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ABSTRACT

Crop diversification has been shown to enhance a number of ecosystem services, including the regulation of insect pest, weed and pathogen pressure, thereby reducing pesticide needs and use. However, the quantitative relationship between crop diversification at the cropping system scale and pesticide use has been rarely addressed and is mostly supported by evidence from landscape scale or a few long-term experiments. Nevertheless, crop diversification can reduce pesticide use both as a result of the use of crops with lower inherent pesticide reliance (the effect of crop species), and as a result of the pest regulation effect due to the number of different crops in the cropping system (the effect of crop diversity). These two effects combine into a net effect at the cropping system scale which can be difficult to differentiate through experimental design or a modeling approach. We employed the DEPHY network database describing 1285 cropping systems and 67 cash crops to disentangle and quantify the two complementary effects on pesticide use at the cropping system level. Our results show that crop species and crop diversity explain 37.1 % and 1.3 % of the cropping systems total pesticide use variance respectively, while 38.7 % explained by other factors (Residuals). Excluding the crop species effect reveals that adding one crop in the cropping system decreases total pesticide use by 0.09 units of treatment frequency index, on average. Further studies are needed to shed light on the effects of crop species characteristics, as well as take into account other factors such as climate conditions.

1. Introduction

Pesticides, as one of the pillars of the 20th century agricultural revolution, have made a major contribution to global food production and food security (Paarlberg and Paarlberg, 2008). Their use has increased drastically since the mid 20th century (Sharma et al., 2019) leading to severe problems such as soil contamination (Silva et al., 2019; Tang et al., 2021), water pollution (Stehle and Schulz, 2015; Stehle et al., 2023), biodiversity reduction (Beketov et al., 2013; Tsiafouli et al., 2014) and human health issues (Nicolopoulou-Stamati et al., 2016).

Most current agricultural systems are dependent on pesticides (IPES-Food, 2016, Hu, 2020) in part because of the reduction of ecosystem services related to self-regulation (Tilman et al., 2002). Efforts have been made to reduce pesticide use (Candel et al., 2023) and this challenge remains one of the priorities for transitioning to sustainable agriculture in France and Europe. An illustration of these difficulties can be seen in the 2008 French Ecophyto plan. The plan aimed to halve pesticide use by 2018, a challenging target that was unable to be met and has been postponed to 2025. The objective of the plan is however still far from being reached (Ministère de la transition écologique, 2022). Similarly to the French Ecophyto plan, the Farm-to-Fork strategy of the European Commission is aiming for the same reduction target, but by 2030 (European Commission, 2020). Pesticide use reduction requires multifaceted solutions (Jacquet et al., 2022) and crop diversification practices (e.g. cover crops, intercrops, more diverse crop sequences, agroforestry, etc.) at different scales (field, farm and landscape) are considered one of the main tools allowing for a reduction in pest pressure (Ratnadass et al., 2012; Isbell et al., 2017; Vialatte et al., 2023).

The beneficial effects of crop diversification on pesticide use reduction are obtained through improved ecosystem services (Duru et al., 2015; Tamburini et al., 2020; Beillouin et al., 2021) related to both the

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crop species and the crop diversity (number of different crops in the cropping system, where cropping system is referring to a set of fields from a given farm managed under the same management strategy). Indeed, on one hand, crops differ in their sensitivity to insect pests and pathogens, in their competitive ability against weeds, and are associated with specific pests (Smith et al., 2008; Savary et al., 2019). Therefore, changing the crop species grown can *per se* affect pesticide use. On the other hand, the number of crops (crop diversity) can aid in the regulation of weeds, insect pests, and pathogens through a range of processes such as: (i) disruption of the spatial and temporal cycle, (ii) resource dilution for hosting insect pests and pathogens, (iii) allelopathic interference and (iv) varied soil disturbance which prevents the proliferation of a particular weed species (Liebman and Dyck, 1993; Kirkegaard et al., 2008; Ratnadass et al., 2012). As a result, pesticide use varies considerably between crops and cropping systems.

As pointed out by Eisenhauer et al. (2011), there is currently an ongoing debate regarding the relative effects of crop diversity (changing the numbers of crops) *versus* crop species on ecosystem services. In studies that addressed the link between crop diversification practices and pesticide use at the cropping system scale, the effects were not attributed separately to either crop species or crop diversity (Bonnet et al., 2021; Alletto et al., 2022) highlighting the difficulty to tease apart these two effects.

Crop diversity was identified as one discriminating factor for low pesticide management strategies at the cropping system scale (Lechenet et al., 2016), while the link between crop diversity and pesticide use requires quantitative investigation. There have been ample reports concerning the effects of crop diversification practices in reducing pest pressure and crop damage (Letourneau et al., 2011; Ratnadass et al., 2012; Kremen and Miles, 2012). However, crop diversification effects on pesticide use reduction were mostly deduced from the lower pest pressure and confirmed by only a few quantitative studies at the landscape scale (Larsen and Noack, 2021; Nicholson and Williams, 2021). Indeed, a reduction in pest pressure is not directly linked to lower pesticide use, notably because the diminution in pests has to be significant enough for farmers to decide not to treat (Czapar et al., 1997). Guinet et al. (2023) showed that for most field crops, except for winter cereals, pesticide use was reduced when these crops were introduced into more diversified cropping systems. However, Guinet et al. (2023) did not examine the link between crop diversification and pesticide use at the cropping system level. Introducing a new crop into a cropping system may reduce pesticide use at the crop level through a regulatory effect, but may increase pesticide use at the cropping system scale if the new crop has a high reliance on pesticides. Some studies quantified the effects of crop diversification practices on pesticide reduction at the cropping system scale through experimental design (Gurr et al., 2016; Bonnet et al., 2021), which are not necessarily representative of farmers' practices and contexts, making their conclusions difficult to transpose (Hashemi and Damalas, 2010).

This study aims to disentangle and quantify the effects of crop species and crop diversity on pesticide use at the cropping system level. In this work, crop diversity was estimated by the number of different crops in the crop sequence over all fields belonging to the same cropping system. The study is based on data from the French national network DEPHY representing a large range of farms and contexts. Pesticide use (total pesticides, also decomposed into herbicides, fungicides and insecticides) was quantified through the Treatment Frequency Index (TFI) and the effect sizes of crop species and crop diversity were quantified through the partitioning of the cropping system TFI variance.

2. Material and methods

2.1. Data description

2.1.1. Database

Data was extracted from the DEPHY network, which contains up to 3000 farmers who have voluntarily committed to the process of reducing pesticide use, across all agricultural sectors (Lamichhane et al., 2019). This study focused on 795 farms growing arable field crops with or without cattle production, excluding organic farms. Data were collected from farmers through a survey on a yearly basis after they joined the network. The first farmers joined the network in 2010, and the most recent data correspond to crops harvested in 2021.

2.1.2. Identification of cropping systems

A cropping system is defined here as the set of management operations applied sequentially over a set of fields from a given farm, that are managed with the same strategy (e.g., the same criteria when selecting cultivars for a given crop, or same level of tolerance of pests). This includes the rules defining the crop sequence, having in mind that crop sequences are most often not pre-defined according to a fixed pattern in diversified arable cropping systems (Vandevoorde and Baret, 2023).

A given farm might include one (most frequent case) or several cropping systems (e.g. when the farmer is managing fields with different soil types). In the database, cropping systems were described by farmers in terms of the frequency of each crop on all fields belonging to the same cropping system and the associated management practices and synthetic inputs (products, timing, doses) for each crop.

Farmers were asked to describe precisely one specific cropping system from their farm (crop grown and crop management for each crop) when they joined the network, based on the three previous years. Thereafter they were asked to describe the same cropping system each year. For those subsequent years, we considered cropping system entities over periods of three years, i.e. we counted the number of crops over three years and averaged pesticide use over the same three years.

This merging of three years was done: (i) to be consistent with the first description of cropping systems when farmers joined the network, (ii) to smooth possible inter-annual variations in pesticide use due to climate and pest pressure variability, but not related to crop diversity, and (iii) to maximize the chances to count all crops of the crop sequence over all fields belonging to the same cropping system, notably when the number of fields is low and the number of crops of the crop sequence is high.

Cropping systems were therefore considered as stable entities, with no major change in strategies over periods of three years. However, changes in cropping systems over longer monitoring periods could be accounted for because a cropping system in a given farm could be described over 1, 2, 3, or 4 three-year periods (never overlapping), corresponding to 346, 227, 83, and 59 farms, respectively. The dataset used for the study included 1285 cropping system entities described over three years and hereafter referred to as 'cropping systems' (CS_j where 'j' varies from 1 to 1285).

2.2. Indicators of crop diversity and pesticide use

2.2.1. Crop diversity

67 different cash crops ($Crop_i$) were identified across the 1285 cropping systems. Most crops were monospecific (n=64), but some were mixtures grown for grain (merged into one group 'intercrop') or forage (merged into one group 'temporary grassland') and a group of 'Others'.

The number of different crops counted in CS_j ($NbCrop\_CS_j$) was the metric used to quantify crop diversity at the cropping system level. This metric captures both the temporal and spatial scale of cropping system diversity. For a given crop sequence (temporal scale), the different crops are typically grown each year on different fields (spatial scale). Only cropping systems where the number of fields exceeded the number of crops by at least two were chosen, to ensure that the number of fields was not a limiting factor in counting the number of crops.

Of the 1285 cropping systems (see Supplementary material 1 for details), 3 % were one-crop CS (n=38; all maize monocultures), 7 % were two-crop CS (n=92, where 62 CS were based on the soft wheat–maize crop rotation), 24 % were three-crop CS (n=311, with a typical crop rotation being soft wheat–barley–rapeseed), 23 % were four-crop

CS (n=301), 17 % were five-crop CS (n=221), 10 % were six-crop CS (n=131), 6 % were seven-crop CS (n=76), and 4 % were eight-crop CS (n=47). Only 5 % of cropping systems had nine crops or more (n=68), and were therefore merged in the same group (≥ 9) for subsequent analyses.

The frequency of each crop across the whole dataset ($Freq\_Crop_i$) was computed as the ratio between the number of cropping systems including this specific crop ($Crop_i$) and the total number of cropping systems (n=1285).

The proportion of $Crop_i$ in CS_j ($Prop\_Crop_i\_CS_j$) was computed as the ratio of the number of fields of CS_j grown with $Crop_i$ over the three years and the total number of fields of CS_j over the three years.

2.2.2. Pesticide use

The Treatment Frequency Index (TFI) was used to assess the level of reliance on pesticides. TFI compiles the number of treatments during one growing season, the doses, and the proportion of the field area treated (Guinet et al., 2023). TFI quantifies both the frequency and intensity of pesticide use to solve insect pest, pathogen, and weed problems. TFI is therefore an indicator of reliance on pesticides, which is different from any indication of the amount of active ingredient applied, and also different from any indication of ecological and environmental impact.

For each $Crop_i$ in CS_j, TFI was computed ($TFI\_Crop_i\_CS_j$) as follows:

$$TFI\_Crop_i\_CS_j = 1/N * \left[\sum_{n=1}^{N}\sum_{k=1}^{K}(Applied\_dose_k/Registered\_dose_k \times Treatment\_area_k/Field\_area_n)\right] \quad (1)$$

where N is the total number of fields grown with $Crop_i$ over the three years of CS_j and K is the number of treatments during a growing season in a given field grown with $Crop_i$.

For each CS_j, TFI was then computed (TFI_CS_j) as the average of $TFI\_Crop_i\_CS_j$ weighted by $Prop\_Crop_i\_CS_j$ as follows:

$$TFI_{CS_j} = \sum_{i=1}^{NbCrop\_CS_j} TFI\_Crop_i\_CS_j \times Prop\_Crop_i\_CS_j \quad (2)$$

2.2.3. Typology of crops according to their reliance on pesticide

For each $Crop_i$, a mean TFI ($\overline{TFI\_Crop_i}$) was calculated by averaging $TFI\_Crop_i\_CS_j$ over the whole database. $\overline{TFI\_Crop_i}$ was used to classify crops according to their reliance on pesticide into seven groups (see Supplementary material 2 for details): (i) very-very low (VVL; 22 crops) when $\overline{TFI\_Crop_i} < 0.5$, (ii) very low (VL; 15 crops) when $0.5 \leq \overline{TFI\_Crop_i} < 1.5$, (iii) low (L; 10 crops) when $1.5 \leq \overline{TFI\_Crop_i} < 2.5$, (iv) Intermediate (I; 10 crops) when $2.5 \leq \overline{TFI\_Crop_i} < 4.0$, (v) High (H; 5 crops) when $4.0 \leq \overline{TFI\_Crop_i} < 5.0$, (vi) very high (VH; 3 crops) when $5.0 \leq \overline{TFI\_Crop_i} < 10.0$, and (vii) very-very high (VVH; 2 crops) when $10.0 \leq \overline{TFI\_Crop_i}$.

2.3. Predicted cropping system TFI according to the crop species

Specific metrics were calculated to disentangle the effect of crop species (and their specific requirements on pesticides) from the effect of diversity *per se*. The mean TFI for each crop species over the whole data set ($\overline{TFI\_Crop_i}$) was used to represent the crop-specific pesticide reliance. Values of $\overline{TFI\_Crop_i}$ of all crops grown in a given cropping system were used to compose a predicted cropping system TFI ($TFI\_\widehat{CS_j}\_Crop$) representing the level of TFI in a cropping system related to the nature of crops grown. For each CS_j, the predicted TFI ($TFI\_\widehat{CS_j}\_Crop$) was computed as the $\overline{TFI\_Crop_i}$ weighted by $Prop\_Crop_i\_CS_j$ as follows:

$$TFI\_\widehat{CS_j}\_Crop = \sum_{i=1}^{NbCrop\_CS_j} \overline{TFI\_Crop_i} \times Prop\_Crop_i\_CS_j \quad (3)$$

2.4. Disentangling crop diversity effect from crop species effect

The effect of crop diversity *per se* was unraveled by making the difference between the observed CS TFI (Eq.2) and the predicted CS TFI (Eq.3). This difference represents the part of CS TFI remaining after removing the part of TFI related to the nature of crops grown. For each CS_j, the difference between TFI_CS_j and $TFI\_\widehat{CS_j}\_Crop$ was computed ($Diff\_TFI\_CS_j$) as follows:

$$Diff\_TFI\_CS_j = \sum_{i=1}^{NbCrop\_CS_j}(TFI\_Crop_i\_CS_j - \overline{TFI\_Crop_i}) \times Prop\_Crop_i\_CS_j \quad (4)$$

This metric reflects the variation in cropping system TFI caused by all factors except crop species. These factors include crop diversity, other factors such as soil and climate conditions, as well as crop management choices which can affect weeds, insect pests, and pathogens pressure (e.g. cultivars, sowing date, fertilization regime, mechanical weeding, etc.). $Diff\_TFI\_CS_j$ was plotted against the number of crops in CS to assess the specific effect of crop diversity on pesticide use at the cropping system level.

2.5. Partitioning variance of cropping system TFI

The variance of observed CS TFI over the whole dataset was analysed by distinguishing the variances of the different components, namely: (i) the variance of predicted TFI related to the nature of crops grown, (ii) the variance explained by crop diversity, and (iii) the variance explained by other factors (Residuals). The variance explained by crop diversity was estimated as the variance over the whole dataset of the metric $\overline{Diff\_TFI\_NbCS_q}$, i.e. the average of $Diff\_TFI\_CS_j$ for all CS with the same 'q' number of crops. $\overline{Diff\_TFI\_NbCS_q}$ was computed as follows:

$$\overline{Diff\_TFI\_NbCS_q} = 1/NbCS_q * \sum_{j=1}^{NbCS_q} Diff\_TFI\_CS_j \quad (5)$$

where $NbCS_q$ is the number of cropping systems with the same 'q' number of crops (q=1 to ≥ 9).

For a given cropping system CS_j with 'q' different crops, its TFI can be summarized as the effect of crop species ($TFI\_\widehat{CS_j}\_Crop$), crop diversity ($\overline{Diff\_TFI\_NbCS_q}$), and other factors ($Residuals_j$) as follows:

$$TFI\_CS_j = TFI\_\widehat{CS_j}\_Crop + \overline{Diff\_TFI\_NbCS_q} + Residuals_j \quad (6)$$

Then, for the 1285 values of TFI_CS_j we analysed and partitioned their variance, namely $Var(TFI\_CS_j)$, into the variance due to: (i) crop species: $Var(TFI\_\widehat{CS_j}\_Crop)$, (ii) crop diversity allocated to each cropping system according to its number of crops: $Var(\overline{Diff\_TFI\_NbCS_q})$, and (iii) other factors: $Var(Residuals_j)$.

These variances were considered as ratios of the total $Var(TFI\_CS_j)$. Co-variances between the three components (namely crop species, crop diversity and residuals) were computed to finalize the analysis of variance partitioning.

The method used to disentangle the effects of the nature of grown crops, the crop diversity *per se*, and other factors was applied to the total TFI and to the sub-groups of pesticides, namely herbicides (53 % of the total TFI), fungicides (27 % of the total TFI), and insecticides (13 % of the total TFI).

2.6. Statistical analysis

All statistical analyses were carried out with R software version 4.3.1 (R Core Team, 2023). Linear and polynomial second-order regressions were performed by root-mean-square error (RMSE) minimization. Correlation analyses between the number of crops per cropping system and crop species based on Pearson's chi-square test (function chisq.test in base R) were conducted.

A linear model was fitted using the 'lm' function from the base '*stats*' package to investigate the link between the number of crops per cropping system and Diff_TFI_CS$_j$. Correlation coefficients between crop species, crop diversity, and residuals were computed with the 'cor' function from the base '*stats*' package using the Pearson method.

3. Results

3.1. Crop frequency and reliance on pesticide

The average total pesticide use per crop ($\overline{TFI\_Crop_i}$) ranged from 0 (for a series of very rare crops, namely Miscanthus, Leek, Melissa, etc.) to 14.6 for Onion (Fig. 1). The most frequently grown crops were: (i) Soft wheat (Intermediate reliance on pesticide with an average total TFI of 3.2) grown in 87 % of cropping systems, (ii) Maize (Low reliance on pesticide with an average total TFI of 1.7) grown in 72 % of cropping systems, (iii) Barley (Intermediate reliance on pesticide with an average total TFI of 2.8) grown in 53 % of cropping systems, and (iv) Rapeseed (High reliance on pesticide with an average total TFI of 4.6) grown in 47 % of cropping systems. Those four crops (such as those located on top right of Fig. 1) were those with the highest contribution to overall pesticide use, because they were both very frequently grown and rely rather heavily on pesticides. Alfalfa and Temporary grasslands (all species mixtures grown for forage) were the most frequently grown crops of groups with Very-Low and Very-Very-Low reliance on pesticides, respectively (see Supplementary Material 2 for the detailed information on groups of pesticide reliance, and Supplementary Material 3 for the mean use of herbicides, fungicides and insecticides).

3.2. Analysing pesticide use as a function of crop diversity

Total pesticide use at the cropping system level (TFI_CS$_j$) ranged from 0.0 to 11.4, with an average at 2.8 over all 1285 values. This huge variability was not simply explained by the number of crops grown within each cropping system (Fig. 2). The non-linear regressions on the mean of the total TFI, fungicide TFI and insecticide TFI (Figs. 2a, 2c, 2d) show a bell-shaped curve (regression only significant for fungicide TFI), with the highest TFI for cropping systems with 5–7 crops. The non-significant regression on the total TFI mean shows that TFI increases

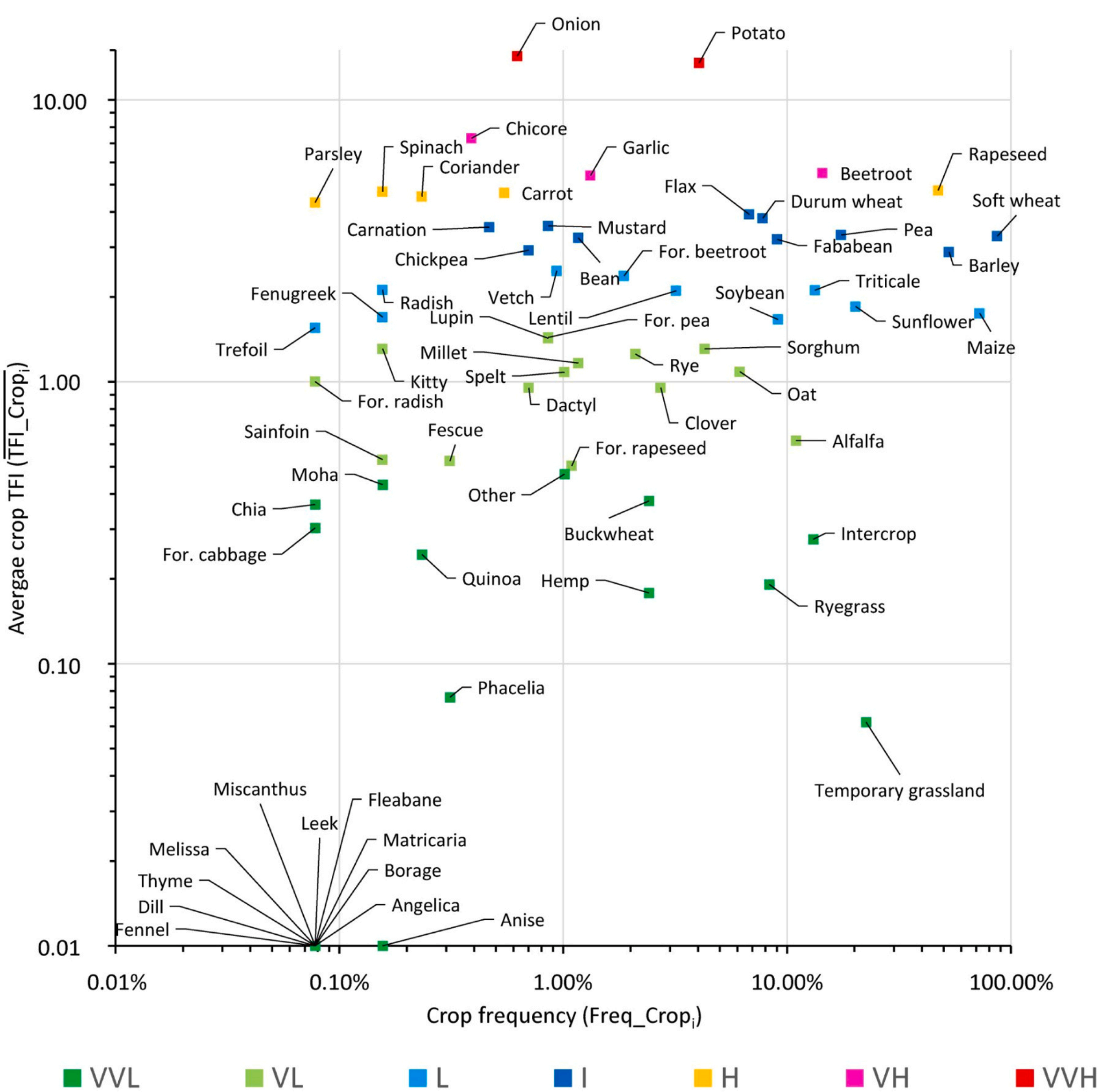

Fig. 1. Average TFI of Crop$_i$ as a function of the frequency of Crop$_i$. The color of the points distinguishes the seven classes regarding TFI of Crop$_i$ (VVL for very-very low in dark green, VL for very low in clear green, L for Low in clear blue, I for Intermediate in dark blue, H for High in orange, VH for very-high in pink and VVH for very-very high in red). Note that because of the logarithmic scales, all crops at TFI=0 are represented at TFI=0.01.

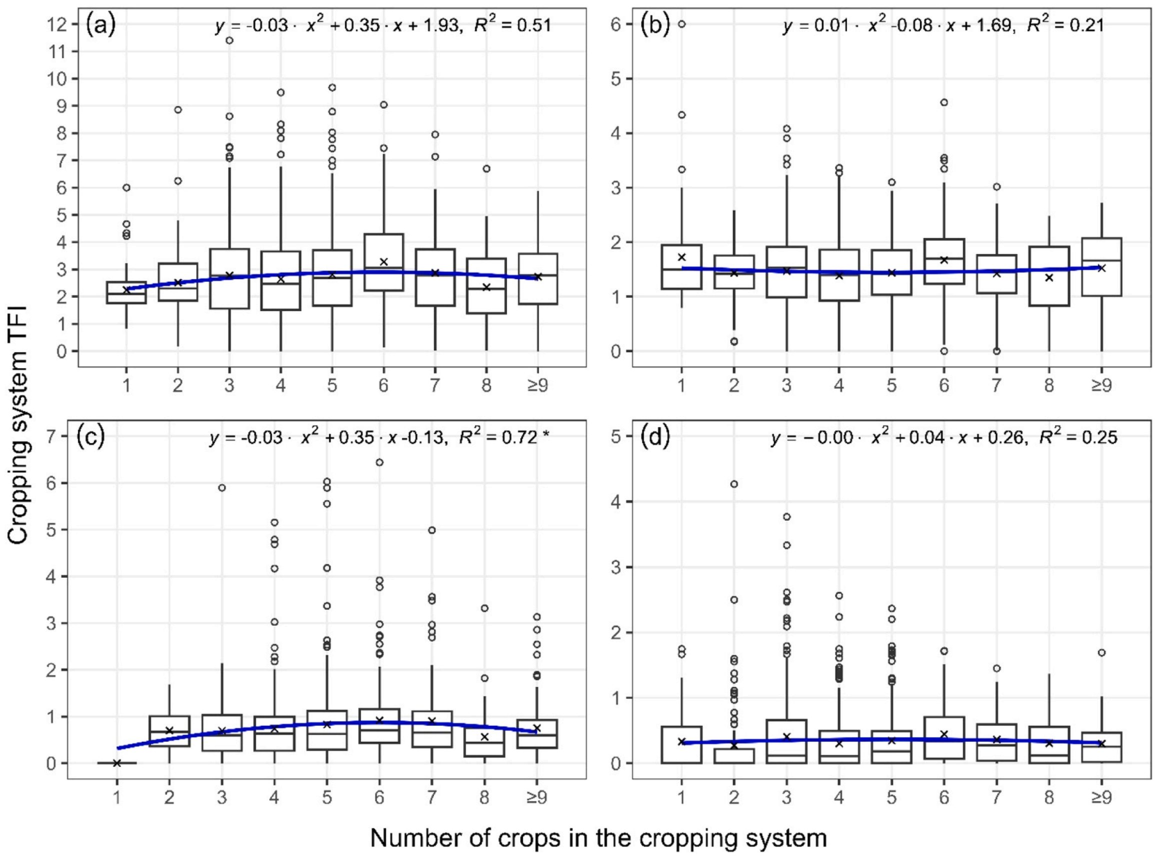

Fig. 2. Cropping system TFI as a function of crop number for (a) total TFI, (b) herbicide TFI, (c) fungicide TFI, and (d) insecticide TFI. The blue lines represent second-order polynomial regression on the mean for each pesticide group. Box plots represent 25th, 50th, 75th percentiles, and means (cross). Outliers (circles) correspond to values outside the space bounded by the two furthest values within a radius of 1.5 times the interquartile range from each end of the box. Significant levels are shown by the asterisk after R square value (* for p<0.05, ** for p<0.01, and *** for p<0.001).

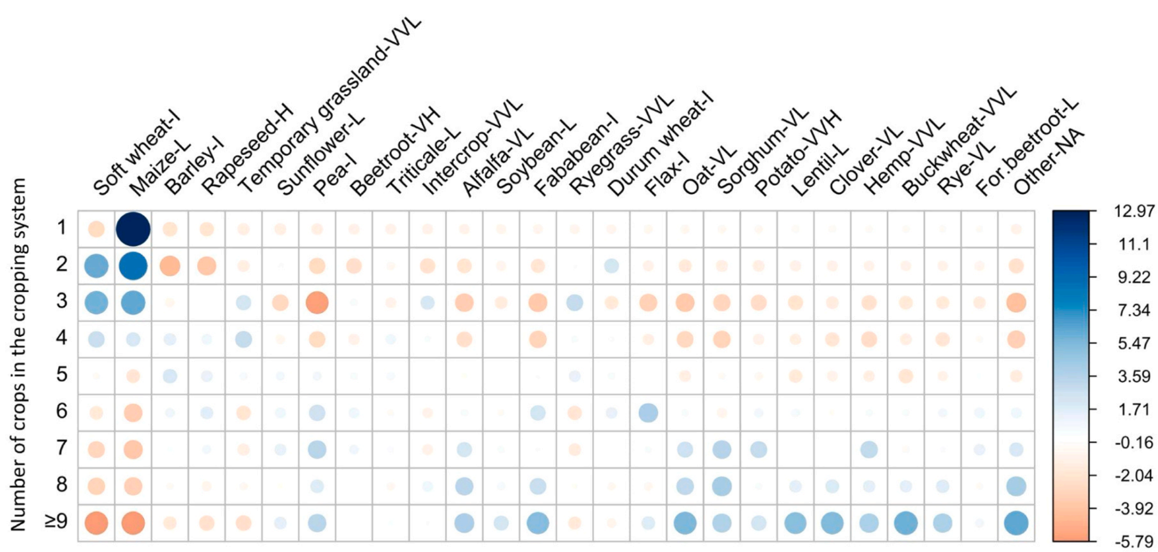

Fig. 3. Pearson's chi-square test highlights the correlation between the 25 main crops (according to their frequency in the 1285 cropping systems) with the remaining ones being summarized as 'other' and the number of crops in a cropping system. The letters following the crop names correspond to the seven classes defined based on the total TFI of $Crop_i$. Positive (attraction) and negative (repulsion) correlation are colored in blue and red respectively with their level of intensity being proportional to the standardized residuals (r) and their size to the amount of the cell contribution (r^2/x^2) where x^2 is $\sum(\text{observed}-\text{expected})^2/\text{expected}$.

from 2.2 for one-crop CS to a maximum of 2.9 and then decreases to 2.6 for cropping systems with nine crops or more (R^2=0.51, p >0.05). The non-linear regression on the mean of herbicide TFI not significantly showed a reverse bell-shaped curve, with the lowest TFI for cropping systems with four crops (Fig. 2b).

3.3. Exploratory analysis of crop diversity and crop species

3.3.1. Correlation between crop species and cropping system diversity

The correlation plot for the Pearson's chi-square test residuals for the crop species against the number of crops highlights that the crop species was significantly correlated with the number of crops in a cropping system (x^2=1380; df=200; p-value<0.001; Fig. 3). Maize was strongly associated with one-crop CS (all the one-crop CS were maize-based) and with poorly diversified cropping systems. Two-crop CS mostly included maize or wheat and often both (84 %, 78 % and 67 % respectively of two-crop CS). Maize, wheat, ryegrass, temporary grassland (all species mixtures grown for forage), and intercrop (all species mixtures grown for grain) were overrepresented in three- and four-crop CS. Finally, more diversified cropping systems (six and more crops) were associated with legume crops and/or rustic crops with low pesticide reliance like pea (I), alfalfa (VL), faba bean (I), oat (VL), sorghum (VL), lentil (L), clover (VL), hemp (VVL), buckwheat (VVL), rye (VL), and with the group of 'other' crops.

3.3.2. Crop pesticide demanding group and cropping system diversity

The L group represented 100 % of one-crop CS because all were maize-based, and maize belongs to the L group (Fig. 4). The share of L group tended to decrease with the increase of the number of crops, both in terms of frequency (50–22 % from two to ≥ 9 crops, Fig. 4a) and proportion (51–17 % from two to ≥ 9 crops, Fig. 4b). This decrease was partly offset by an increase in the share of crops with a lower reliance on pesticides (groups VL and VVL), from 4 % to 31 % in terms of frequency (Figs. 4a) and 6% to 20 % in terms of proportion for the two groups as a whole (Fig. 4b). However, we observed simultaneously an increase in the share of groups with higher pesticide reliance (groups H, VH and VVH) from 2 % to 13 % in terms of frequency (Figs. 4a) and 2% to 14 % in terms of proportion, for the three groups as a whole (Fig. 4b). In between, crops belonging to group I were the most common, either in terms of frequency or proportion (40 % and 46 %, respectively on average for two-crop and more CS).

In terms of contribution to the total pesticide use (proportion*$\overline{\textit{TFI\_Crop}_i}$; Fig. 4c), crops belonging to group I were the most important (56 % on average for two-crop and more CS and varying from 51 % to 59 %). The share of H, VH and VVH groups increased with the number of crops in the cropping system from 3 % to 30 % (for the three groups as a whole) while that of VVL, VL and L groups decreased from 38 % to 15 % (for the three groups as a whole). Therefore, regarding the total pesticide use at cropping system level, the effects of introducing crops with low pesticide reliance (L, VL, VVL) was diluted by the increase of crops with high pesticide reliance (H, VH, VVH).

3.4. Disentangling the effects of crop species and crop diversity

The difference between observed and predicted cropping system TFI was negatively correlated to the number of crops in the cropping system for all groups of pesticides except for herbicides (Fig. 5). For total TFI, the linear regression on the means revealed a decrease in TFI of 0.09 points per additional crop grown in the cropping system with values being negative for six-crop or more CS. Fungicide and insecticide TFI decreases were of 0.03 and 0.02 TFI points, respectively, per additional crop.

3.5. Effect sizes of crop species and crop diversity on cropping system TFI

Overall, crop species, crop diversity and all other factors (Residuals) explained 37.1 %, 1.3 %, and 38.7 % of the total variance of total cropping system TFI, respectively (Fig. 6a). Crop species explained 46.4 % of cropping system TFI variance for fungicide use, 31 % of TFI variance for herbicide use, and 19.2 % of TFI variance for insecticide use. Crop diversity consistently accounted for around 1 % of the total pesticide use variance for each sub-group of pesticides. Other factors (Residuals) contributed to 67.5 % of the variance of insecticide TFI, to 54.4 % of the variance of herbicide TFI and to 30.1 % of the variance of fungicide TFI. The covariance between crop species and Residuals accounted for 12.3 % of the total variance (Fig. 6a) with a significant positive correlation coefficient (0.32, p<0.001). No covariance was displayed between crop diversity and Residuals for any category of pesticide. For total TFI, a small negative covariance was shown for crop species and crop diversity with a significant negative correlation coefficient (-0.12, p<0.001).

4. Discussion

4.1. Contrasted levels of pesticide use and frequency between crops

Arable field crops grown by farmers of the French DEPHY network covers a wide range of pesticide use (Fig. 1). This is attributable to the differences among crops regarding potential insect pests and pathogens able to damage them in terms of frequency, severity and for competitive ability against weeds (Smith et al., 2008; Savary et al., 2019). Crop-specific pesticide use was not correlated with crop frequency,

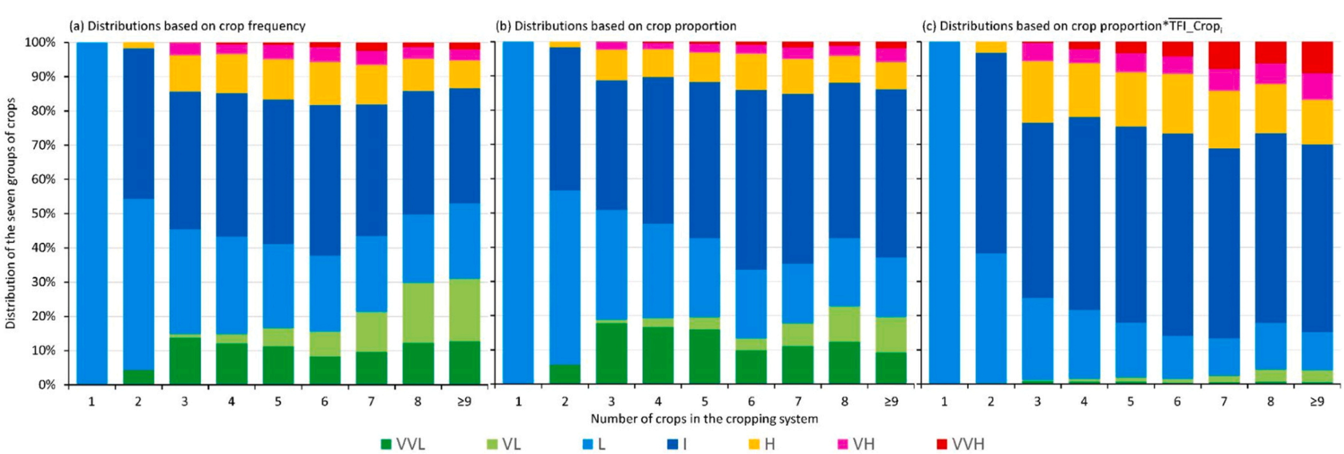

Fig. 4. For each number of crops in the cropping systems, the share of each of the seven crop classes according to their total TFI is calculated from (a) crop frequency, (b) crop proportion, and (c) contribution to the total pesticide use (crop proportion*$\overline{\textit{TFI\_Crop}_i}$).

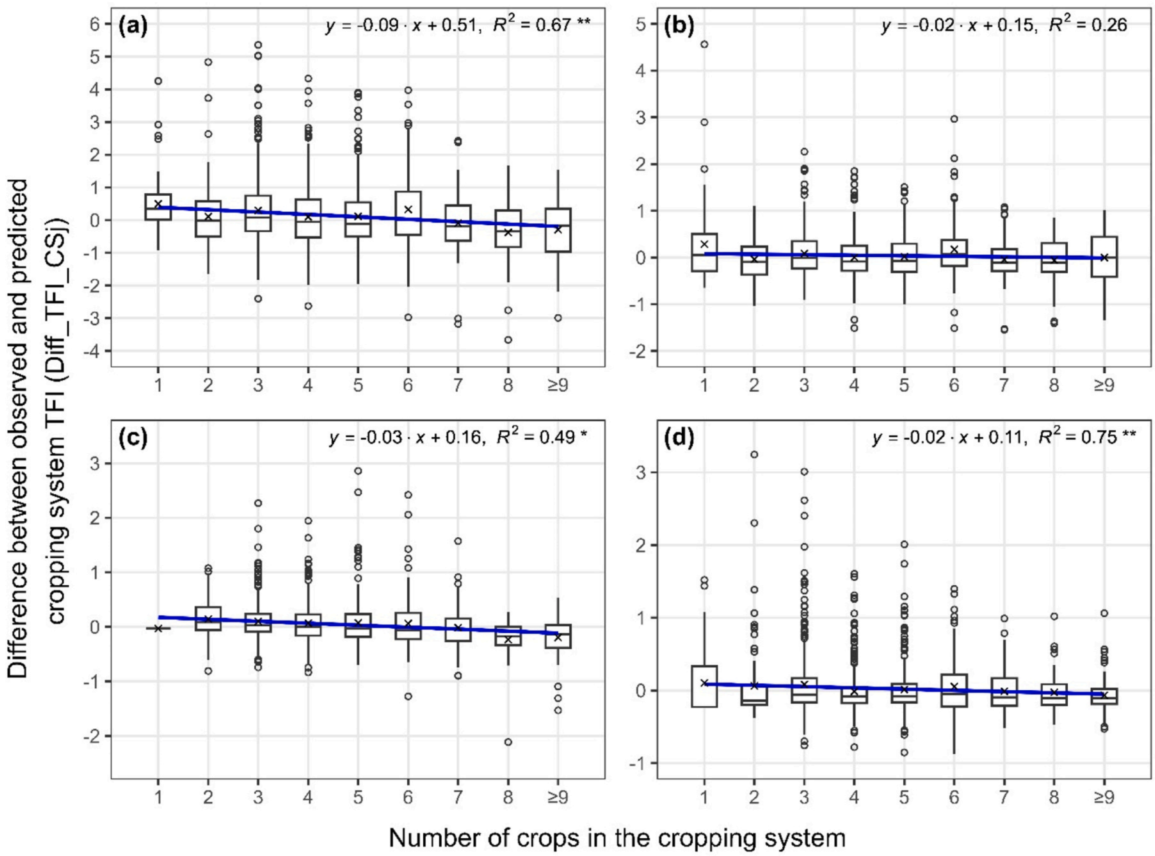

Fig. 5. Difference between observed and predicted cropping system TFI as a function of crop number for (a) total TFI, (b)herbicide TFI, (c) fungicide TFI, and (d) insecticide TFI. The blue lines represent the linear regression on the mean (cross) for each pesticide group. Box plots represent 25th, 50th, 75th, percentiles and means (cross). Outliers (circles) correspond to values outside the space bounded by the two furthest values within a radius of 1.5 times the interquartile range from each end of the box. Significant levels are shown by the asterisk after R square value (* for $p<0.05$, ** for $p<0.01$, and *** for $p<0.001$).

whereas it could have been expected that the most frequent crops were those requiring the most pesticides. It is evident that increasing the frequency of a given crop, both in time and space, favors the development of associated pests and tends to increase the intensity of pesticide use for that crop (Rusch et al., 2010; Ratnadass et al., 2012). Frequent crops could have benefitted from previously strong breeding efforts, including improving the resistance to invertebrate pests and to pathogens, which could have contributed to reducing their current needs for pesticides (Jørgensen, 1992; Piffanelli et al., 2004). However, this hypothesis is not entirely convincing since maize (TFI=1.7), soft wheat (TFI=3.2) and rapeseed (TFI=4.6) have all benefited from strong breeding efforts, but still differ significantly in terms of pesticide use. Breeding efforts have not always been made with the aim of making crops more tolerant of pests but rather to maximize their productivity with the support of inputs. The difference in pesticide use across crops could therefore be the consequence of complex processes which are difficult to decipher (Van der Putten et al., 1993). Furthermore, crops are associated with specific weeds, invertebrate pests (Smith et al., 2008), and affect weed seedbank composition (Bohan et al., 2011) which is in line with our results.

4.2. Pesticide use at the cropping system scale is influenced by crop species

The relationship between cropping system TFI and crop diversity was complex, as the TFI was not simply negatively correlated to crop diversity (Fig. 2). This is contrary to the common hypotheses of agronomists and ecologists (e.g. Vialatte et al., 2023). This was seen by the bell-shaped curve of the cropping system TFI as a function of the number of crops, with the non-linear regression only being significant for fungicides (Fig. 2). This is partly due to differences in the crop species along the gradient of crop diversity. Some crops such as maize and wheat are preferentially grown in farms with low cropping system diversity whereas others are associated with strategies of high cropping system diversity. Since crops differ a lot in terms of reliance on pesticides, the crop species grown is likely to impact the overall pesticide use at the cropping system scale. As an illustration, in the dataset, all one-crop cropping systems were maize-based, a crop with low-pesticide reliance. Maize is still important in two-crop cropping systems and frequently combined with wheat, a crop with intermediate pesticide reliance. Such crop sequences, alternating a winter and a summer crop, is a technical feature known to regulate weed pressure (Meiss et al., 2010).

On the contrary, farmers with a clear strategy of high diversification tended to introduce rustic crops with low pesticide reliance such as oat, buckwheat, or sorghum. This contributes to reducing the share of crops with high to very-very high pesticide reliance (potatoes, onion, beetroot) in those diversified cropping systems (Fig. 4c). Consequently, this leads to a TFI of 2.6 for cropping systems with eight and more crops which is similar to that of two-crop and three-crop cropping systems. In cropping systems with an intermediate level of diversification, the increased share of crops with high to very-very high pesticide reliance is not compensated for, thus leading to the highest TFI values of the non-significant bell-shaped curve at 2.9 on average for cropping systems with four crops to seven crops.

4.3. Crop diversity per se reduces pesticide use

Our result supports the general conclusion that crop diversity

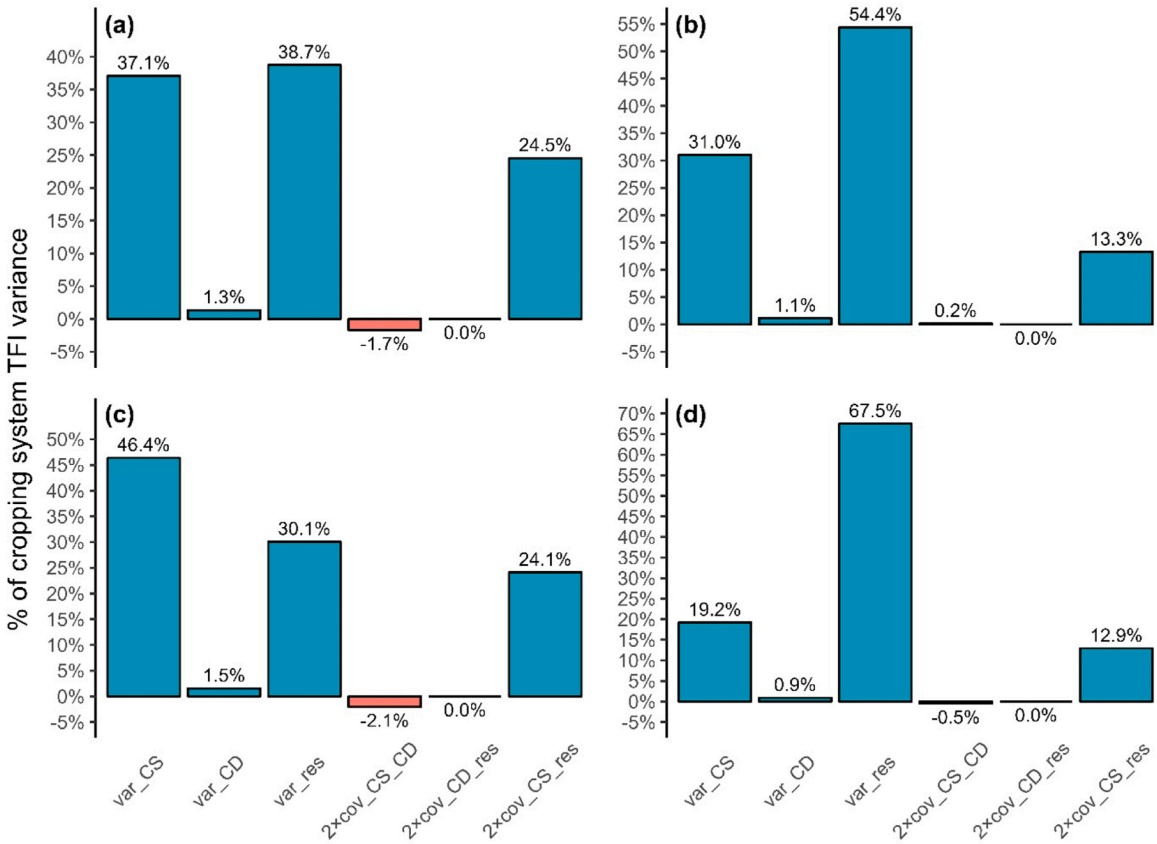

Fig. 6. Partitioning of the cropping system TFI variance across the various sources of variance, namely crop species (var_CS), crop diversity (var_CD), all other factors (var_res), and covariances for (a) total TFI, (b) herbicide TFI, (c) fungicide TFI, and (d) insecticide TFI (cov_CS_CD: the covariance between crop species and crop diversity; cov_CD_res: the covariance between crop diversity and other factors; cov_CS_res: the covariance between crop species and other factors). Covariances were multiplied by a factor of two to make the sum of variances and covariances equal to 100 % of the TFI variance.

(number of crops) decreases pesticide use at the cropping system level, regardless of the crop species in the cropping system (Fig. 5). The effect of crop number is additive and independent to that of crop species. Since we did not monitor insect pests, weeds and pathogens pressure, it is not possible to strictly demonstrate the link between crop diversity and these pressures. However, considering that pesticide use is adapted by farmers according to pest pressure (particularly within a network of farmers motivated to decrease pesticide use, as in the DEPHY network), the results suggest that the disruption of the spatial and temporal processes involved in the life cycle of weeds, insect pests, and pathogens through diversification could reduce their pressure, and therefore the need to apply pesticides to avoid yield losses (Kirkegaard et al., 2008; Ratnadass et al., 2012). Crop diversity might also be related to other factors that could affect pesticide use, such as farm size, or the farmer's specific objectives and motivations, and this would deserve further investigations. The reduction in the total TFI (-0.09 TFI per crop) was driven by the decreased fungicides (-0.03 TFI per crop) and insecticides (-0.02 TFI per crop). No significant reduction was shown on the herbicides TFI by increasing the number of crops. These results are contradictory to our expectations as we assumed weed demography to be determined by processes at the field scale, with pluri-annual cumulative effects, while pathogens and insect pests pressure being affected by processes at the landscape level. Our approach to the data analysis made it possible to remove the specific effect of crops on the cropping system TFI and to conclude that introducing one supplementary crop in the cropping system could reduce the cropping system TFI by 0.09 units on average.

This quantified effect was not as large as in previous studies. In Bonnet et al. (2021), the introduction of sorghum or faba bean in a durum wheat–sunflower sequence decreased the cropping system TFI by 1.13 and 0.33, respectively. However, these new cropping systems were co-designed on an experimental station with the specific aim of reducing the use of pesticides. Additionally, these strong quantitative effects were not due to the effect of crop diversity alone but were the combined effect of introducing low pesticide reliance crops and of breaking the spatial and temporal pest life cycles (crop diversity).

In a recent study also based on pesticide use in farms of the French DEPHY network, Guinet et al. (2023) quantified the decrease in pesticide use in some crops (-23 % in soybean, −21 % in beetroot, −20 % in sunflower, −19 % in maize) as an effect of the drastic increase in functional crop diversity at the crop level (diversity of taxonomic families, and/or within-family diversity of species). However, according to Guinet et al. (2023), the effect of a cropping system's diversity (estimated through a different diversity metric) on pesticide use at the crop level varied a lot. An example being no significant effect on winter cereals such as wheat and barley. The effect of crop diversity on the pesticide use of some crops is diluted by the others on the cropping system scale. This was quantified in our study, as winter cereals are very frequently grown crops in the DEPHY network. Our approach is therefore complementary to other studies analysing pesticide use on specific crop species.

Tilman et al. (1997) describes the tangled relationship between species identity, species diversity and functional diversity in impacting ecosystem processes. They showed that the results of quantitative studies of the effects of diversity may vary according to the metric used to assess diversity. In our study, the number of crops was chosen because it reflects the basic unit of crop diversity that has not been addressed in pesticide reduction at the cropping system scale. The choice to use the number of crops does not encompass all aspects of functional diversity, nor does it represent all structural compositions of crop diversity, which could outweigh the impact of the crop richness alone (Weisberger et al., 2019). For example, the number of crops cannot reflect the taxonomic diversity nor their functional diversity (Finn et al., 2013) or their sowing season (Gunton et al., 2011; Hilton et al., 2018; Weisberger et al., 2019). Since these aspects are associated, notably with competitiveness against weeds, they might therefore affect pesticide use. This limit of our metric could partly explain the rather low effect size of diversification as quantified by our study. A comparison of different metrics assessing crop diversity could further refine our understanding of the link between crop diversification and pesticide use.

4.4. Crop species effect surpasses that of crop diversity

The proportion of cropping system TFI variance that was explained by the crop species effect was much higher than that of crop diversity (37.1 and 1.3 %, respectively). This suggests that differences across crops in terms of sensitivity to insect pests, pathogens, and competitiveness against weeds, are much more important than disrupting their life cycle by crop diversity. The variances explained by crop species were the highest for fungicide applications (46.4 %), which implies that fungicide diseases are more crop-dependent. This is in agreement with Hilton et al. (2018), who suggested that crops could affect soil microbial communities and therefore the level of some pathogens in the agro-ecosystem (and potentially the need for fungicides), more than the sowing season or preceding crops. Herbicides were shown to have lower crop-dependency, as weed life cycles are associated more with crop sowing time than to crop types (Gunton et al., 2011). Insect pests, which can feed on a wide range of plants, had an even lower variance explained by crop species (19.2 %).

Still, 38.7 % of cropping system TFI variance is attributed to residual effects encompassing many other factors such as soil, climate conditions, and crop management practices which are known to regulate pesticide needs and use (Lechenet et al., 2016; Hofmeijer et al., 2019). This number was higher for insecticides (67.5 %) as many factors on the landscape level could impact natural pest control, whereas fungal diseases and weed competitions happen mostly on a smaller scale (Bianchi et al., 2006). Additionally, 12.3 % of cropping system TFI variance (covariance between crop species and the residuals) reflects the geographical distribution of crops on the French territory (e.g. beetroot in the northern part with a cool and humid climate and durum wheat in the southern part with a warmer and drier climate). The absence of a correlation between crop diversity and the residuals for each pesticide group suggests that crop diversity is an independent factor in reducing cropping system pesticide, regardless of various conditions of soil, climate, and management practices.

4.5. Assessing crop diversity at the cropping system scale

The processes involved in pest regulation and pesticide use related to crop diversity are mainly driven by time (e.g. the return delay of a given crop on the same field), but also by space as farmers grow several fields simultaneously which are linked to the crop sequence. In our study we chose the cropping system scale to describe crop diversity both spatially and temporally. This scale makes it possible to take into account, through the crop sequence, the temporal component and the cumulative processes involved. An example being in the dynamic of the weed seed bank (Bohan et al., 2011). The cropping system scale also makes it possible to consider the spatial component. This is because it aggregates several fields from a given farm, which are managed the same way, with the same strategy. In this study, linking pesticide use and crop diversity over the same three years relies on the assumption that both the cropping system composition and the management strategy are stable over this period. Although this is not absolutely true for all farms, the changes in crop sequences and crop management strategies over the three years would be minor compared to the variability of cropping systems across this large national network of farms.

5. Conclusion

This study is, to our knowledge, the first quantitative analysis at the cropping system level, of the links between crop diversity and crop species on pesticide use. Our results disentangled the two specific effects of: (i) the crop species grown which is not independent of (ii) the crop diversity *per se*. The methodology allowed to quantify these effects for a large number of cropping systems with a rather small effect of diversity, corresponding to an average of 0.09 TFI point decrease for each additional crop, independent of the crop species effect. A large part of the relationship between crop diversity and pesticide use at the cropping system level was driven by: i) the strong weight of maize, a crop with low pesticide reliance, in poorly diversified systems, and ii) the introduction of rustic crops requiring little treatments such as oat, buckwheat, or even intercrops in very diversified cropping systems which could be qualified as agroecological.

The interconnection between crop diversity and crop species was the main reason for the non-significant bell-shaped relationship between crop diversity and pesticide use. Both the number of crops and the crop species coincide with cropping system diversification, even though crop species appeared to play a bigger role in pesticide use. From a systemic point of view, this would mean that the intrinsic properties of the components of the system (i.e. crop species with specific reliance on pesticide) are more important than the structural properties of the full system (i.e. crop diversity *per se*). Still, manipulating the structure of the system by increasing its diversity appears to provide some benefits to reduce its reliance on pesticide use. Nevertheless, crop diversity and crop species only explained a small part of the large overall variability in pesticide use. This variability is also strongly related to crop management strategies in interaction with pedoclimatic conditions and pest pressure. Overall, this study indicates that pesticide reduction at the cropping system level could be achieved by enhancing crop diversity, and more effectively by substituting current crops with low pesticide reliance crops, as well as with crop management optimization.

The method used to assess the relationship between crop diversity and pesticide use was based on real commercial farms, taking into account a large range of pedoclimatic situations and farmers' practices, thus enhancing the robustness and generality of the results. The method is complementary to other methods such as factorial experiments, system experiments or modeling. Further studies will be needed to test indicators other than 'the number of crops', which does not account for all aspects of a crop's functional traits involved in ecosystem services. Finally, distinguishing between the various pedoclimatic conditions would allow for more refined conclusions concerning the benefits crop diversification has on agricultural sustainability.

CRediT authorship contribution statement

Yaoyun Zhang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Chaochun Zhang:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Laurent Bedoussac:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis. **Nicolas Munier-Jolain:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Maé Guinet:** Writing – review & editing, Software. **Wen-Feng Cong:** Writing – review & editing, Supervision, Project administration. **Romain Nandillon:** Writing – review & editing, Software.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yaoyun Zhang reports financial support was provided by Chinese

Scholarship Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data Availability

The authors do not have permission to share data.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127263.

References

Alletto, L., Vandewalle, A., Debaeke, P., 2022. Crop diversification improves cropping system sustainability: an 8-year on-farm experiment in South-Western France. Agric. Syst. 200, 103433 https://doi.org/10.1016/j.agsy.2022.103433.

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., Makowski, D., 2021. Positive but variable effects of crop diversification on biodiversity and ecosystem services. Glob. Change Biol. 27, 4697–4710. https://doi.org/10.1111/gcb.15747.

Beketov, M.A., Kefford, B.J., Schäfer, R.B., Liess, M., 2013. Pesticides reduce regional biodiversity of stream invertebrates. Proc. Natl. Acad. Sci. 110 (27), 11039–11043. https://doi.org/10.1073/pnas.1305618110.

Bianchi, F.J.J.A., Booij, C.J.H., Tscharntke, T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. Proc. R. Soc. B: Biol. Sci. 273 (1595), 1715–1727. https://doi.org/10.1098/rspb.2006.3530.

Bohan, D.A., Powers, S.J., Champion, G., Haughton, A.J., Hawes, C., Squire, G., Cussans, J., Mertens, S.K., 2011. Modelling rotations: can crop sequences explain arable weed seedbank abundance? Weed Res. 51 (4), 422–432. https://doi.org/10.1111/j.1365-3180.2011.00860.x.

Bonnet, C., Gaudio, N., Alletto, L., Raffaillac, D., Bergez, J.E., Debaeke, P., Gavaland, A., Willaume, M., Bedoussac, L., Justes, E., 2021. Design and multicriteria assessment of low-input cropping systems based on plant diversification in southwestern France. Agron. Sustain. Dev. 41 (5) https://doi.org/10.1007/s13593-021-00719-7.

Candel, J., Pe'er, G., Finger, R., 2023. Science calls for ambitious European pesticide policies, 272–272 Nat. Food 4 (4). https://doi.org/10.1038/s43016-023-00727-8.

R. Core Team (2023). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ⟨https://www.R-project.org/⟩.

Czapar, G.F., Curry, M.P., Wax, L.M., 1997. Grower acceptance of economic thresholds for weed management in Illinois. Weed Technol. 11 (4), 828–831. https://doi.org/10.1017/s0890037x00043517.

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.-A., Justes, E., Journet, E.-P., Aubertot, J.-N., Savary, S., Bergez, J.-E., Sarthou, J.P., 2015. How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron. Sustain. Dev. 35 (4), 1259–1281. https://doi.org/10.1007/s13593-015-0306-1.

Eisenhauer, N., Milcu, A., Sabais, A.C.W., Bessler, H., Brenner, J., Engels, C., Klarner, B., Maraun, M., Partsch, S., Roscher, C., Schonert, F., Temperton, V.M., Thomisch, K., Weigelt, A., Weisser, W.W., Scheu, S., 2011. Plant diversity surpasses plant functional groups and plant productivity as driver of soil biota in the long term. PLoS ONE 6 (1), e16055. https://doi.org/10.1371/journal.pone.0016055.

European Commission. (2020) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. COM(2020) 381 final. (⟨https://eur-lex.europa.eu/resource.html?uri=cellar:ea0f9f73-9ab2-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1&format=PDF⟩).

Finn, J.A., Kirwan, L., Connolly, J., Sebastià, M.T., Helgadottir, A., Baadshaug, O.H., Bélanger, G., Black, A., Brophy, C., Collins, R.P., Čop, J., Dalmannsdóttir, S., Delgado, I., Elgersma, A., Fothergill, M., Frankow-Lindberg, B.E., Ghesquiere, A., Golinska, B., Golinski, P., Grieu, P., Gustavsson, A., Höglind, M., Huguenin-Elie, O., Jørgensen, M., Kadziuliene, Z., Kurki, P., Llurba, R., Lunnan, L., Porqueddu, C., Suter, M., Thumm, U., Lüscher, A., 2013. Ecosystem function enhanced by combining four functional types of plant species in intensively managed grassland mixtures: A 3-year continental-scale field experiment. J. Appl. Ecol. 50 (2), 365–375. https://doi.org/10.1111/1365-2664.12041.

Guinet, M., Adeux, G., Cordeau, S., Courson, E., Nandillon, R., Zhang, Y., Munier-Jolain, N., 2023. Fostering temporal crop diversification to reduce pesticide use. Nat. Commun. 14, 7416. https://doi.org/10.1038/s41467-023-43234-x.

Gunton, R.M., Petit, S., Gaba, S., 2011. Functional traits relating arable weed communities to crop characteristics. J. Veg. Sci. 22 (3), 541–550. https://doi.org/10.1111/j.1654-1103.2011.01273.x.

Gurr, G.M., Lu, Z., Zheng, X., Xu, H., Zhu, P., Chen, G., Yao, X., Cheng, J., Zhu, Z., Catindig, J.L., Villareal, S., Van Chien, H., Cuong, L.Q., Channoo, C., Chengwattana, N., Lan, L.P., Hai, L.H., Chaiwong, J., Nicol, H.I., Perovic, D.J., Wratten, S.D., Heong, K.L., 2016. Multi-country evidence that crop diversification promotes ecological intensification of agriculture. Nat. Plants 2 (3). https://doi.org/10.1038/nplants.2016.14.

Hashemi, S.M., Damalas, C.A., 2010. Farmers' perceptions of pesticide efficacy: reflections on the importance of pest management practices adoption. J. Sustain. Agric. 35 (1), 69–85. https://doi.org/10.1080/10440046.2011.530511.

Hilton, S., Bennett, A.J., Chandler, D., Mills, P., Bending, G.D., 2018. Preceding crop and seasonal effects influence fungal, bacterial and nematode diversity in wheat and oilseed rape rhizosphere and soil. Appl. Soil Ecol. 126, 34–46. https://doi.org/10.1016/j.apsoil.2018.02.007.

Hofmeijer, M., Krauss, M., Berner, A., Peigné, J., Mäder, P., Armengot, L., 2019. Effects of reduced tillage on weed pressure, nitrogen availability and winter wheat yields under organic management. Agronomy 9, 180. https://doi.org/10.3390/agronomy9040180.

Hu, Z., 2020. What socio-economic and political factors lead to global pesticide dependence? A critical review from a social science perspective. Int. J. Environ. Res. Public Health 17 (21), 8119. https://doi.org/10.3390/ijerph17218119.

IPES-Food. (2016). From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems. International Panel of Experts on Sustainable Food systems. (⟨https://www.ipes-food.org/_img/upload/files/UniformityToDiversity_FULL.pdf⟩).

Isbell, F., Adler, P.R., Eisenhauer, N., Fornara, D., Kimmel, K., Kremen, C., Letourneau, D. K., Liebman, M., Polley, H.W., Quijas, S., Scherer-Lorenzen, M., 2017. Benefits of increasing plant diversity in sustainable agroecosystems. J. Ecol. 105 (4), 871–879. https://doi.org/10.1111/1365-2745.12789.

Jacquet, F., Jeuffroy, M.-H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., Reboud, X., Huyghe, C., 2022. Pesticide-free agriculture as a new paradigm for research. Agron. Sustain. Dev. 42 (1) https://doi.org/10.1007/s13593-021-00742-8.

Jørgensen, I.H., 1992. Discovery, characterization and exploitation of Mlo powdery mildew resistance in barley. Euphytica 63 (1–2), 141–152. https://doi.org/10.1007/bf00023919.

Kirkegaard, J., Christen, O., Krupinsky, J., Layzell, D., 2008. Break crop benefits in temperate wheat production. Field Crops Res. 107 (3), 185–195. https://doi.org/10.1016/j.fcr.2008.02.010.

Kremen, C., Miles, A., 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecol. Soc. 17, 342. https://doi.org/10.5751/ES-05035-170440.

Lamichhane, J.R., Messéan, A., Ricci, P., 2019. Research and innovation priorities as defined by the Ecophyto plan to address current crop protection transformation challenges in France. Adv. Agron. 154, 81–152. https://doi.org/10.1016/bs.agron.2018.11.003.

Larsen, A.E., Noack, F., 2021. Impact of local and landscape complexity on the stability of field-level pest control. Nat. Sustain. 4, 120–128. https://doi.org/10.1038/s41893-020-00637-8.

Lechenet, M., Makowski, D., Py, G., Munier-Jolain, N., 2016. Profiling farming management strategies with contrasting pesticide use in France. Agric. Syst. 149, 40–53. https://doi.org/10.1016/j.agsy.2016.08.005.

Letourneau, D.K., Armbrecht, I., Rivera, B.S., Lerma, J.M., Carmona, E.J., Daza, M.C., Escobar, S., Galindo, V., Gutiérrez, C., López, S.D., Mejía, J.L., Rangel, A.M.A., Rangel, J.H., Rivera, L., Saavedra, C.A., Torres, A.M., Trujillo, A.R., 2011. Does plant diversity benefit agroecosystems? A synthetic review. Ecol. Appl. 21 (1), 9–21. https://doi.org/10.1890/09-2026.1.

Liebman, M., Dyck, E., 1993. Crop rotation and intercropping strategies for weed management. Ecol. Appl. 3 (1), 92–122. https://doi.org/10.2307/1941795.

Meiss, H., Médienne, S., Waldhardt, R., Caneill, J., Munier-Jolain, N.M., 2010. Contrasting weed species composition in perennial lucernes and six annual crops: implications for Integrated Weed Management. Agron. Sustain. Dev. 30 (3), 657–666. https://doi.org/10.1051/agro/2009043.

Ministère de la transition écologique (2022). État des lieux des ventes et des achats de produits phytopharmaceutiques en France en 2020. Datalab essentiel 270 (⟨https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2022-03/datalab_essentiel_270_etat_des_lieux_phyto_mars2022_0.pdf⟩).

Nicholson, C.C., Williams, N.M., 2021. Cropland heterogeneity drives frequency and intensity of pesticide use. Environ. Res. Lett. 16 (7), 074008 https://doi.org/10.1088/1748-9326/ac0a12.

Nicolopoulou-Stamati, P., Maipas, S., Kotampasi, C., Stamatis, P., Hens, L., 2016. Chemical pesticides and human health: the urgent need for a new concept in agriculture. Front. Public Health 4. https://doi.org/10.3389/fpubh.2016.00148.

Paarlberg, D., Paarlberg, P., 2008. The agricultural revolution of the 20th century, first ed. John Wiley & Sons, New York.

Piffanelli, P., Ramsay, L., Waugh, R., Benabdelmouna, A., D'Hont, A., Hollricher, K., Jørgensen, J.H., Schulze-Lefert, P., Panstruga, R., 2004. A barley cultivation-associated polymorphism conveys resistance to powdery mildew. Nature 430 (7002), 887–891. https://doi.org/10.1038/nature02781.

Ratnadass, A., Fernandes, P., Avelino, J., Habib, R., 2012. Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: A review. Agron. Sustain. Dev. 32 (1), 273–303. https://doi.org/10.1007/s13593-011-0022-4.

Rusch, A., Valantin-Morison, M., Sarthou, J.P., Roger-Estrade, J., 2010. Biological control of insect pests in agroecosystems: effects of crop management, farming systems and semi-natural habitats at the landscape scale. A review. Adv. Agron. 109, 219–260. https://doi.org/10.1016/B978-0-12-385040-9.00006-2.

Savary, S., Willocquet, L., Pethybridge, S.J., Esker, P., McRoberts, N., Nelson, A., 2019. The global burden of pathogens and pests on major food crops. Nat. Ecol. Evol. 3 (3), 430–439. https://doi.org/10.1038/s41559-018-0793-y.

Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G.P.S., Handa, N., Kohli, S.K., Yadav, P., Bali, A.S., Parihar, R.D., Dar, O.I., Singh, K., Jasrotia, S., Bakshi, P., Ramakrishnan, M., Kumar, S., Bhardwaj, R., Thukral, A.K., 2019. Worldwide pesticide usage and its impacts on ecosystem. SN Appl. Sci. 1 (11) https://doi.org/10.1007/s42452-019-1485-1.

Silva, V., Mol, H.G.J., Zomer, P., Tienstra, M., Ritsema, C.J., Geissen, V., 2019. Pesticide residues in European agricultural soils – a hidden reality unfolded. Sci. Total Environ. 653, 1532–1545. https://doi.org/10.1016/j.scitotenv.2018.10.441.

Smith, V., Bohan, D.A., Clark, S.J., Haughton, A.J., Bell, J.R., Heard, M.S., 2008. Weed and invertebrate community compositions in arable farmland. Arthropod-Plant Interact. 2 (1), 21–30. https://doi.org/10.1007/s11829-007-9027-y.

Stehle, S., Ovcharova, V., Wolfram, J., Bub, S., Herrmann, L.Z., Petschick, L.L., Schulz, R., 2023. Neonicotinoid insecticides in global agricultural surface waters – exposure, risks and regulatory challenges. Sci. Total Environ. 867, 161383 https://doi.org/10.1016/j.scitotenv.2022.161383.

Stehle, S., Schulz, R., 2015. Agricultural insecticides threaten surface waters at the global scale. Proc. Natl. Acad. Sci. 112 (18), 5750–5755. https://doi.org/10.1073/pnas.1500232112.

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M., Hallin, S., 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci. Adv. 6 (45) https://doi.org/10.1126/sciadv.aba1715.

Tang, F.H.M., Lenzen, M., McBratney, A., Maggi, F., 2021. Risk of pesticide pollution at the global scale. Nat. Geosci. 14 (4), 206–210. https://doi.org/10.1038/s41561-021-00712-5.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418 (6898), 671–677. https://doi.org/10.1038/nature01014.

Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M., Siemann, E., 1997. The influence of functional diversity and composition on ecosystem processes. Science 277 (5330), 1300–1302. https://doi.org/10.1126/science.277.5330.1300.

Tsiafouli, M.A., Thébault, E., Sgardelis, S.P., de Ruiter, P.C., van der Putten, W.H., Birkhofer, K., Hemerik, L., de Vries, F.T., Bardgett, R.D., Brady, M.V., Bjornlund, L., Jørgensen, H.B., Christensen, S., Hertefeldt, T.D., Hotes, S., Gera Hol, W.H., Frouz, J., Liiri, M., Mortimer, S.R., Setälä, H., Tzanopoulos, J., Uteseny, K., Pižl, V., Stary, J., Wolters, V., Hedlund, K., 2014. Intensive agriculture reduces soil biodiversity across Europe. Glob. Change Biol. 21 (2), 973–985. https://doi.org/10.1111/gcb.12752.

Van der Putten, W., Van Dijk, C., Peters, B., 1993. Plant-specific soil-borne diseases contribute to succession in foredune vegetation. Nature 362, 53–56. https://doi.org/10.1038/362053a0.

Vandevoorde, N., Baret, P.V., 2023. Assessing crop sequence diversity and agronomic quality in grassland regions. Eur. J. Agron. 151, 126958 https://doi.org/10.1016/j.eja.2023.126958.

Vialatte, A., Martinet, V., Tibi, A., Alignier, A., Angeon, V., Bedoussac, L., Bohan, D., Bougherara, D., Carpentier, A., Castagneyrol, B., Cordeau, S., Courtois, P., Deguine, J., Doelher, M., Enjalbert, J., Fabre, F., Femenia, F., Fréville, H., Goulet, F., Grateau., R., Grimonprez, B., Gross, N., Hannachi, M., Jeanneret, P., Labarthe, P., Launay, M., Lelievre, V., Lemarié, S., Martel, G., Masson, A.L., Navarrete, M., Plantegenest, M., Ravigné, V., Rusch, A., Suffert, F., Tapsoba, A., & Thoyer, S.S. (2023). Protéger les cultures en augmentant la diversité végétale des espaces agricoles. Rapport scientifique de l'Expertise scientifique collective. INRAE. 954 p. https://doi.org/10.17180/q7wm-q442.

Weisberger, D., Nichols, V., Liebman, M., 2019. Does diversifying crop rotations suppress weeds? A meta-analysis. PLoS One 14 (7), e0219847. https://doi.org/10.1371/journal.pone.0219847.