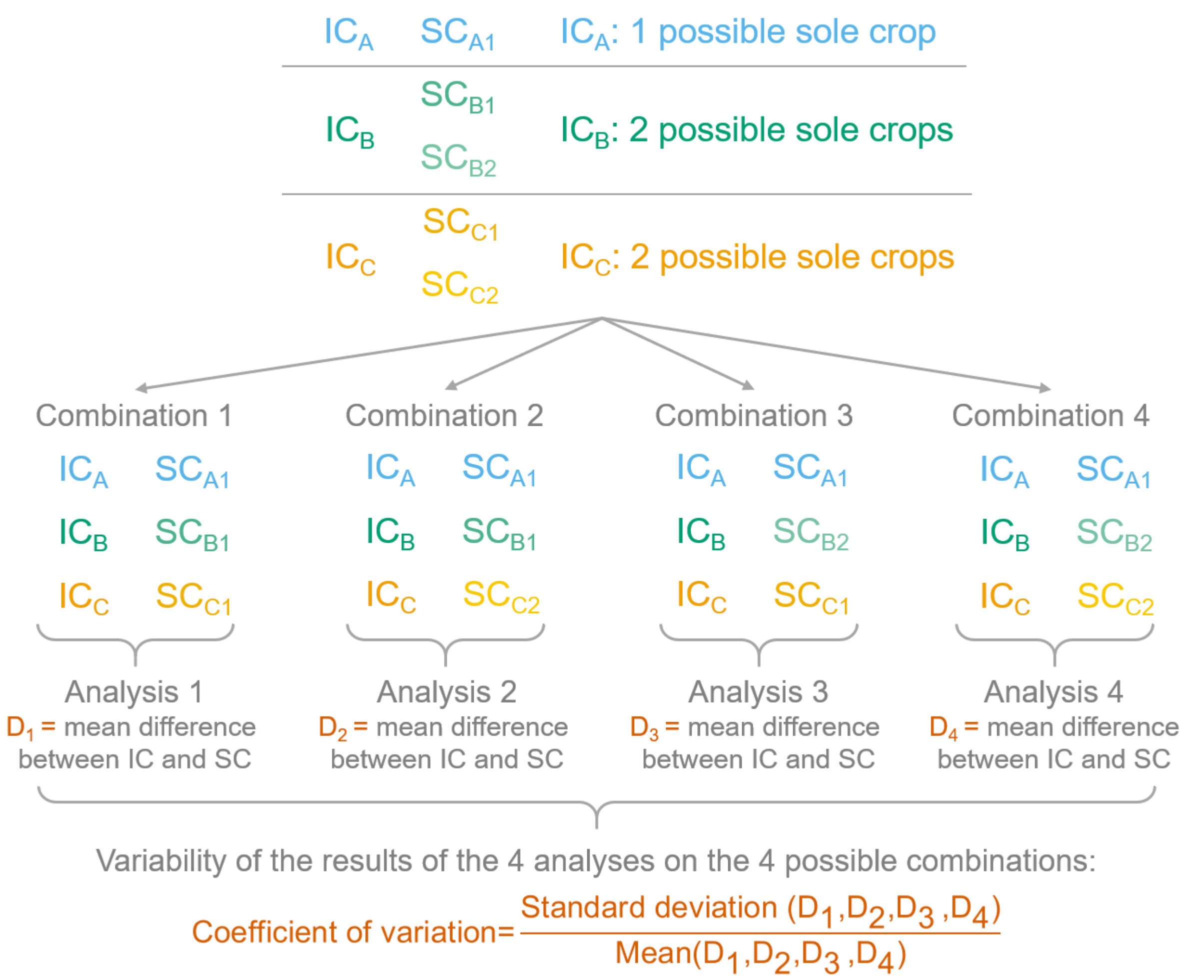

Figure 1: Methodology used to test the variability of the datasets when one intercrop (IC) could be paired with several equidistant sole crops (SCs)

We obtained two possible combinations for wheat (one intercrop had two equidistant sole crops), one for barley (each intercrop only had one sole crop at the minimal distance), 512 for peas (five intercrops had two to four equidistant sole crops) and 225 for rapeseed (four intercrops had three to five equidistant sole crops). In each possible combination, we had 16 pairs for wheat, 12 for barley, 30 for peas and 31 for rapeseed. Table 1 reports the number of intercrops and sole crops for each farming sector.

Table 1: Number of farm–years with sole crops and intercrops involving wheat, barley, peas or rapeseed, and number of intercrop–sole crop pairs used to perform the analysis.

	Wheat	**Barley**	**Peas**	**Rapeseed**
Number of cropping systems with sole crops	1813	936	122	860
- field crop production system	881	465	90	491

- crop–livestock production system	932	471	32	369
Number of cropping systems with intercrops	16	12	30	31
- field crop production system	4	4	5	21
- crop–livestock production system	12	8	25	10

Using those pairs, we compared pesticide use, fertiliser inputs and gross margins between intercrops and sole crops. We used the Treatment Frequency Index (TFI) as a metric for pesticide use. This index is used to monitor the frequency and intensity of pesticides applied at different spatial scales (e.g., crop, cropping system, groups of cropping systems). In our study, we considered the TFI at the crop scale following Pingault et al. (2009):

$$TFI = \sum_{T} \frac{Applied\ Dose_T}{Reference\ Dose_T} * \frac{Treated\ area_T}{Total\ area_T}$$

For each treatment *T* on the considered crop, the applied dose per hectare is normalised to the reference dose per hectare. The crop-scale TFI is then calculated as a weighted sum of all normalised doses for the considered crop, with weights being the ratio of the treated area over the total area of the considered crop. The reference dose we used to compute TFI was the registered dose for the plant protection product on the considered crop for the targeted pest/weed/disease, based on the marketing authorisation database (E-Phy, ANSES, 2023). Our study used TFI computed for four distinct categories:

- All types of pesticides (e.g., herbicides, fungicides, insecticides, seed coating, fumigants, molluscicides), excluding biopesticides and "low-risk" pesticides according to French legislation
- All herbicides, excluding biopesticides and "low-risk" pesticides according to French legislation
- All fungicides, excluding seed coating, biopesticides and "low-risk" pesticides according to French legislation
- All insecticides, excluding seed coating, biopesticides and "low-risk" pesticides according to French legislation

We used the total amount of mineral nitrogen applied to the crop during the whole growing period (in kg N ha^{-1}) as a metric for fertilisation inputs.

We used the gross margin (€ ha^{-1}) as a metric for crop profitability, defined as:

$$Gross\ margin = Gross\ product - Operating\ costs$$

where the gross product is the product of yield and selling price (provided by the database user) and operating costs include, e.g., seed, seed coating, fertilisation, pesticide and irrigation costs. In the database, crops that were self-used on the farm (e.g., for animal feed) were assigned a gross product value corresponding to the value they would have had if they had been sold. In order to compare gross margins between farms that may have different levels of self-use, the farm gross margin was calculated taking into account both the self-used and the sold parts of the production. We chose to analyse the gross margin rather than the gross product because we assumed that intercrops can affect the gross product (by affecting yields) as well as the operating costs, and the gross margin better reflects the balance between the effects of intercropping on the gross product and those on the operating costs.

Finally, we compared the TFI, N fertilisation and gross margin between the sole crops and intercrops using paired t-tests. This test compares two groups of observations with the specification that an observation from one group is paired with another observation from the other group. Figure 2 recapitulates the study methods, from cropping system selection to data analysis.

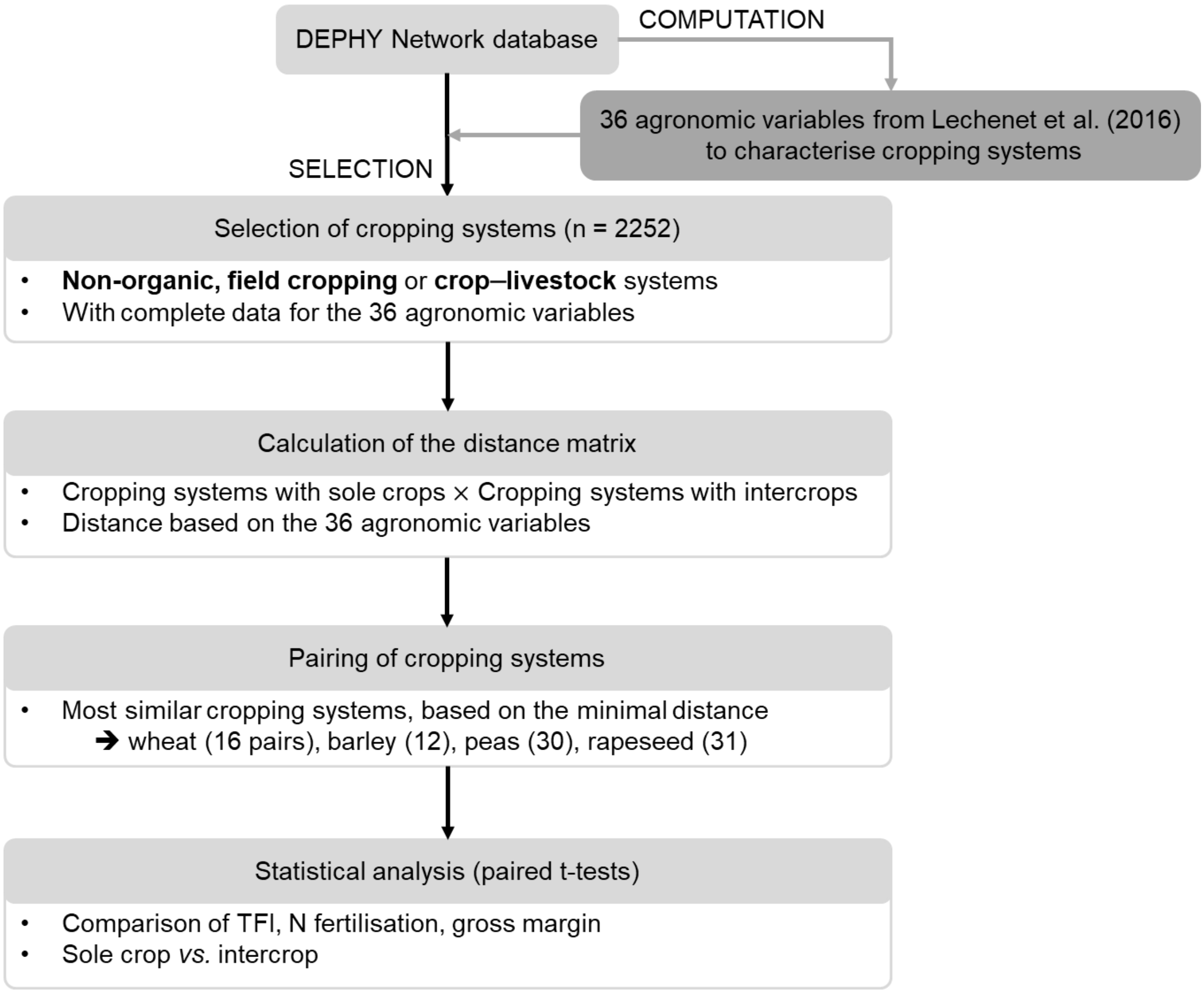

Figure 2: Flowchart of the study methods, from data selection and pairing to statistical analysis. TFI, treatment frequency index; N, nitrogen.

3 Results

In this section, we first present the results of the analyses conducted over all possible combinations between intercrops and sole crops for the studied crops. Then, we present the results of the paired comparisons of TFI, N fertilisation and gross margin for one combination. In the following, an increase (or decrease) in an indicator refers to an increase (or decrease) in that indicator for the intercrop compared with the corresponding sole crop.

3.1 Variability of intercrop–sole crop combinations

To assess the variability of our results, we computed the coefficient of variation of the mean intercrop − sole crop difference over all the possible combinations (Figure 1) for each species and indicator (TFI, N fertilisation, gross margin). Between the two possible combinations for wheat crops, the coefficient of variation for TFI varied from 0% for insecticides to 1.98% for fungicides. The coefficient of variation for N fertilisation of wheat was 0.09%, and that for the gross margin was 0.98%. For the 512 combinations of pea crops, the coefficients of variation were 0%, 1.15% and 0.42% for TFI, N fertilisation and gross margin, respectively. For the 225 combinations of rapeseed crops, the coefficients of variation were 0% for both the TFI and N fertilisation and 4.34% for the gross margin. Barley had a unique combination, so calculating a coefficient of variation was not relevant in this case.

For wheat and peas, the p-values were homogeneous for all indicators across all the different combinations, which means that the significance of the results was stable across the combinations ($p<0.01$). For rapeseed, the results were not significant for the TFI and N fertilisation ($p>0.05$), but they were significant for the gross margin in 136 of the 225 combinations ($p<0.05$). Overall, we found little variability in the results across the different combinations. Therefore, in the following sections, we present the results for a random combination of wheat, peas and rapeseed, and we present the results of the unique combination of barley.

3.2 Pesticide use

Our results show a significant overall reduction in the TFI for intercrops compared with sole crops for wheat, barley and peas (Figure 3). Considering all the pesticide categories, TFI was reduced on intercropped wheat by −1.46 (or −49.5%, $p<0.01$) on average compared with sole wheat (Figure 6). This reduction was of a similar magnitude for intercropped barley compared with sole barley crops (−1.80 or −49.7%, $p<0.001$) and was the highest for intercropped peas compared with sole pea crops (−3.34 or −83.2%, $p<0.01$) (Figure 6). We also noticed that the interquartile range for intercropped pea TFI was much smaller than that of sole peas, though we did not observe such a difference between sole crops and intercrops for the other species (Figure 3). Rapeseed sole crops and intercrops showed no significant difference in the TFI.

The herbicide TFI in intercrops was significantly reduced for wheat (−0.52, $p<0.01$), barley (−0.57, $p<0.01$) and peas (−0.99, $p<0.001$) compared with sole crops (Figure 6). We noted an increase of +0.27 in the herbicide TFI for rapeseed cultivated in intercrops (Figure 6). However, this increase was not significant ($p>0.05$).

A reduction in the fungicide TFI was observed for all intercrops, though this reduction was not significant for wheat and rapeseed ($p>0.05$). The fungicide TFI was reduced by −0.84 ($p<0.01$) for barley and −1.19 ($p<0.001$) for peas, which resulted in an average fungicide TFI close to 0 for barley- and pea-based intercrops (Figure 6).

For insecticides, our results showed no significant difference in the TFI for wheat, barley and rapeseed (p>0.05), but we observed a significant average reduction of −0.485 (p<0.01) for peas (Figure 6).

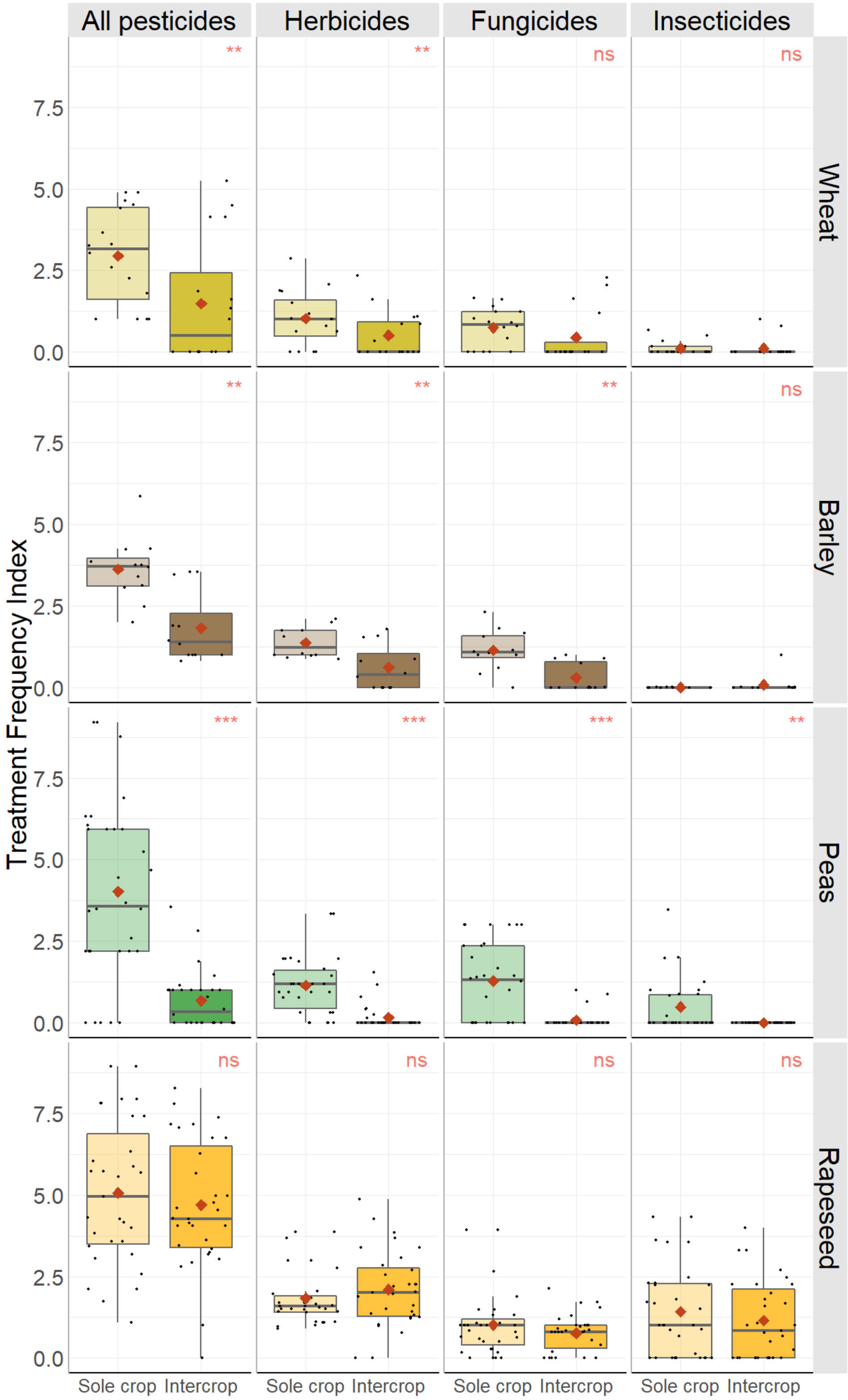

Figure 3: Treatment Frequency Index for wheat, barley, pea and rapeseed sole crops and intercrops. The boxplots are based on the TFI values for each individual in each group. The significance codes (ns = $p>0.05$; * = $p\leq0.05$; ** = $p\leq0.01$; *** = $p\leq0.001$) apply to the paired t-test results. The red diamonds show the mean values.

3.3 Nitrogen fertilisation

Our results show a significant reduction of −72.2 kg N ha^{-1} (or −46.8%) applied to intercropped wheat (Figure 6). Although not statistically significant ($p>0.05$), we observed an average reduction of −11.8 kg N ha^{-1} (or −12.3%) for intercropped barley compared with sole barley crops (Figure 6). Peas, on the other hand, showed a significant increase of +45.8 kg N ha^{-1} ($p<0.001$) (Figure 6) for intercrops compared with sole crops, which received an average of 6.8 kg N ha^{-1} (Figure 4). For rapeseed, the results did not show any significant difference ($p>0.05$) between fertilisation on intercrops and sole crops. However, we observed lower variability in the amount of mineral nitrogen applied to intercrops versus sole crops (Figure 4).

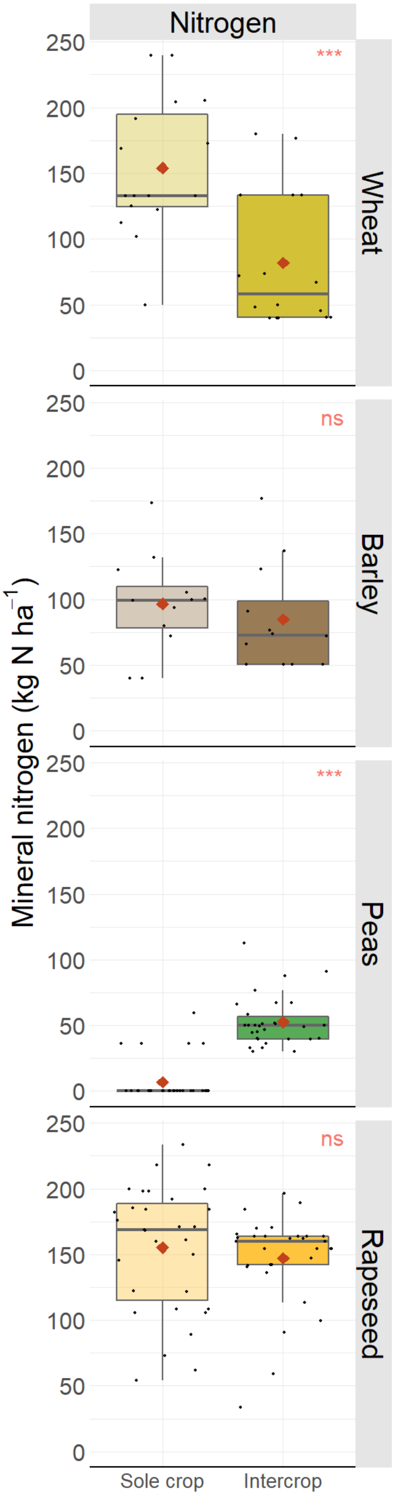

Figure 4: Amount of mineral nitrogen applied to sole crops and intercrops for wheat, barley, peas and rapeseed. The boxplots are based on the amount of mineral nitrogen applied to each individual in each group. The significance codes (ns = $p>0.05$; * = $p\leq0.05$; ** = $p\leq0.01$; *** = $p\leq0.001$) apply to the paired t-tests. The red diamonds show the mean values.

3.4 Gross margin

Our results show reductions in the gross margin for intercropped wheat (−184 € ha^{-1} on average, or −17.1%) and barley (−97 € ha^{-1} on average, or −14.7%) and an increase in the gross margin for intercropped rapeseed (+327 € ha^{-1} on average, or +40.9%), but these differences were not significant ($p>0.05$) (Figure 6). However, the gross margins for intercropped wheat and barley had lower variability than the corresponding sole crops (Figure 5). For peas, we observed a significant increase of 711 € ha^{-1} (or + 1514%, $p<0.001$) for intercrops compared with sole crops (Figure 6).

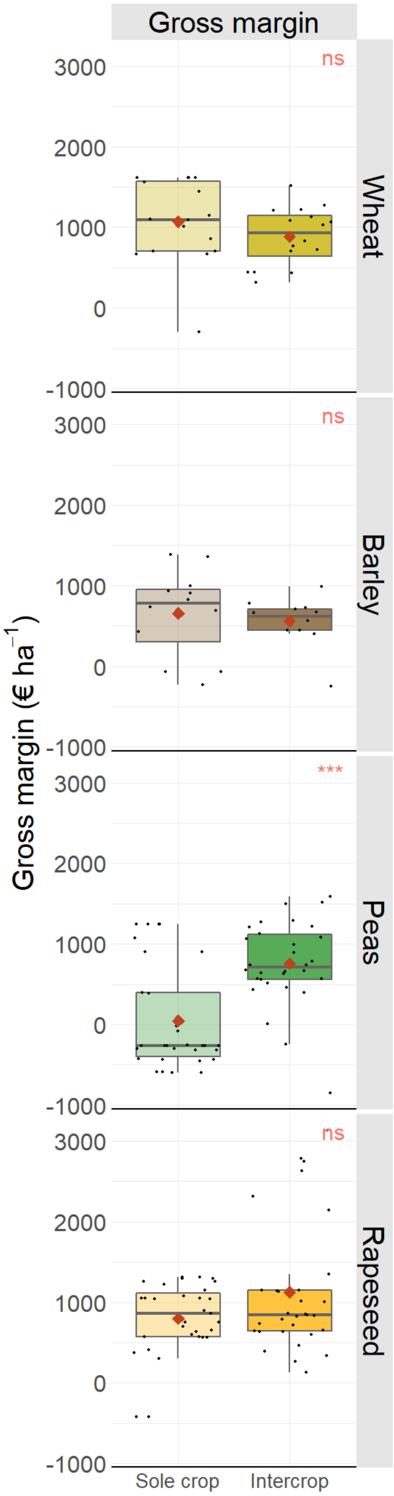

Figure 5: Gross margin of sole and intercropped wheat, barley, peas and rapeseed. The boxplots are based on the gross margin of each individual in each group. The significance codes (ns = p>0.05; * = p≤0.05; ** = p≤0.01; *** = p≤0.001) apply to the paired t-tests. The red diamonds show the mean values.

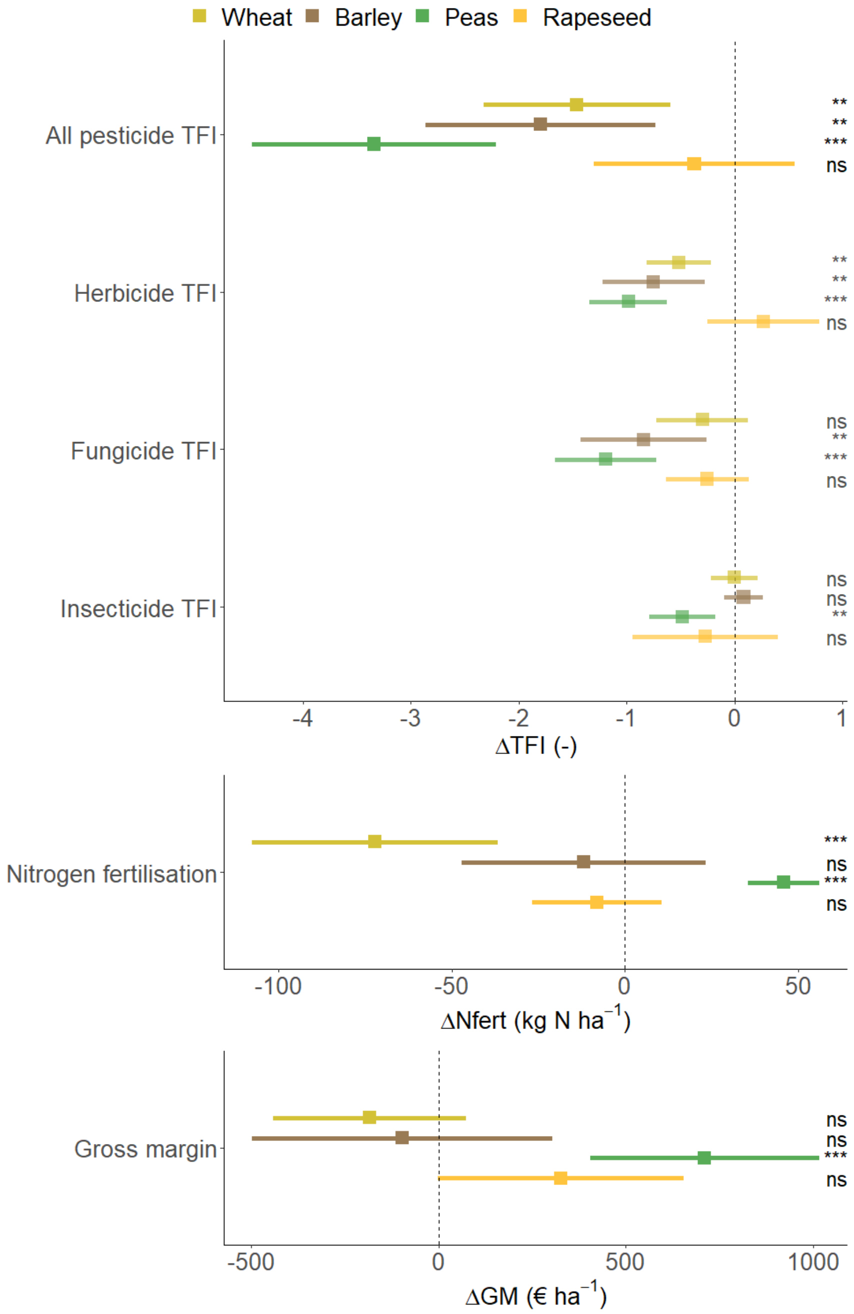

Figure 6: Average difference between the sole crop and intercrop groups for the Treatment Frequency Indexes (ΔTFI), nitrogen fertilisation (ΔNfert) and gross margins (ΔGM), estimated by the paired t-tests. Points represent the average difference and lines represent the 95% confidence intervals. A negative value indicates a reduction in the intercrop group compared to the sole crop group. The significance codes (ns = $p>0.05$; * = $p\leq0.05$; ** = $p\leq0.01$; *** = $p\leq0.001$) apply to the paired t-tests.

4 Discussion

4.1 Limited number of situations

Our data show a limited number of non-organic farms growing wheat-, barley-, pea- or rapeseed-based intercrops. The majority of the wheat, barley and pea intercrops studied were grown in crop–livestock mixed farms. Verret et al. (2020) and Timaeus et al. (2022) observed similar repartitions, which can be explained by the sorting difficulties that hinder the adoption of intercrops in arable field crop farming (Mamine & Farès, 2020). On the contrary, most of the rapeseed-based intercrops studied were grown in arable field crop farms. This difference can be explained by the nature of the intercrops: rapeseed is mainly intercropped with companion plants that are not harvested, so sorting difficulties are less critical.

4.2 Effects of intercropping on pesticide use

We showed that intercropping enabled TFI reductions of 50% for wheat- and barley-based intercrops and 83% for pea-based intercrops. The overall TFI was, on average, 1.5 for intercropped wheat, 1.8 for intercropped barley and 0.7 for intercropped peas (Figure 3), which are below the national averages of 5.1 for wheat, 4.4 for barley and 4.6 for peas in France, according to the 2017 "Pratiques culturales" (cropping practice) national survey (Agreste, 2017). Though our results do not show a significant overall reduction in the TFI for intercropped rapeseed, the average TFI (4.7) was still lower than the national average of 5.7 (Agreste, 2017). It is also worth noting that in the DEPHY data, the average TFIs for pure stands of wheat, barley and peas were lower than the national average, whereas the TFI for pure rapeseed in arable field crop farms in the DEPHY data was equal to the national average (Figure S1).

Our analysis showed a reduction in herbicide use for intercropped wheat, barley and peas. One reason for this might be that the number of available herbicide molecules that are selective for both/all mixed crops and can efficiently control weeds is often limited (more limited than for sole crops). Moreover, in our data, wheat and barley were often mixed with legumes, such as peas, thus creating an intercrop highly competitive with weeds (Corre-Hellou et al., 2011; Gu et al., 2021; Hauggaard-Nielsen et al., 2008). Wheat, barley and peas were also involved in more complex mixtures with at least another cereal and/or legume (e.g., wheat–triticale–oat–pea–vetch; Table S2). Such intercrops have a high coverage potential that can help suppress weeds (Pelzer et al., 2014), thus reducing the need for herbicides. Grown as a sole crop, peas have low competitive ability against weeds (Lemerle et al., 1995). Our results confirmed that intercropping peas can foster stronger competitiveness against weeds: of the 30 sole pea crops studied, 25 received herbicide treatments, whereas only seven intercropped peas were treated with herbicide. As for rapeseed, we did not observe a significant difference in herbicide use, although it seems that in some cases, more treatments were applied to intercropped rapeseed than sole rapeseed crops. In our dataset, rapeseed was mainly intercropped with legume companion plants that are not harvested (e.g., faba beans, white clover and/or common vetch). Companion plants can help reduce weeds in rapeseed crops but cannot totally suppress weeds (Lorin et al., 2015; Verret et al., 2017), and some plants have better control over weeds than others. According to Emery et al. (2021), spring faba beans and clover are better suited to controlling weeds than winter faba beans and peas. Herbicides are then likely to be used if the farmer is unsatisfied with the weed control provided by the companion plant (Verret et al., 2020). Moreover, though most companion crops are frost-sensitive legumes, frost may not be enough to destroy them, so chemical weeding may still be necessary.

Our results show a net reduction in fungicide use for wheat-, barley- and pea-based intercrops. Although the reduction was not significant for wheat, we found that of the 16 sole wheat crops studied, nine were treated with fungicides, whereas only four wheat intercrops received fungicides. Notably, no wheat–legume intercrops received fungicides. Eleven of the 12 sole barley crops studied received a fungicide treatment, whereas only four barley intercrops were treated with fungicides. Only three pea intercrops were treated with fungicides (vs. 19 sole pea crops). These observed reductions in fungicide treatments are consistent with the barrier effect created by the species mixtures, which limit the spread of diseases (Boudreau, 2013; Finckh et al., 2000). We did not observe any differences in fungicide treatments in rapeseed intercrops versus sole crops. According to Cadoux & Sauzet (2016), no study has yet shown the effect of companion plants on rapeseed diseases. Furthermore, the barrier effect observed in wheat-, barley- and pea-based intercrops is less likely to work for rapeseed because the rapeseed companion plants are destroyed (either by frost or weeding, usually during the winter) and cannot mechanically protect the rapeseed until the end of its growing cycle.

We did not observe any decrease in the insecticide TFI, except for pea-based intercrops. The insecticide TFI was already close to zero in the wheat and barley sole crops and could therefore hardly be decreased by intercropping. Insecticide treatments for cereals, such as wheat and barley, are primarily done through seed coating, which was not included in our insecticide TFI metric. Our data (Table S2) show that of the 16 pure wheat stands, 13 were sown using coated seeds, and the remaining three, which were not sown using coated seeds, received an insecticide treatment. Among all the wheat-based intercrops, six were sown using coated seeds, whereas none of the wheat–legume intercrops (n=9) used coated seeds. Barley seed coating was used for both sole crops and intercrops (10 in each case). Regarding peas, we observed a reduction in the insecticide TFI for intercrops, which suggests that the mixture may have helped establish natural predators of pea pests (Puliga et al., 2023) and/or created a barrier effect (Ratnadass et al., 2012). For rapeseed, there was no difference in the insecticide TFI between sole crops and intercrops. The effects of companion plants on rapeseed pests in the literature are nuanced: although companion plants can favour natural predators and create a barrier or even a repellent effect, these effects may not necessarily be sufficient to reduce the use of insecticides (Cadoux et al., 2015). Furthermore, depending on the chosen companion plants, the effects on insects are not always beneficial. In an experiment by Emery et al. (2021), faba bean companion plants did not reduce the damage caused by pollen beetles compared with sole rapeseed crops, and the association with berseem clover even resulted in more significant damage. Lastly, the rapeseed–companion plant association can be effective against adult cabbage stem flea beetles but not always against larvae (Breitenmoser et al., 2020).

4.3 Effects of intercropping on mineral nitrogen fertilisation

Our results showed a 50% reduction in the amount of mineral nitrogen applied to intercropped wheat compared with sole wheat. This result is in line with other research showing that cereal–legume combinations enable better use of soil nitrogen (e.g. Jensen et al., 2020; Rodriguez et al., 2020). However, this decrease was less marked for intercropped barley. Although fertilisation needs can be reduced by cereal–legume intercrops, depending on the farmer's objectives, mineral fertilisation can be employed as an adaptation tool. If they aim to obtain fodder, then even a small amount of nitrogen will result in higher productivity for a barley–pea intercrop, as Cowden et al. (2020) reported. If the farmer needs to grow a larger proportion of cereals than legumes, then applying mineral nitrogen will negatively affect biological nitrogen fixation by the legumes, reducing their growth (Ghaley et al., 2005; Naudin et al., 2010). This also explains the increase in nitrogen applied to intercropped peas in our results, whereas no application was necessary for sole pea crops. Conversely, one of the main advantages of combining rapeseed with companion plants is that the mineralisation of the companion plant improves the nitrogen nutrition of the rapeseed (Cadoux et al., 2015; Lorin et al., 2016). However, our analysis did not show any significant reduction in the amount of nitrogen applied to the intercropped rapeseed, though it was reduced for 22 of 31 rapeseed intercrops. The need for fertilisation can be highly dependent on various factors, such as the date of the destruction of the companion plant (the use of herbicides can lead to later destruction than by frost, thus reducing the period of mineralisation of the companion plant), the soil mineral nitrogen content and the species chosen as companion plants (Lorin et al., 2016). However, for the 22 cases where nitrogen fertilisation was reduced, the average reduction was 35 kg N ha^{-1} (Figure 4). This finding is consistent with the results of Lorin et al. (2016), which show that choosing the best legumes for the circumstances can reduce nitrogen fertilisation by 20–40 kg ha^{-1}. This reduction is also close to that of 30 kg N ha^{-1} observed by Cadoux et al. (2015).

4.4 Effects of intercropping on gross margins

For wheat, there were only four cases out of 16 in which the gross margin of the intercrop was better than that of the sole crop, thanks to improved gross production and lower production costs for the intercrops (Table S2). This may be linked to the intercrops' greater resilience to weeds and diseases (Li et al., 2023), possibly resulting in a reduction in herbicide and fungicide use. Otherwise, in most cases, gross production was lower in intercrops than in sole crops. However, lower production costs compensated for this reduction, so there was no significant gross margin loss. Conversely, in the case of barley, a possible increase in intercropping production costs was offset by higher gross production, which limited the reduction in the gross margin or even improved it. For peas, we observed a significant increase in the gross margin of intercrops compared with sole crops. In 19 of the 30 cases, the increase was linked to both higher gross production and lower production costs. Pea production can be improved in intercrops thanks to the staking function of cereals, which limits the lodging of the pea and therefore allows for a better harvest (Kontturi et al., 2011; Verret et al., 2020). The reduction in pesticide-related costs partly offset the increase in nitrogen-related costs.

We observed higher gross production for intercropped rapeseed in 18 of the 31 cases (Table S2). In 17 cases, this resulted in a higher gross margin (even with additional production costs in seven cases). We did not observe any significant differences in the use of pesticides or nitrogen fertilisation between rapeseed intercrops and sole crops, but intercropping rapeseed tended to improve GMs. Depending on the farmers' objectives, rather than reducing inputs, intercropping rapeseed with companion plants could be a lever for improving production without changing crop management practices. However, some farmers who grew rapeseed with companion plants to promote biocontrol and limit pesticide use eventually abandoned the practice as they did not consider it effective enough in this respect (Verret et al., 2020).

4.5 Limitations of the study

Our study compared sole crops and intercrops grown under conditions that were as similar as possible. The DEPHY data did not allow us to locate the crops more precisely than at the municipal level, so we could not combine our data with additional soil data. We also could not construct intercrop–sole crop pairs based on climate, soil or seasonal pest pressure. As a result, the paired intercrops and sole crops were in municipalities distant of 250 km on average, which might have generated statistical noise but we assume that by comparing sole crops and intercrops grown under similar farming practices, we limited bias in our analysis. Nevertheless, our study showed an overall reduction in TFI for intercrops compared with sole crops for wheat, barley and peas, suggesting that intercrops effectively reduced pesticide use in different soil and climate contexts. Finally, farmers' decisions regarding inputs are not conditioned solely by the agronomic variables we used: social aspects, particularly those concerning both the farmer and their farm, can influence these decisions (Darnhofer et al., 2012; Salembier et al., 2015), but no information on these factors was reported in our database. Thus, a more comprehensive study of farmers is needed to better understand their motivation for intercropping and the associated crop management strategies.

5 Conclusion and perspectives

Our study showed that intercrops enabled the studied farms (conventional arable field crop and crop–livestock mixed farming) to reduce pesticide use by 50% for wheat- and barley-based intercrops and up to 83% for pea-based intercrops. The effect of intercropping on herbicide use was particularly strong, with a decrease of more than 50% for wheat and barley and 86% for peas. The effect of fungicides and insecticides was also striking for peas, with reductions of 93% and 100%, respectively. This effect was less clear for insecticides used on wheat and barley as these two crops benefit more from seed coating than insecticide sprays. According to our results, intercropping can also enable a reduction in mineral nitrogen fertilisation by up to 50% for wheat without eliminating the need for fertilisation. Finally, by improving production and/or reducing production costs, intercropping does not harm GMs and even improves margins on intercropped peas compared with sole-cropped peas. Rapeseed intercropping consisted mostly of growing rapeseed with sown but not harvested companion plants, and we could not demonstrate any significant effects of this intercropping on pesticide use or nitrogen fertilisation. Tools such as CAPS (Médiène et al., 2016) can be used to choose the best companion plants for rapeseed. Finally, our results show that intercropping efficiently reduces chemical inputs, but the effectiveness depends on the types of intercrops. We found that intercropping is especially relevant for reducing the use of pesticides or mineral fertilisers and should be integrated into a broader strategy of integrated pest management. According to the DEPHY data, few farmers grow intercrops in France, especially in conventional arable field crop farms. In order to better promote intercropping, it is necessary to highlight the farming conditions under which intercrops are grown as well as the reasons leading farmers to adopt this practice.

CRediT authorship contribution statement

Elodie Yan: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. Nicolas Munier-Jolain: Conceptualization, Resources, Writing – review & editing. Philippe Martin: Conceptualization, Writing – review & editing. Marco Carozzi: Conceptualization, Writing – review & editing.

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