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Cover crops and intercropping help reduce nitrate and pesticide leaching in low-input systems

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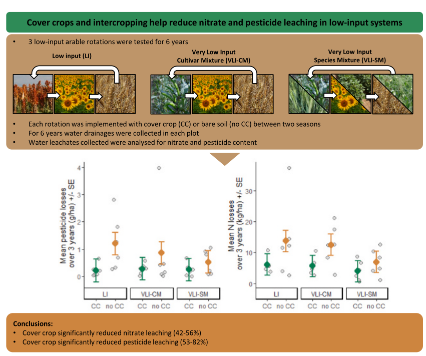
HIGHLIGHTS

- Six low-input diversified arable cropping systems were tested for six years.
- Nitrate and pesticide leaching were collected over the six years of monitoring.
- Cover crops cut nitrate leaching by 42–56% under field conditions.
- First evidence that cover crops reduce pesticide leaching by 53–82%.
- S-metolachlor loss is the main driver of the pesticide leaching pattern observed.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: The agroecological transition offer opportunities to reduce agriculture's environmental impacts by reducing reliance on synthetic fertilisers and pesticides. Crop diversification, in both time and space, is a key strategy including extended crop rotations, intercropping, and cover crops. Yet, relationships between reduced input use and associated environmental impacts remain insufficiently quantified.
Objective: We assessed the environmental performance of six innovative low-input cropping systems that used cover crops, cultivar mixture and intercropping in term of nitrogen fertiliser and pesticide use, as well as nitrate and pesticide losses.
Methods: From 2010 to 2016, cropping systems were monitored for input use and drainage water was collected with tension plate lysimeters at 1 m depth. Nitrate and up to 44 pesticide compounds were analysed annually.
Results and Conclusions: Nitrogen fertiliser application varied across systems, with more diversified systems applying less thanks to legumes. Pesticide use remained similar among systems but reduced by over 50% compared to conventional rates. Cover crops played a key role in reducing pollution. Nitrate leaching reduced by 42–56% in systems with cover crops. More originally, pesticide leaching decreased by 53–82% for these systems with S-metolachlor representing more than 50% of the quantity of pesticide losses.

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Significance: These results demonstrate that diversifying cropping systems, particularly through cover cropping, can reduce agriculture's environmental footprint greatly. When combined with reducing input use, such strategies provide a promising pathway towards more sustainable and resilient farming systems, with clear benefits for water quality and agroecosystem functioning.

1. Introduction

Intensification of agriculture over the past century has led to a large increase in food production but has also contributed to environmental degradation, including biodiversity loss and environmental pollution by nitrate and pesticides, which has had impacts on human health (de Vries, 2021; Nicolopoulou-Stamati et al., 2016; Robinson and Sutherland, 2002). Reducing the use of chemical pesticides and synthetic fertilisers is thus the main challenge for modern agriculture, and this issue is increasingly considered by policies in Western countries (Boix-Fayos and de Vente, 2023). Innovative farming systems need to be developed that rely less on pesticides and fertilisers while maintaining high yields and being able to meet new environmental and social goals.

Diversifying cropping systems is considered a relevant pathway to enhance the sustainability of cropping systems by reducing the need for pesticides and fertilisers (Beillouin et al., 2021; Tamburini et al., 2020). Systems can be diversified temporally and spatially (Duru et al., 2015). The species diversity in a rotation can be increased by extending the rotation or by using cover crops (CC), which are crops grown during the fallow period to keep the soil covered between two main crops. They can consist of mixtures of species, with the aim of providing multiple ecosystem services such as reducing N losses (Couëdel et al., 2018a), bringing organic matter to the soil, improve soil structure and reduce the need for herbicides (Adetunji et al., 2020; Nouri et al., 2022). Cropping systems can be diversified spatially by growing multiple cultivars or plant species simultaneously on the same field (i.e., intercropping or cultivar mixtures). These practices have been found to increase nutrient-use efficiency (Huang et al., 2024) due to niche complementarity and facilitation processes that exceed competition for resources, as highlighted by the “4C” approach (i.e., competition, complementarity, cooperation and compensation) (Justes et al., 2021). Intercropping and cultivar mixtures can also help control pests, diseases and weeds, and consequently reduced the need for pesticides (Gu et al., 2021; Koricheva and Hayes, 2018; Osipitan et al., 2018; Rakotomalala et al., 2023). These strategies can also increase the abundance and diversity of beneficial insects, which in return help control the pests (Beillouin et al., 2021; Tamburini et al., 2020). While effects of CC and intercropping on yield and pest or disease management have been studied well (Li et al., 2020; Peng et al., 2024; Wan et al., 2022), their effects on pesticide and nitrate leaching in the soil is less understood.

Cover crops are known to manage N losses by assimilating excess N left in the soil after the main crop (Abdalla et al., 2019; Couëdel et al., 2018b; Tribouillois et al., 2016). A recent meta-analysis also indicated that CC tend to reduce water drainage compared to that under bare soil, perhaps by removing water from the soil through evapotranspiration, which can influence nitrate leaching (Meyer et al., 2019). However, other studies found contradictory results, with CC having no effect on drainage or increasing it, likely due to differences in the climate, soil type and plant species used (Nouri et al., 2022). Intercropping and cultivar mixtures can reduce N losses indirectly by reducing the need for N fertilisers. This is particularly true for intercropping of legumes and non-legumes, as the latter can use some of the N that the former contributes to the soil. The effects of intercropping and cultivar mixtures on water drainage and solute transfer is however not well understood.

Large percentages of the pesticides applied do not reach their target pests and are lost to the environment through leaching, runoff and volatilisation, which cause environmental pollution (e.g., Alletto et al., 2010). This led to a global situation where ca. 75% of agricultural land is at risk of some pesticide pollution (Tang et al., 2021), which is particularly concerning for humans when it contaminates drinking water sources (Arias-Estévez et al., 2008). The environmental fate of pesticides in the soil and water depends greatly on the processes of retention (adsorption/desorption) and degradation, which themselves depend on the physicochemical properties of the pesticides (Wauchope et al., 2002). The intensity of these processes determines the proportion and dynamics of compounds that are likely to migrate. Agricultural

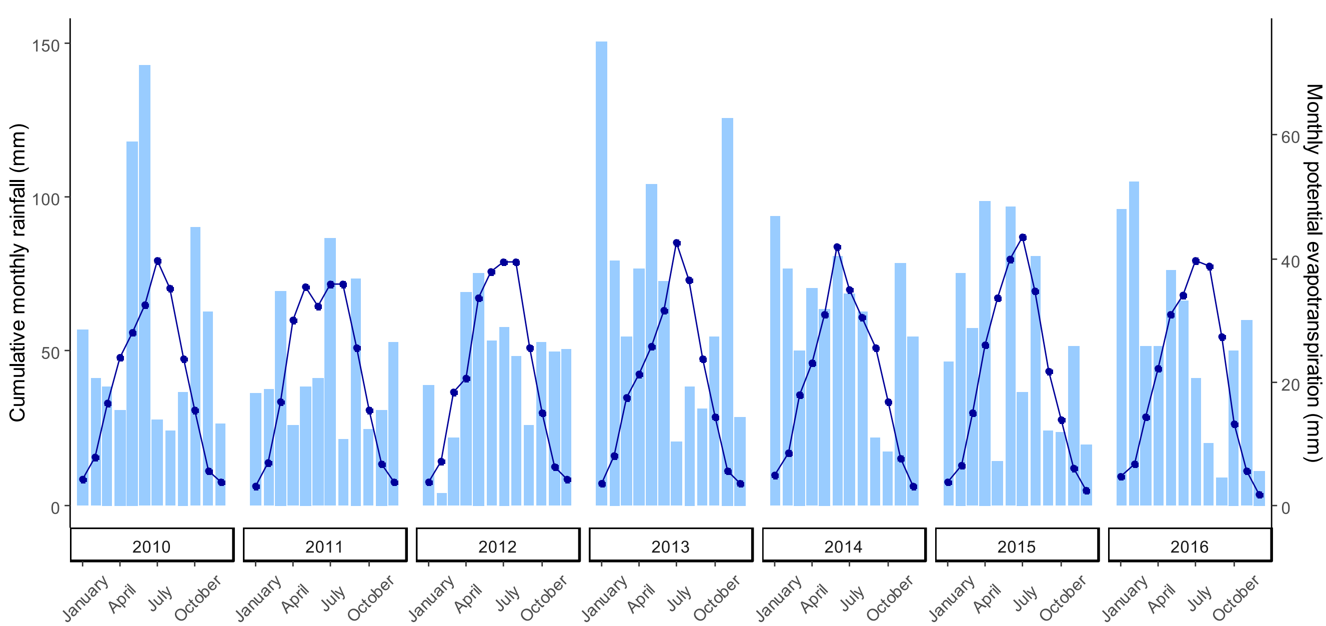

Fig. 1. Cumulative monthly rainfall (mm) from 2010 to 2016 (blue bars) and monthly potential evapotranspiration (mm, Penman-Monteith method) (blue dots and lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Main soil characteristics of the experimental site (mean ± SE). CEC: cation exchange capacity.

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Organic C (%)	pH	Organic N (%)	CEC (cmol/kg)
0–30	27.6 ± 0.8	36.7 ± 0.4	31.9 ± 0.1	1.0 ± 0.22	6.9 ± 0.1	1.02 ± 0.01	11.8
30–60	29.3 ± 0.7	37.9 ± 0.6	30.7 ± 1.5	0.7 ± 0.02	7.8 ± 0.1	0.83 ± 0.02	21.3
60–90	29.2 ± 1.2	35.7 ± 1.4	27.9 ± 2.7	0.4 ± 0.02	8.4 ± 0.1	0.5 ± 0.02	26.9
90–110	21 ± 1.6	32.4 ± 2.4	32.1 ± 4.9	0.2 ± 0.02	8.6 ± 0.1	0.32 ± 0.03	21.8

practices, especially CC and intercropping, can change pesticide retention and degradation, thereby influencing the risk of transfer in the environment (Alletto et al., 2010; Locke and Bryson, 1997). In the soil, pesticide sorption tends to increase as the organic carbon content increases (Alletto et al., 2013); thus, the organic matter that CC bring to the soil can change the soil's ability to retain pesticides and increase pesticide biodegradation by increasing biological activity (Rodriguez et al., 2020). As mentioned, CC also helps manage weeds and can reduce pesticide losses indirectly by reducing the need for herbicides in cropping systems. Similarly, intercropping and cultivar mixtures can reduce pesticide losses indirectly by reducing pest pressure and thus the need for pesticides.

To increase knowledge about the effects of crop diversification on reducing input use and mitigating negative externalities at the cropping system scale, a study was initiated in 2010 at the Auzeville experimental unit of the National Research Institute for Agriculture, Food and Environment (INRAE) (south-western France). The main objectives of the study were to design cropping systems with ambitious targets for reducing inputs, particularly fertilisers and pesticides; implement these systems under field conditions to assess the degree of input reduction achieved; and assess their agronomic and environmental performances. Bonnet et al. (2021) described the rotations and their main agronomic results in detail. In comparison, the present study focused on the environmental performance of the cropping systems, examining six years of data on nitrogen and pesticide use and transfer in drainage water. Differences in environmental performances between rotations were tested and allowed to investigate the efficacy of diversification practices, such as cultivar mixture, intercropping and CC, in mitigating negative externalities. Other variables such as weather conditions, soil characteristics and agronomic practices were also considered to better explain the patterns observed.

2. Materials and methods

2.1. Study site

A field experiment was conducted at the Auzeville station of INRAE (south-western France, 43°31′N, 1°30′E, 150 m.a.s.l.). The site experiences an altered oceanic climate, with a mean annual rainfall of 648 mm and mean annual temperature of 13.8 °C (Fig. 1, Table S1). The soil on the site is characterised as deep silt-clay to clay (0–120 cm) (Table 1).

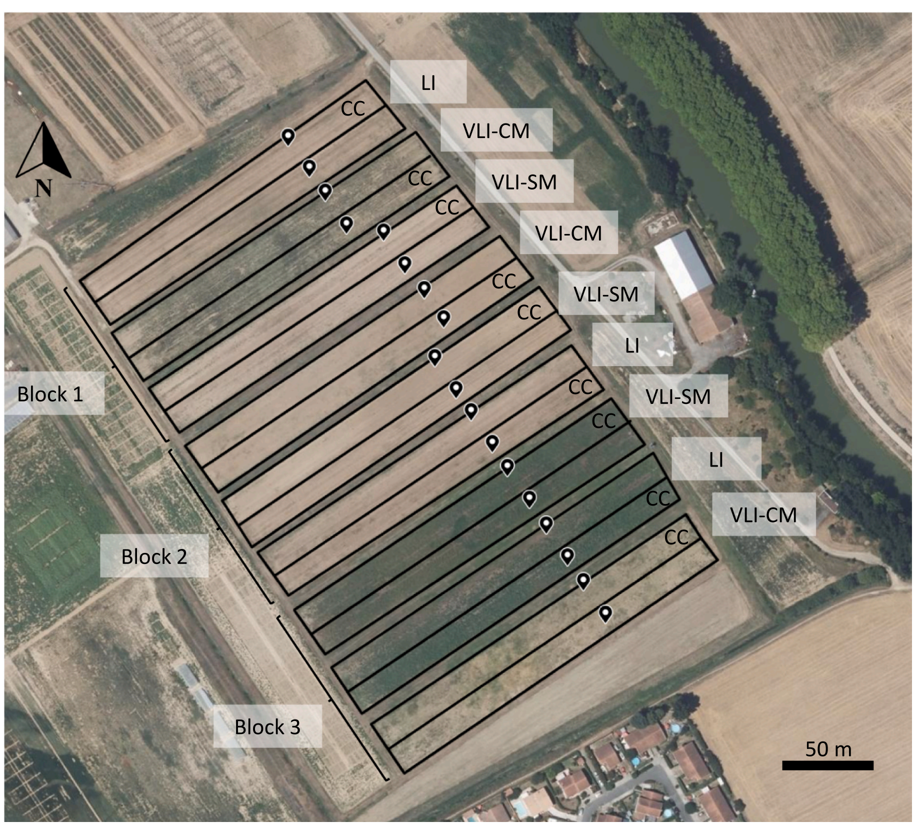

Fig. 2. Aerial view of the experimental site in south-western France (43°31′N, 1°30′E). The nine plots were divided among three equal blocks, and each block contained one plot of each rotation: low input (LI), very low input - cultivar mixture (VLI-CM) and very low input - species mixture (VLI-SM). Each plot was divided into two subplots, one with cover crops (CC) and one without CC, which created six cropping systems. The location symbols indicate the approximate locations of the tension plate lysimeters. A black arrow indicates the direction of north.

2.2. Experimental design

The experiment contained nine plots of 200 × 30 m, each divided into two subplots (200 × 15 m), one with CC and one without CC (Fig. 2). The subplots were designed to enable the use of common agricultural machinery and consequently fit with farmers technical constraints. Plots were separated from each other by 6 m grass strips. The nine plots were divided among three equal blocks, and each block contained one plot of each rotation treatment tested attributed randomly. Every year the three crops from a rotation were present in the trial, one in each block allowing to have all the component of the rotations present each year. See Bonnet et al. (2021) and Table S2 for details of the experimental design.

2.3. Cropping systems

Experimental subplots on the study site were divided among six low-input cropping systems (three rotation treatments and two sub-treatments with CC or not). These systems were designed to reduce pesticide application by at least 50% in term of Treatment Frequency Index (TFI), in line with objectives of the French Ecophyto plan, compared to the standard durum wheat – sunflower rotation in the area. The rotation treatments were designed to maintain durum wheat and sunflower:

- A low-input rotation with a 3-year rotation of sunflower, durum wheat and sorghum cash crops (LI). This rotation was designed to reduce the use of N fertilisers by 25% compared to that of the standard durum wheat – sunflower rotation (230 kg N/ha: 186 kg N/ha for the durum wheat and 44 kg N/ha for the sunflower) and achieve 100% of the semi-net margin of this rotation (1282 €/ha for two years (Agreste, 2019)).
- A very low-input rotation with a 3-year rotation of durum wheat in a cultivar mixture, sunflower and faba bean (VLI-CM). This rotation was designed to reduce the use of N fertilisers by 50% while achieving 90% of the semi-net margin of the standard rotation.
- A very low-input rotation with a 3-year rotation of three species mixtures of sunflower intercropped with soybean, durum wheat intercropped with pea and triticale or soft wheat intercropped with faba bean (VLI-SM). This rotation was designed to reduce the use of N fertiliser by 50% while achieving 85% of the semi-net margin of the standard rotation.

Each rotation treatment was implemented in two cropping systems, one with bare soil between two crops (LI, VLI-CM, VLI-SM) and another with a CC (LI-CC, VLI-CM-CC, VLI-SM-CC) for a total of six systems.

The experiment ran for two 3-year temporal rotations from 2010 to 2016 to consider weather variability, which is a key factor in agriculture. See Table S2 for details of the systems and experiment. The farming practices applied to the plots were performed to meet the objectives of each system and varied among systems and among years to consider the risks related to pests, weather and the inorganic N content of the soil. See Bonnet et al. (2021) for details of the decision rules applied in the experiment and the standard durum wheat – sunflower rotations.

2.4. Description of the cropping systems

The total quantity of each pesticide's active ingredient(s) used on each subplot (g/ha) each cropping season (including the CC from the fallow period before the cash crop), was calculated based on the technical operations performed and the pesticide compositions in the *E*-Phy database of the French Ministry of Agriculture https://ephy.anses.fr/). Pesticides were applied based on crop, pest and disease observations. The same method was used to estimate how much N to apply (kg N/ha) based on the N balance-sheet method and measuring soil inorganic N in early spring. Based on the technical operations performed, the TFI (the total quantity of each active ingredient applied to each crop during a growing season based on standard doses for each use of the active ingredient) was calculated, which indicated the pest pressure during the experiment.

2.5. Plant and crop biomass

The main cash crops and CC were collected at harvest and destruction, respectively, in two areas per subplot located ca. 40 m from the north and south end of the subplot, respectively. At each location, the aboveground biomass of the crops was manually collected from an area that depended on the density of the crop species (i.e., 2.4 m^2 for durum wheat and cereal-legume mixtures; 3 m^2 for faba bean, sunflower and sunflower-soya bean mixtures, and 0.5 m^2 for CC). Fresh plant biomass was sorted by species before being dried at 80 °C for 48 h. Sampling dates varied by crop and season. The mean total dry biomass for all crops or CC of the two sampling locations sampled was used per subplot and season in the analysis. When clover was undersown in sunflower (system LI-CC) and left after harvest, no biomass was collected, and all residues were incorporated into the soil.

2.6. Drainage and quantification of pesticide and nitrate leaching

As the field's slope did not exceed 1%, water runoff was not observed. Drained water and pesticide and nitrate leaching were measured in each subplot using two 0.075 m^2 tension plate lysimeters (SIC300, UMS GmbH, München, Germany) installed at a depth of 1 m in 2010. The plates ($n = 4$ per experimental plot) had been installed by digging pits vertically and then cavities horizontally to place the plates under a column of undisturbed soil. Pumps maintain a constant suction of 0.1 bar under the plates, which allows drained water to be collected throughout the entire growing season and fallow period and stored in a 2.5 L glass bottle. The frequency of leachate sampling was adapted to the drainage flux: leachates were sampled every month during the months with the most drainage (December–May) but only every three months during the rest of the year (June–November). Piezometers installed in the plots allowed the groundwater level to be monitored, and drainage collection stopped if the groundwater level reached that of the plates, which occurred only for 8 weeks during one of the 6 years monitored (i.e. 2014).

Leachate samples were stored at 4 °C until analysis. If a sample's volume reached 1 L, it was sent for analysis; if not, it was pooled with the sample from the next collection date and sent for analysis if the pooled volume reached 1 L. Otherwise, the two samples were pooled with the sample from the next collection date and sent for analysis regardless of the volume. Samples were analysed by the Laboratoire Départemental d'Analyses de la Drôme (Valence, France), accredited by the Comité Français d'Accréditation. If a compound was not detected, its concentration was considered to be zero. If a compound was detected but not quantified, its concentration was set at the detection limit. All compounds applied since 2004 were analysed in the leachate samples, which resulted in analysis of 33–44 compounds, depending on the plot.

The concentration of inorganic N (nitrate and ammonium) was measured in all drainage samples collected before the samples were pooled for pesticide analysis. The sample volume analysed was 10 mL, and N concentrations were measured using a continuous flow auto-analyser (Skylar 51,000, Skalar Analytic, Breda, Netherlands) (standard NF ISO 14256-2).

2.7. Statistical analysis

Several complementary indicators were used to comprehensively assess the performance of the six cropping systems (defined as combinations of rotation treatments and CC treatments). These indicators included the quantity of pesticides applied (total, and separated between herbicides, insecticides and fungicides), the quantity of N applied, the

Table 2
Results of the Wald χ^2 tests performed on models explaining different response variables. Significance levels: * = p < 0.05, ** = $p < 0.01$, *** = $p < 0.001$. Significant *p*-values are in bold.

	Rotation treatment		Cover crop		Rotation treatment × Cover crop		Block	
Response variables	χ^2_2	*p-value*	χ^2_1	*p-value*	χ^2_2	*p-value*	χ^2_2	*p-value*
Quantity of pesticide applied	2.525	0.283	1.01	0.315	0.106	0.948		
Quantity of herbicide applied	0.274	0.872	1.018	0.313	0.065	0.968		
Quantity of fungicide applied	12.565	**0.002****	0.042	0.838	0.086	0.958		
Quantity of insecticide applied	5.139	0.077	0	1	0	1	0.226	0.893
Treatment Frequency Index	34.526	**< 0.001*****	0.15	0.698	0.667	0.716		
Quantity of N fertiliser applied	146.528	**< 0.001*****	0.713	0.398	0.339	0.844		
Water drainage	15.388	**< 0.001*****	3.283	**0.009****	6.423	**0.001****		
Total pesticide leaching	1.136	0.567	6.293	**0.012***	1.376	0.503	0.703	0.704
Nitrate leaching	4.711	0.095	10.521	**0.001****	1.346	0.51		

TFI, the water drainage, the quantity of pesticide losses and N losses. To analyse system-level responses, data were pooled for each subplot over the three years composing each temporal rotation (2011–2013 and 2014–2016). This aggregation strategy was chosen to reflect the cumulative effects of management practices over a full rotation cycle and to limit the influence of interannual variability.

Linear Mixed Models (LMM) were fitted to predict each performance indicator as a function of rotation treatment (LI, VLI-CM, and VLI-SM), the presence or absence of CC during the fallow period, and their interaction, which were specified as fixed effects. Blocks and temporal rotations (2011–2013 or 2014–2016) were included as random effects to account for spatial structure and temporal dependency inherent to the experimental design. In cases where LMMs resulted in singular fit, indicating negligible variance associated with one or more random effects, models were progressively simplified. First, block was included as a fixed effect; if singularity persisted, a linear model including all terms as fixed effects was fitted. The significance of fixed effects was assessed using Wald χ^2 tests for LMMs and F-tests for linear models. When significant effects were detected, pairwise comparisons based on estimated marginal means were performed to identify differences between factor levels, thereby facilitating a detailed interpretation of treatment effects. Pooling data at the subplot and temporal rotation levels reduced the number of sampling units from 18 (three blocks observed over six years) to 6 (three blocks observed over two temporal rotations). Although this approach reduced sample size, it substantially decreased the proportion of zero values and overall variability in the dataset, thereby improving model stability and the reliability of statistical inference. To assess the robustness of this aggregation strategy, a complementary analysis was conducted using non-pooled data. This secondary analysis relied on LMMs with the same fixed effects as described above, while including block and cropping season as random effects. The same model simplification procedure was applied when singular fits were detected, allowing for a consistent comparison between analytical approaches.

As pesticide residues can exhibit contrasting behaviours in soil depending on their physicochemical properties, differences in pesticide quantities in water were also exanimated at the individual compound level across cropping systems. This compound-specific analysis allowed for a more refined assessment of potential differential leaching dynamics among systems. Given the low concentrations of pesticide losses observed for individual compounds and the high variability among samples, LMMs were not suitable. To address these limitations, the concentration of each compound in leachates was therefore summed per subplot over the three years of each temporal rotation. This aggregation approach increased the signal-to-noise ratio and enabled a more robust statistical comparison at the rotation scale. The resulting data were analysed using permutation-based ANOVA (10,000 permutations) with a restricted permutation scheme by block and temporal rotation, in order to respect the experimental design. This non-parametric framework was specifically chosen because it does not rely on assumptions of normality or homoscedasticity, making it well suited to sparse and highly variable environmental concentration data. In parallel with the analysis conducted at the system level, individual pesticide concentrations in leachates were also analysed using non-pooled data at the subplot and cropping season levels. In this case, permutation-based ANOVA was applied with a restricted permutation scheme by block and cropping season, ensuring consistency with the underlying spatial and temporal structure of the experiment.

To attempt to explain the patterns of water drainage and leaching observed, relationships between these variables and potential relevant covariables were assessed. For water drainage, relationships with the sum of the crop biomass, CC biomass, duration of the CC (from sowing to destruction) and number of tillage operations were assessed. For pesticide losses, relationships with water drainage over the three years of the temporal rotation, quantity of pesticides applied, crop biomass, CC biomass, duration of the CC and number of tillage operations were assessed. The same was done for nitrate leaching, except that the quantity of pesticides applied was replaced with the quantity of N applied. To assess these relationships, LMM were fitted to explain the given variable as a function of a covariable, considered as a fixed effect, and the temporal rotation, considered as a random factor. A Wald χ^2 test was then performed to test the effect of the fixed covariable. The rotation and presence of CC was not included in these LMM due to the few datapoints available per system (only six) to test a linear relationship.

All statistics were performed using R software (v. 4.3.1) (R Core Team, 2024) with packages such as *lme4* (Bates, 2010), *emmeans* (Lenth and Lenth, 2018), *car* (Fox et al., 2012), and *permuco* (Frossard and Renaud, 2021).

3. Results

Results of the analysis performed without pooling data by temporal rotation are presented in Fig. S1, S2 and Table S3 and S5. Overall, this complementary analysis revealed similar patterns of CC and rotation treatment effects that were consistent with those obtained using pooled data, thereby supporting the generality of the observed responses. However, five out of nine of the initial LMMs fitted for this analysis exhibited singular fit issues, reflecting limited variance associated with random effects and reduced model reliability at this level of data resolution. As a result, the interpretation of results was primarily based on the analysis using data pooled per temporal rotation, for which model statistical inference was more robust. Furthermore, the analysis of the individual pesticide concentrations in leachates at the subplot and cropping season levels yielded results identical to those obtained with data pooled by temporal rotation (Table S4). This match across analytical scales further demonstrates the robustness of the findings and confirms that the main conclusions are not sensitive to the chosen data aggregation strategy.

3.1. Effects of rotations and cover crops on the inputs applied

The total quantity of pesticides applied per cropping system did not differ significantly among the three rotation and was not influenced by

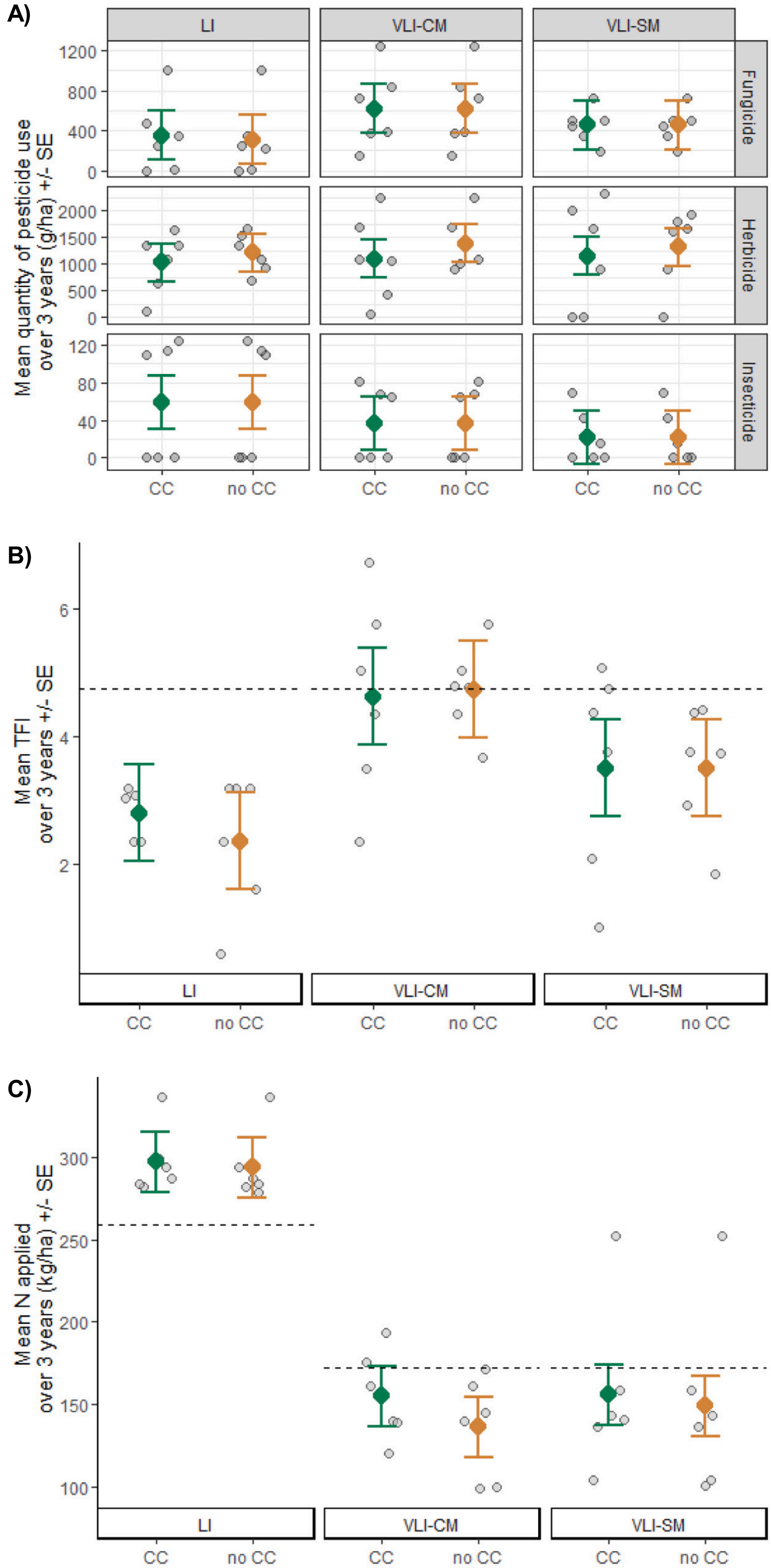

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Fig. 3. A) Mean (Estimated Marginal Mean, EMM) quantity of active ingredient per pesticide class per cropping system (summed over the three years of a temporal rotation of the system) (g/ha); B) mean (EMM) Treatment Frequency Index (TFI) per cropping system over three years; and C) mean (EMM) quantity of N fertiliser applied per cropping system over three years (kg N/ha). Error bars represent the standard error of the mean. The rotation treatments tested are low input (LI), very low input - cultivar mixture (VLI-CM) or very low input - species mixture (VLI-SM). Each rotation was cropped with cover crops (CC) (CC: green dots) or without CC (no CC: brown dots), which resulted in six cropping systems. Individual values per plot are represented by grey dots. Horizontal dashed lines represent the targeted values for TFI and N application depending on the rotation treatment. Results of the statistical tests performed to test differences between rotation treatments, and the effect of CC use are presented in the text Section 3.1 and Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

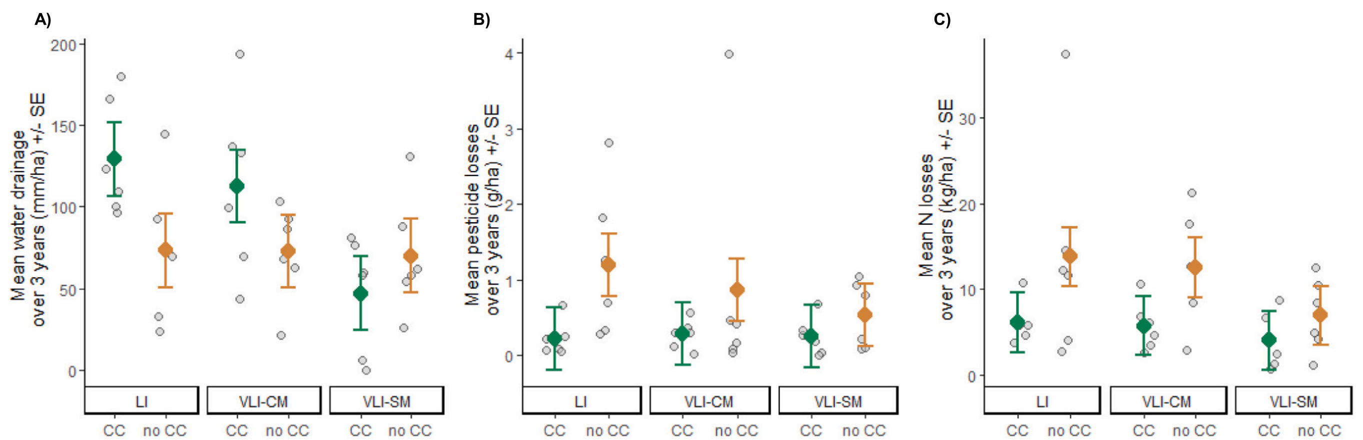

Fig. 4. Mean (Estimated Marginal Mean) (A) drainage (mm/ha), (B) pesticide losses (g/ha) and (C) nitrogen losses (kg/ha) per cropping system. Error bars represent the standard error of the mean. The rotation tested are low input (LI), very low input - cultivar mixture (VLI-CM) or very low input - species mixture (VLI-SM). Each rotation was cropped with cover crops (CC) (CC: green dots) or without CC (no CC: brown dots), which resulted in six cropping systems. Individual values per plot are represented by grey dots. Results of the statistical tests performed to test differences between rotation treatments, and the effect of CC use are presented in the text Section 3.2 and Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the presence of a CC (Table 2). Herbicides were used the most among the pesticide classes (mean of 1194 g/ha for all systems), with system LI using the least (1116 g/ha) and VLI-CM using the most (1234 g/ha) (Fig. 3A). No effect of the rotation, the CC or their interaction was observed on herbicide use (Table 2). Fungicides were the second-most-used class of pesticides (mean of 465 g/ha for all systems). LI used significantly less fungicides than VLI-CM did (327 and 618 g/ha, respectively), but its fungicide use did not differ from that of VLI-SM (452 g/ha) (Table 2). Insecticides were the least-used classes of pesticides (mean of 38.3 g/ha for all systems) and were significantly more used, in LI (58.0 g/ha) than in VLI-CM (35.5 g/ha) and VLI-SM (21.3 g/ha) (Table 2).

The TFI, an index of pesticide use accounting for the toxicity of the active ingredients, of the six cropping systems was lower than that commonly used in the 2-year rotation of durum wheat-sunflower in the Occitanie region of south-western France (average of 9.45 over three years (Agreste, 2019)). Specifically, the TFI was reduced by 50% and 51% in VLI-CM and VLI-CM-CC, respectively, 63% in both VLI-SM and VLI-SM-CC, and 70% and 75% in LI and LI-CC, respectively. The TFI differed significantly between the three rotation treatments with VLI—CM the highest (TFI of 4.67), LI the lowest (TFI of 2.57) and as intermediary VLI-SM (TFI of 3.50) (Fig. 3B, Table 2). For VLI—CM, the highest TFI over the six cropping seasons (2.43) was observed for durum wheat. For VLI-SM, the highest TFI (1.91) was observed for the crop mixture of soft wheat and faba bean, whereas for LI, the highest TFI (1.04) was observed for sorghum.

The quantity of N fertiliser applied differed significantly among the three rotation treatments, in agreement with the experimental design, particularly the objective of applying less N fertiliser in VLI than in LI due to growing legumes in the former (Fig. 3C, Table 2).

3.2. Effects of cropping systems on drainage and nitrate and pesticide losses

Water drainage differed significantly among rotation treatments, with VLI-SM having significantly less drainage than LI and VLI-CM (Fig. 4A). The presence of CC and its interaction with the rotation treatment significantly influenced water drainage, with higher drainage observed in plots with CC than without CC (Table 2). Cropping systems with CC tended to have higher drainage in LI and VLI-CM, but the opposite was observed for VLI-SM. Nevertheless, the differences in water volumes remained low.

Over the six cropping seasons, 539 leachate samples were collected and analysed, with a mean of 2.5 samples per year per lysimeter (range = 0 to 5). These samples contained a mean of 7.2 L per year per plot (range = 575 mL to 20.2 L) of drained water. Overall, 79 and 51 samples contained at least one pesticide compound with a concentration higher than 0.1 or 0.5 μg/L, respectively, which are the two thresholds for potable drinking water captured from surface or groundwater sources (European Union (EU) Water Framework Directive 2000/60/CE). Sixteen of the samples had a total concentration of all pesticide compounds higher than 2 μg/L, which makes the water undrinkable even after purification (EU Water Framework Directive 2000/60/CE). These concentrations provide an estimate of potential pesticide concentrations in the groundwater if equivalent transfers occur over larger areas.

Pesticide leaching did not differ significantly among rotation treatments, but the presence of CC had a significant effect, with systems with CC having lower pesticide losses than those without CC (Fig. 4B, Table 2). Comparing rotations with CC to those without CC, the presence of CC reduced pesticide leaching greatly: by 82% in LI, 68% in VLI-CM and 53% in VLI-SM.

Nitrate leaching had a pattern similar to that of pesticide leaching (Fig. 4C). Wald χ^2 test showed a no significant effect of the rotation treatment on nitrate leaching (Table 2). A significant reduction in nitrate leaching in systems with CC compared to those without CC was

Table 3
Mean pesticide losses per cropping system (mg/ha) (standard error) for each pesticide molecule detected, whether applied or not during the experiment. LI (low input), VLI-CM (very low input with cultivar mixture), VLI-SM (very low input with species mixture). Cropping systems are divided into those with a cover crop (CC) or without them.

			Mean (SE) pesticide losses over three years (mg/ha)					
Applied during the experiment	Classes	Compounds	LI CC	LI	VLI-CM CC	VLI-CM	VLI-SM CC	VLI-SM
Yes	Fungicides	Boscalid			0.76 (0.76)			
		Cyproconazole			0.14 (0.14)	1.49 (1.49)		
		Epoxyconazole			4.27 (4.27)			
		Metalaxyl	10.01 (9.78)	5.96 (5.96)	3.2 (2.45)	24.2 (12.41)		4.59 (4.59)
		Metconazole					0.3 (0.3)	
		Pyrimethanil		0.38 (0.38)		0.4 (0.4)		
		Tebuconazole			1.37 (1.37)			
	Herbicides	Aminomethylphosphonique acid (metabolite of glyphosate)			2.81 (2.81)	1.76 (1.76)		3.31 (2.46)
		Flurochloridone		2.6 (2.6)				
		Glyphosate	4.94 (3.25)	3.21 (3.21)		1.18 (1.18)		6.78 (6.78)
		Mesosulfuron-Methyl		1.76 (1.76)				
		S-Metolachlore	108.85 (73.69)	999.84 (336.65)	105.85 (72.92)	652.26 (420.66)	129.41 (64.8)	334.97 (267.12)
	Insecticides	Imidacloprid	20.41 (15.88)	61.1 (60.87)	22.91 (18.38)	42.82 (41.07)	3.15 (3.15)	
No (applied before the experiment)	Fungicides	Flusilazole	1.05 (1.05)					
		Prothioconazole	6.44 (6.44)	5.84 (5.84)	8.71 (8.71)	4.34 (4.34)	4.65 (4.65)	6.04 (6.04)
	Herbicides	2,4-MCPA			0.28 (0.28)	0.1 (0.1)		
		Atrazine			0.21 (0.21)		0.19 (0.19)	
		Atrazine-desethyl (metabolite of atrazine)	1.6 (1.11)	7.76 (5.21)	4.4 (4.4)	3.05 (2.53)		
		Bentazone	0.19 (0.19)	0.74 (0.74)	4.31 (3.03)	3.86 (2.01)	4.68 (3.75)	7.69 (3.53)
		Chlortoluron				2.59 (2.59)		
		DiNitroOrthoCresol		0.48 (0.48)		0.46 (0.46)		
		Dinoterbe	0.23 (0.23)	2.53 (2.53)				
		Diuron						8.14 (8.14)
		Fenuron	44.68 (19.21)	103.09 (47.65)	87.29 (44.9)	105.9 (78.45)	94.73 (52.48)	152.75 (84.69)
		Glufosinate of ammonium			10.6 (10.6)			
		Hydroxyatrazine-2-hydroxy (metabolite of atrazine)	7 (5.05)		1.89 (1.89)	4 (2.64)		
		Hydroxyterbuthylazine (metabolite of atrazine)	0.1 (0.1)		4.43 (4.43)	2 (2)	5.94 (5.94)	
		Mecoprop-P			0.34 (0.34)			
		Metribuzine	0.37 (0.37)					
		Monuron	0.23 (0.23)	0.48 (0.48)	3.17 (3.17)	0.55 (0.55)	3.82 (3.82)	0.19 (0.19)
		Sebuthylazine	0.37 (0.37)					
		Simazine-2-hydroxy (metabolite of artazine)	5.45 (5.45)		5.07 (4.6)	3.57 (3.1)	0.47 (0.47)	
		Terbutylazine				0.1 (0.1)		
		Triclopyr			0.11 (0.11)			
	Insecticides	Hexythiazox	1.62 (0.73)	1.52 (1.24)	1.77 (1.58)	0.89 (0.7)		
		Oxydemeton-methyl	1.93 (1.93)		0.82 (0.82)	1.98 (1.98)		
	Other	Piperonyl-butoxide						2.71 (2.71)

observed: 56% in LI, 55% in VLI-CM and 42% in VLI-SM.

3.3. Effects of rotation and cover crops on leaching of specific pesticide compounds

A total of 37 pesticide compounds and known degradation products were quantified in the leachate samples. The pesticide compounds found most frequently in drained water were herbicides and their degradation products (22 of the 37 compounds detected), followed by fungicides (12) and insecticides (3). Overall, 13 applied compounds were detected in the drained water, 24 applied compounds were not detected, and 24 detected compounds had not been applied during the six years of the experiment (Table 3).

Significant differences in compound quantities were found only for the degradation product of the herbicide atrazine, hydroxyatrazine-2-hydroxy (Table S4), but this compound was found in only seven out of 108 subplot-season combination.

3.4. Relationship between water drainage, pesticide losses, nitrate losses, and agronomic variables

Water drainage was not significantly influenced by crop biomass, CC biomass, CC duration or the number of tillage operations over the three years of the rotation (Fig. 5, Table 4). Pesticide losses decreased significantly as the number of operations increased but was not significantly influenced by the quantity of pesticides applied, the water drainage, the crop biomass, the CC biomass or the CC duration over the three years of the rotation (Fig. 6, Table 4). Nitrate leaching increased significantly as water drainage increased but was not significantly influenced by the quantity of N applied, crop biomass, CC biomass, CC duration, or the number of tillage operations over the three years of the rotation (Fig. 7, Table 4).

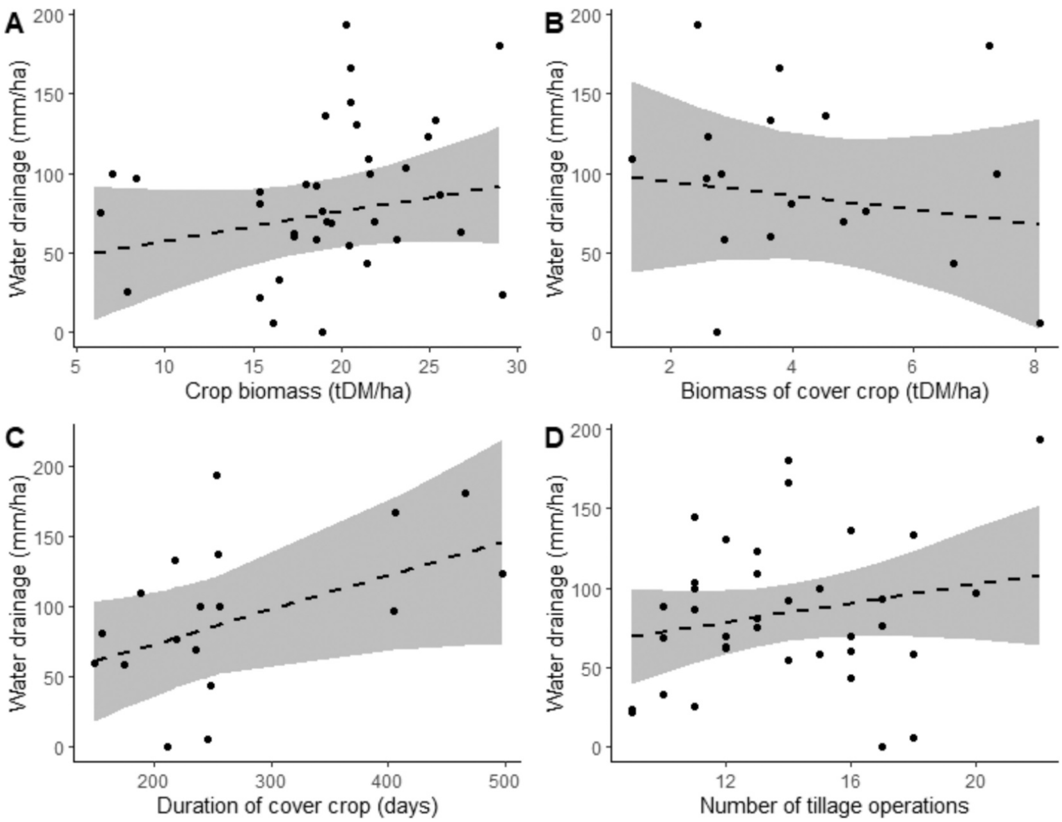

Fig. 5. Soil water drainage per plot over three years (mm/ha) for each cropping system as a function of (A) crop biomass (t DM/ha), (B) cover crop biomass (t DM/ha), (C) duration (days) of the cover crop and (D) number of tillage operations. Black lines indicate linear mixed-model regressions between the two variables using the year as random factor, and grey shading indicates the 95% confidence interval. Solid and dashed lines represent significant ($p < 0.05$) and non-significant regressions, respectively.

4. Discussion

4.1. Pesticide and fertiliser use can be reduced greatly in cropping systems

The cropping systems tested in this study were designed to reduce pesticide use by 50% compared to that in the current 2-year rotation that farmers have practiced for decades in the Occitanie region of France. This underlying objective was met for all systems, with an effective mean reduction in TFI, an indicator of pesticide use accounting for the quantity of pesticides use and their reference doses, of 50–75% during the experiment compared to the reference for farmers in the region. However, even if mean values reached the target reduction, the variability in the experiment led to some specific cropping systems having higher values than the objective, mainly in the VLI-CM treatment. Rotation LI had a significantly lower TFI than VLI-SM and VLI-SM had a significantly lower TFI than VLI-CM did, and the presence of CC did not decrease yield because they were managed effectively, particularly by using mechanical destruction instead of chemical destruction (Bonnet et al., 2021). However, the total quantity of pesticides applied did not differ significantly among cropping systems, and fungicide use differed significantly only between LI and VLI-CM. Contrary to the initial objective, the most diversified systems studied (VLI-CM and VLI-SM) still depended on pesticides, especially herbicides, in part due to the presence of winter crops, which depend more on herbicides to reduce yield losses than other crops do. Indeed, weeds are easier to manage mechanically in spring crops than in winter crops, because autumn and winter weather is often unsuitable for mechanical weeding (Giuliano et al., 2016). Improving the design of and decision rules applied to highly diversified systems could help reduce the need for pesticides. For example, faba bean could be replaced by another legume crop, as it was highly sensitive to fungal diseases during the experiment (Bonnet et al., 2021), or always intercropped with a cereal crop to reduce fungal pressure (Luo et al., 2022).

The objectives were also to reduce N application by 25% in LI and 50% in VLI compared to that in the standard 2-year rotation. On average this objective was met for VLI treatments where a reduction of more than 50% was observed for almost all the cropping systems, but not for LI treatment where all cropping systems used more N (Bonnet et al., 2021). However, the quantity of N applied differed among rotations, with LI applying significantly more N than VLI did. In addition, the 50% reduction in N application in VLI-CM compared to that in LI did not reduce durum wheat or sunflower yields greatly (Bonnet et al., 2021). Introducing a legume crop into a rotation to precede durum wheat, which is the most N-demanding crop in the rotations, increased soil fertility and helped maintain high yields (Duchene et al., 2017; Kuo and Sainju, 1998; Stagnari et al., 2017).

4.2. Cover cropping is a key diversification practice to reduce pesticide and nitrate leaching

Over the six years, the cropping systems studied influenced water drainage differently, with a reduction on water drainage when intercropping is used compared to the two other rotation treatments. The lower drainage observed in the intercropping system compared with sole crops is consistent with a more efficient use of soil water by associated species. This effect is commonly attributed to functional complementarity in rooting depth and water uptake dynamics, leading to a more complete extraction of available water from the soil profile and reduced deep percolation (Brooker et al., 2015). Recent syntheses further indicate that intercropping systems enhance water use efficiency and reduce non-productive water losses, including drainage, relative to monocultures (Liu et al., 2025). Nevertheless, introducing CC into fallow

Table 4
Results of the Wald χ^2 and F-tests performed on models explaining different response variables. Significance levels: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Significant p-values are in bold.

Models	Response variables	Statistics	
Water drainage ~ Water input	Water input	$\chi^2_1 = 3.896$	**$p = 0.048$***
Water drainage ~ Crop biomass	Crop biomass	$\chi^2_1 = 0.519$	$p = 0.472$
Water drainage ~ Biomass of cover crop	Biomass of cover crop	$F_1 = 1.777$	$p = 0.192$
	Temporal rotation	$F_1 = 1.708$	$p = 0.2$
Water drainage ~ Duration of cover crop	Duration of cover crop	$F_1 = 4.233$	$p = 0.057$
	Temporal rotation	$F_1 = 0.302$	$p = 0.591$
Water drainage ~ Number of tillage operations	Number of tillage operations	$\chi^2_1 = 1.514$	$p = 0.219$
Pesticide losse ~ Quantity of pesticide applied	Quantity of pesticide applied	$\chi^2_1 = 0$	$p = 0.992$
Pesticide losse ~ Water drainage	Water drainage	$\chi^2_1 = 0.757$	$p = 0.384$
Pesticide losse ~ Crop biomass	Crop biomass	$\chi^2_1 = 0.233$	$p = 0.629$
Pesticide losse ~ Biomass of cover crop	Biomass of cover crop	$\chi^2_1 = 0.353$	$p = 0.552$
Pesticide losse ~ Duration of cover crop	Duration of cover crop	$\chi^2_1 = 0.070$	$p = 0.791$
Pesticide losse ~ Number of tillage operations	Number of tillage operations	$\chi^2_1 = 6.809$	**$p = 0.009$****
Nitrate losse ~ Quantity of N applied	Quantity of N applied	$\chi^2_1 = 2.184$	$p = 0.139$
Nitrate losse ~ Water drainage	Water drainage	$\chi^2_1 = 6.053$	**$p = 0.014$***
Nitrate losse ~ Crop biomass	Crop biomass	$\chi^2_1 = 0.489$	$p = 0.484$
Nitrate losse ~ Biomass of cover crop	Biomass of cover crop	$\chi^2_1 = 0.164$	$p = 0.686$
Nitrate losse ~ Duration of cover crop	Duration of cover crop	$\chi^2_1 = 1.101$	$p = 0.294$
Nitrate losse ~ Number of tillage operations	Number of tillage operations	$\chi^2_1 = 2.935$	$p = 0.087$

periods did not always reduce drainage, as predicted by Meyer et al. (2019) in soil-crop simulations. This occurs when CC are destroyed early in winter (from mid-February to early March), which avoids high evapotranspiration in spring and reduction of water drainage. The decision rule for destroying CC followed in this experiment was designed to avoid negative effects of CC on the water balance, and thus the water stress of the next cash crop. The decision rule also avoided reducing water drainage to limit impacts of CC on groundwater recharge (Bonnet et al., 2021). Finally, results of the present study agree with those in the literature that show heterogeneous effects of CC depending on the cropping system and climatic conditions (Nouri et al., 2022). The reduction in drainage that CC cause is often considered one of their major disservices (Meyer et al., 2019). However, this reduction is not inevitable, and other effects of CC, such as increasing water infiltration into the soil by improving soil fertility (Blanco-Canqui et al., 2022; Blanco-Canqui and Ruis, 2020), can counteract it. It is noteworthy that a decreasing trend in drainage was observed in VLI-SM with CC, unlike in the other five systems studied, perhaps due to maximising spatial and temporal occupation through species mixtures and growing CC during fallow periods, which led to high rates of photosynthesis and above- and belowground biomass production, and thus higher evapotranspiration over the rotation (Meyer et al., 2022).

While effects of CC on reducing nitrate leaching are well established in the literature (Constantin et al., 2015; Couëdel et al., 2018b; Di and Cameron, 2002; Nouri et al., 2022; Plaza-Bonilla et al., 2015; Tonitto et al., 2006; Tribouillois et al., 2015), the main originality of this study is the observation of similar effects on reducing the leaching of several pesticides, which to our knowledge had not been shown before. Other studies observed lower losses of atrazine or S-metolachlor from plots with plant cover, but the latter were summer plant covers that had high evapotranspiration, which reduced drainage (Potter et al., 2007; White et al., 2009). In the present study, as subplots with CC had less water drainage than those without CC, the reduction in pesticide losses was not due to a reduction in water drainage. No clear relationship between water drainage and pesticide losses was found. The effects of CC can be attributed to several factors that are difficult to identify in the field, but which have been highlighted in laboratory studies. For example, in a previous study of these plots, CC increased soil organic matter contents slightly compared to those of bare soil (Plaza-Bonilla et al., 2015), which can change pesticide sorption and thus increase pesticide retention in the soil, as observed for S-metolachlor and other pesticides (Alletto et al., 2013; Cassigneul et al., 2015). In contrast, increased soil organic matter contents can increase soil biological activity, which can increase the rate of pesticide mineralisation (Vinther et al., 2008). Finally, these results strengthen and enrich the concept of the multi-services that CC provide (Justes and Richard, 2017): CC can recycle nutrients, regulate pests, diseases and weeds (Couëdel et al., 2019) and reduce the pesticide leaching.

For the cropping systems without CC during the fallow period, there was a trend towards a reduction in nitrate and pesticide losses in the rotation with species mixtures (VLI-SM), despite having pesticide use (TFI and quantity of active ingredients) close to that of the other two rotations composed of monospecific cash crops. Lower nitrate leaching in intercropping systems than in sole-cropping systems has been observed in previous studies of cropping systems (Hauggaard-Nielsen et al., 2003; Mariotti et al., 2015; Nie et al., 2012), perhaps due to increased root competition in intercropping systems, which leads to deeper root development and greater nutrient acquisition (Hauggaard-Nielsen et al., 2001). This can lead to a final balance of processes towards net complementarity, as highlighted using the "4C" approach (Justes et al., 2021). Another potential explanation is that a high C:N ratio of the organic matter decreases mineralisation, which leads to slower degradation and release of soil N (Jensen et al., 2020). In contrast, it is difficult to draw conclusions or make comparisons about the trend towards lower pesticide losses with species mixtures, as nearly all published studies of species mixtures focus on organic farming systems (e.g., Bedoussac et al., 2015). Therefore, it would be valuable to perform additional research to better understand effects of intercropping on pesticide leaching in conventional cropping systems.

4.3. Most pesticide losses through leaching were S-metolachlor

Out of the 37 pesticide compounds and degradation products quantified in the leachate samples, S-metolachlor represented more than 50% of the quantity of pesticide losses in the drained water. This herbicide was used often during the experiment, representing 15–31% of the quantity of active ingredients applied, a quantity exceeded only by glyphosate (Table S6). Two of its degradation products – OXA and ESA-metolachlor – were not quantified because they were not considered 'relevant metabolites' under the EU Water Framework Directive during the experiment, but they could greatly increase the contribution of this active ingredient (Steele et al., 2008). S-metolachlor losses did not vary significantly between cropping systems which can be explained by the variability of the data, but follow the general trend of a reduction of the leaching with increase system diversity (Fig. S3A). Removing the S-metolachlor from the analysis changed the pattern of pesticide leaching and the effect of the presence of CC was no more observed (Fig. S3B). When pesticide compounds were taken individually, significant differences between rotation treatment or CC treatments were only found for the hydroxyatrazine-2-hydroxy. This is probably because of the low concentration and high variability of most of the molecules (Table 3). This result highlights that the effect of CC on pesticide leaching observed on this experiment is mainly driven by the S-metolachlor and that the

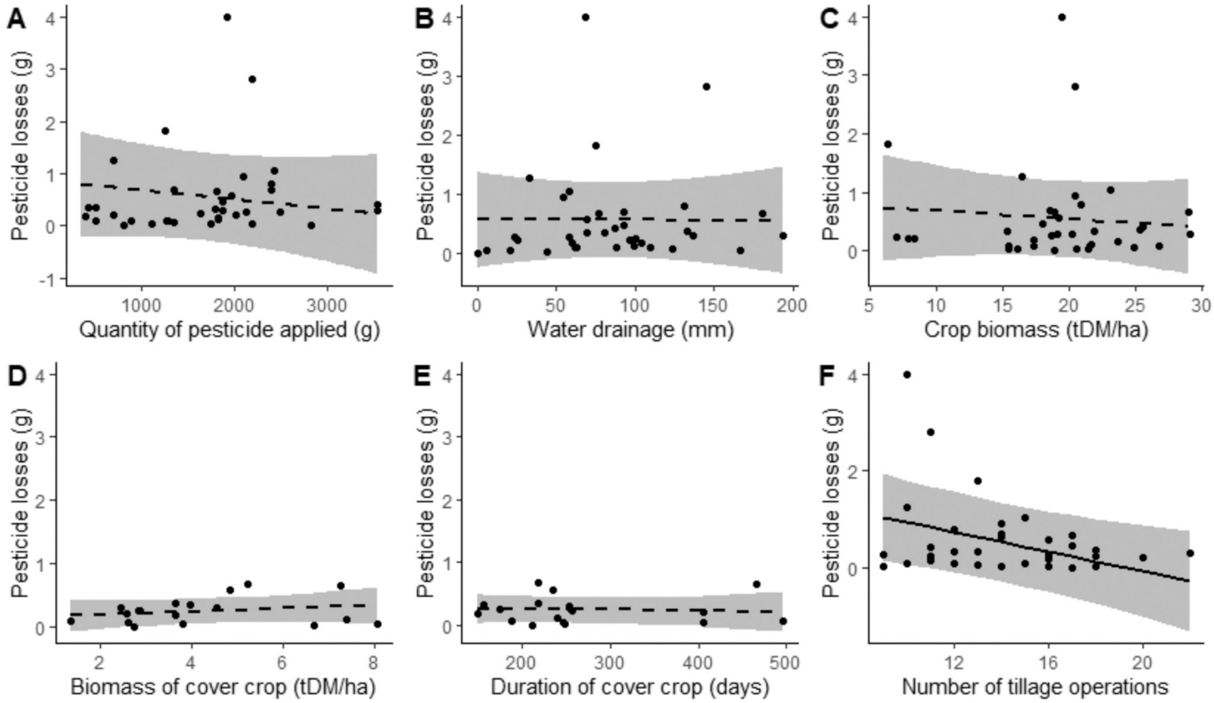

Fig. 6. Soil pesticide losses (g/ha) per plot over three years for each cropping system as a function of (A) the quantity of pesticides applied (g/ha), (B) water drainage (mm/ha), (C) crop biomass (t DM/ha), (D) cover crop biomass (t DM/ha), (E) duration (days) of the cover crop and (F) number of tillage operations. Black lines indicate linear mixed-model regressions between the two variables using the year as random factor, and grey shading indicates the 95% confidence interval. Solid and dashed lines represent significant ($p < 0.05$) and non-significant regressions, respectively.

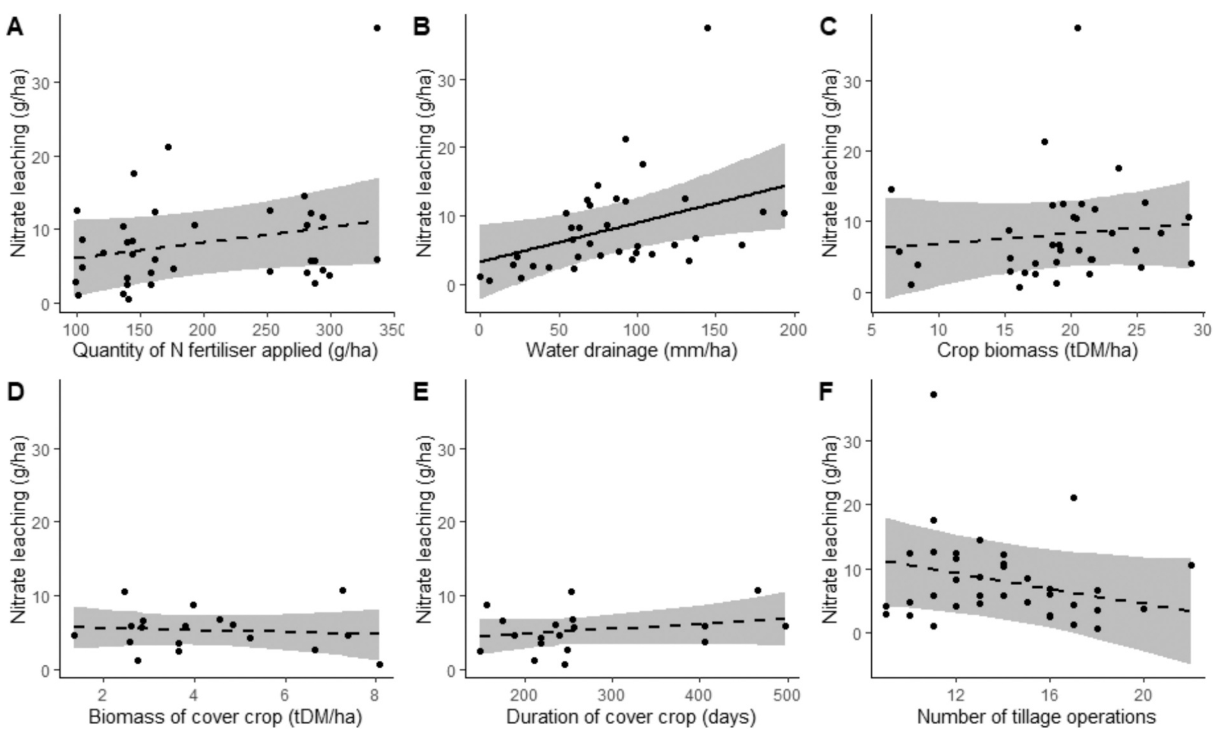

Fig. 7. Nitrate leaching (g/ha) per plot over three years for each cropping system as a function of (A) the quantity of nitrogen (N) fertiliser applied (g/ha), (B) water drainage (mm/ha), (C), crop biomass (t DM/ha), (D) cover crop biomass (t DM/ha), (E), duration (days) of the cover crop and (F) number of tillage operations (F). Black lines indicate linear mixed-model regressions between the two variables using the year as random factor, and grey shading indicates the 95% confidence interval. Solid and dashed lines represent significant ($p < 0.05$) and non-significant regressions, respectively.

effect of CC on pesticide leaching could vary depending on the set of pesticides used in the field and especially of the quantity of S-metolachlor used. This molecule is used by farmers for three decades on a wide variety of crops and has highly mobile degradation products. Currently, it is one of the herbicides detected most often in the groundwater of several countries (Halbach et al., 2021; Le Cor et al., 2021; Steele et al.,

2008) and CC could be used to mitigate the pollution related to this pesticide. Use of S-metolachlor was officially banned in the EU as of July 2024 (European Food Safety Authority (EFSA) et al., 2023), but is still used in many countries.

4.4. Persistence and legacy of pesticides

Of the 38 active compounds applied during the six years of the experiment, 13 were found in the leachates, but 24 of the detected compounds had not been applied during the experiment (Table S4). These compounds had been applied in previous field experiments at the same site, which illustrates the persistence of these active compounds in the top 1 m of the soil and in the environment. Some compounds such as atrazine, simazine and their degradation products (i.e., atrazine-desethyl, hydroxyatrazine-2-hydroxy and simazine-2-hydroxy) were frequently detected in the leachates, even though the use of both had been banned in France since 2003 (Gutierrez and Baran, 2009; Mahé et al., 2020). The detection of a larger number of legacy compounds than currently applied substances is consistent with previous long-term monitoring studies showing that pesticide residues and their transformation products can persist in soils and groundwater for decades after their last application (Baran et al., 2021; Lapworth et al., 2012). Several studies have reported the continued presence of atrazine, simazine and their metabolites in leachates and groundwater long after regulatory bans, highlighting the strong persistence and mobility of these compounds under field conditions (Jablonowski et al., 2011). This long-term persistence has been attributed to a combination of slow degradation rates, strong sorption to soil organic matter and clay fractions, and the formation of non-extractable residues that may be gradually remobilized over time (Fenner et al., 2013; Gevao et al., 2000). Field-based evidence further suggests that preferential flow pathways and episodic drainage events can contribute to the delayed transport of historical pesticide residues towards deeper soil layers and drainage systems (Flury, 1996; Köhne et al., 2009). Similar observations have been reported across a wide range of pedoclimatic contexts, indicating that legacy pesticide contamination is a widespread phenomenon rather than a site-specific anomaly (Silva et al., 2019). This result illustrates the long-term persistence of some pesticides in the soil and the need for long term monitoring of pesticides to identify the effect of agricultural practices on pesticide pollutions. Taken together, our results emphasize that assessments of pesticide pollution based solely on current application practices may substantially underestimate environmental contamination, and that historical pesticide use must be considered when evaluating the effectiveness of cropping systems and mitigation strategies.

5. Conclusions

This study showed that large reductions in pesticide use, exceeding 50% compared to conventional application rates, can be achieved in cropping systems by implementing diversification strategies. These results provide valuable support for major European initiatives aimed at reducing pesticide use, such as the French Ecophyto plan and the European Research Alliance's "Towards a Chemical Pesticide-Free Agriculture." The results also contribute to the growing body of evidence that shows that CC can reduce nitrate leaching greatly. In particular, this effect was consistent even in cropping systems with a large proportion of legumes. The main originality of this study is the observation that introducing CC can significantly reduce the leaching losses of a wide variety of pesticides, including herbicides such as S-metolachlor, which is one of the compounds most commonly detected in groundwater. This result highlights the potential of CC to mitigate a major pathway of pesticide contamination of water resources. These results highlight the multifunctionality of CC by showing their agronomic benefits and environmental value for a variety of cropping systems. Moreover, other diversification strategies, such as intercropping, also appear to help mitigate environmental impacts, but additional targeted research is required to quantify their specific effects more precisely. Although all of the systems studied were low-input, particularly for fertilisers and pesticides, large losses of nitrate and pesticides were still observed, sometimes exceeding the thresholds set at European level for water quality. This highlights the need for real, ambitious and sustainable changes in the way agricultural systems are managed in order to achieve environmental quality objectives.

CRediT authorship contribution statement

Gaëtan Seimandi-Corda: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Eric Justes:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Benoit Gleizes:** Methodology, Investigation. **Eric Lecloux:** Methodology, Investigation. **Eric Bazerthe:** Methodology, Investigation. **Lionel Alletto:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Code availability

The R-code used during the current study is available from the corresponding author on reasonable request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.104719.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R.M., Smith, P., 2019. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. Glob. Chang. Biol. 25, 2530–2543. https://doi.org/10.1111/gcb.14644.

Adetunji, A.T., Ncube, B., Mulidzi, R., Lewu, F.B., 2020. Management impact and benefit of cover crops on soil quality: a review. Soil Tillage Res. 204, 104717. https://doi.org/10.1016/j.still.2020.104717.
Agreste, 2019. Pratiques Culturales en Grandes Cultures en 2017 [WWW Document]. URL https://draaf.occitanie.agriculture.gouv.fr/IMG/pdf/premiers_resultats_pkgc_2017_cle8ff4e6.pdf (accessed 9.16.24).
Alletto, L., Coquet, Y., Benoit, P., Heddadj, D., Barriuso, E., 2010. Tillage management effects on pesticide fate in soils. A review. Agron. Sustain. Dev. 30, 367–400. https://doi.org/10.1051/agro/2009018.
Alletto, L., Benoit, P., Bolognési, B., Couffignal, M., Bergheaud, V., Dumény, V., Longueval, C., Barriuso, E., 2013. Sorption and mineralisation of S-metolachlor in soils from fields cultivated with different conservation tillage systems. Soil Tillage Res. 128, 97–103. https://doi.org/10.1016/j.still.2012.11.005.
Arias-Estévez, M., López-Periago, E., Martínez-Carballo, E., Simal-Gándara, J., Mejuto, J.-C., García-Río, L., 2008. The mobility and degradation of pesticides in soils and the pollution of groundwater resources. Agric. Ecosyst. Environ. 123, 247–260. https://doi.org/10.1016/j.agee.2007.07.011.
Baran, N., Surdyk, N., Auterives, C., 2021. Pesticides in groundwater at a national scale (France): impact of regulations, molecular properties, uses, hydrogeology and climatic conditions. Sci. Total Environ. 791, 148137. https://doi.org/10.1016/j.scitotenv.2021.148137.
Bates, D.M., 2010. lme4: Mixed-Effects Modeling With R.
Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L., Justes, E., 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron. Sustain. Dev. 35, 911–935. https://doi.org/10.1007/s13593-014-0277-7.
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. Chang. Biol. 27, 4697–4710. https://doi.org/10.1111/gcb.15747.
Blanco-Canqui, H., Ruis, S.J., 2020. Cover crop impacts on soil physical properties: a review. Soil Sci. Soc. Am. J. 84, 1527–1576. https://doi.org/10.1002/saj2.20129.
Blanco-Canqui, H., Ruis, S.J., Holman, J.D., Creech, C.F., Obour, A.K., 2022. Can cover crops improve soil ecosystem services in water-limited environments? A review. Soil Sci. Soc. Am. J. 86, 1–18. https://doi.org/10.1002/saj2.20335.
Boix-Fayos, C., de Vente, J., 2023. Challenges and potential pathways towards sustainable agriculture within the European green Deal. Agric. Syst. 207, 103634. https://doi.org/10.1016/j.agsy.2023.103634.
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, 65. https://doi.org/10.1007/s13593-021-00719-7.
Brooker, R.W., Bennett, A.E., Cong, W., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P.M., Jones, H.G., Karley, A.J., Li, L., McKenzie, B.M., Pakeman, R.J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C.A., Zhang, C., Zhang, F., Zhang, J., White, P.J., 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytol. 206, 107–117. https://doi.org/10.1111/nph.13132.
Cassigneul, A., Alletto, L., Benoit, P., Bergheaud, V., Etiévant, V., Dumény, V., Le Gac, A. L., Chuette, D., Rumpel, C., Justes, E., 2015. Nature and decomposition degree of cover crops influence pesticide sorption: quantification and modelling. Chemosphere 119, 1007–1014. https://doi.org/10.1016/j.chemosphere.2014.08.082.
Constantin, J., Le Bas, C., Justes, E., 2015. Large-scale assessment of optimal emergence and destruction dates for cover crops to reduce nitrate leaching in temperate conditions using the STICS soil–crop model. Eur. J. Agron. 69, 75–87.
Couëdel, A., Alletto, L., Justes, É., 2018a. Crucifer-legume cover crop mixtures provide effective sulphate catch crop and sulphur green manure services. Plant Soil 426, 61–76. https://doi.org/10.1007/s11104-018-3615-8.
Couëdel, A., Alletto, L., Tribouillois, H., Justes, É., 2018b. Cover crop crucifer-legume mixtures provide effective nitrate catch crop and nitrogen green manure ecosystem services. Agric. Ecosyst. Environ. 254, 50–59.
Couëdel, A., Kirkegaard, J., Alletto, L., Justes, E., 2019. Crucifer-legume cover crop mixtures for biocontrol: toward a new multi-service paradigm. Adv. Agron. 157, 55–139.
de Vries, W., 2021. Impacts of nitrogen emissions on ecosystems and human health: a mini review. Curr. Opin. Environ. Sci. Health 21, 100249. https://doi.org/10.1016/j.coesh.2021.100249.
Di, H.J., Cameron, K.C., 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. Nutr. Cycl. Agroecosyst. 64, 237–256.
Duchene, O., Vian, J.-F., Celette, F., 2017. Intercropping with legume for agroecological cropping systems: complementarity and facilitation processes and the importance of soil microorganisms. A review. Agric. Ecosyst. Environ. 240, 148–161.
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, 1259–1281. https://doi.org/10.1007/s13593-015-0306-1.
European Food Safety Authority (EFSA), Alvarez, F., Arena, M., Auteri, D., Binaglia, M., Castoldi, A.F., Chiusolo, A., Colagiorgi, A., Colas, M., Crivellente, F., De Lentdecker, C., De Magistris, I., Egsmose, M., Fait, G., Ferilli, F., Gouliarmou, V., Nogareda, L.H., Ippolito, A., Istace, F., Jarrah, S., Kardassi, D., Kienzler, A., Lanzoni, A., Lava, R., Leuschner, R., Linguadoca, A., Lythgo, C., Magrans, O., Mangas, I., Miron, I., Molnar, T., Padovani, L., Panzarea, M., Parra Morte, J.M., Rizzuto, S., Serafimova, R., Sharp, R., Szentes, C., Szoradi, A., Terron, A., Theobald, A., Tiramani, M., Vianello, G., Villamar-Bouza, L., 2023. Peer review of the pesticide risk assessment of the active substance S-metolachlor excluding the assessment of the endocrine disrupting properties. EFSA J. 21. https://doi.org/10.2903/j.efsa.2023.7852.
Fenner, K., Canonica, S., Wackett, L.P., Elsner, M., 2013. Evaluating pesticide degradation in the environment: blind spots and emerging opportunities. Science 341, 752–758. https://doi.org/10.1126/science.1236281.
Flury, M., 1996. Experimental evidence of transport of pesticides through field soils—a review. J. Environ. Qual. 25, 25–45. https://doi.org/10.2134/jeq1996.00472425002500010005x.
Fox, J., Weisberg, S., Adler, D., Bates, D., Baud-Bovy, G., Ellison, S., Firth, D., Friendly, M., Gorjanc, G., Graves, S., 2012. Package 'car.' Vienna R. Found. Stat. Comput. 16, 333.
Frossard, J., Renaud, O., 2021. Permutation tests for regression, ANOVA, and comparison of signals: the permuco package. J. Stat. Softw. 99, 1–32.
Gevao, B., Semple, K.T., Jones, K.C., 2000. Bound pesticide residues in soils: a review. Environ. Pollut. 108, 3–14.
Giuliano, S., Ryan, M.R., Véricel, G., Rametti, G., Perdrieux, F., Justes, E., Alletto, L., 2016. Low-input cropping systems to reduce input dependency and environmental impacts in maize production: a multi-criteria assessment. Eur. J. Agron. 76, 160–175.
Gu, C., Bastiaans, L., Anten, N.P.R., Makowski, D., van der Werf, W., 2021. Annual intercropping suppresses weeds: a meta-analysis. Agric. Ecosyst. Environ. 322, 107658. https://doi.org/10.1016/j.agee.2021.107658.
Gutierrez, A., Baran, N., 2009. Long-term transfer of diffuse pollution at catchment scale: respective roles of soil, and the unsaturated and saturated zones (Brévilles, France). J. Hydrol. 369, 381–391.
Halbach, K., Möder, M., Schrader, S., Liebmann, L., Schäfer, R.B., Schneeweiss, A., Schreiner, V.C., Vormeier, P., Weisner, O., Liess, M., Reemtsma, T., 2021. Small streams–large concentrations? Pesticide monitoring in small agricultural streams in Germany during dry weather and rainfall. Water Res. 203, 117535. https://doi.org/10.1016/j.watres.2021.117535.
Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2001. Temporal and spatial distribution of roots and competition for nitrogen in pea-barley intercrops–a field study employing 32P technique. Plant Soil 236, 63–74.
Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2003. The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. Nutr. Cycl. Agroecosyst. 65, 289–300. https://doi.org/10.1023/A:1022612528161.
Huang, T., Döring, T.F., Zhao, X., Weiner, J., Dang, P., Zhang, Maoxue, Zhang, Miaomiao, Siddique, K.H.M., Schmid, B., Qin, X., 2024. Cultivar mixtures increase crop yields and temporal yield stability globally. A meta-analysis. Agron. Sustain. Dev. 44, 28. https://doi.org/10.1007/s13593-024-00964-6.
Jablonowski, N.D., Schäffer, A., Burauel, P., 2011. Still present after all these years: persistence plus potential toxicity raise questions about the use of atrazine. Environ. Sci. Pollut. Res. 18, 328–331. https://doi.org/10.1007/s11356-010-0431-y.
Jensen, E.S., Carlsson, G., Hauggaard-Nielsen, H., 2020. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis. Agron. Sustain. Dev. 40, 5. https://doi.org/10.1007/s13593-020-0607-x.
Justes, E., Richard, G., 2017. Contexte, concepts et définition des cultures intermédiaires multi-services. Innov. Agron. 62, 1–15.
Justes, E., Bedoussac, L., Dordas, C., Frak, E., Louarn, G., Boudsocq, S., Journet, E.-P., Lithourgis, A., Pankou, C., Zhang, C., Carlsson, G., Jensen, E.S., Watson, C., Li, L., 2021. The 4 c approach as a way to understand species interactions determining intercropping productivity. Front. Agric. Sci. Eng. 0, 0. https://doi.org/10.15302/J-FASE-2021414.
Köhne, J.M., Köhne, S., Šimuunek, J., 2009. A review of model applications for structured soils: b pesticide transport. J. Contam. Hydrol. 104, 36–60.
Koricheva, J., Hayes, D., 2018. The relative importance of plant intraspecific diversity in structuring arthropod communities: a meta-analysis. Funct. Ecol. 32, 1704–1717. https://doi.org/10.1111/1365-2435.13062.
Kuo, S., Sainju, U.M., 1998. Nitrogen mineralization and availability of mixed leguminous and non-leguminous cover crop residues in soil. Biol. Fertil. Soils 26, 346–353.
Lapworth, D.J., Baran, N., Stuart, M.E., Ward, R.S., 2012. Emerging organic contaminants in groundwater: a review of sources, fate and occurrence. Environ. Pollut. 163, 287–303.
Le Cor, F., Slaby, S., Dufour, V., Iuretig, A., Feidt, C., Dauchy, X., Banas, D., 2021. Occurrence of pesticides and their transformation products in headwater streams: contamination status and effect of ponds on contaminant concentrations. Sci. Total Environ. 788, 147715. https://doi.org/10.1016/j.scitotenv.2021.147715.
Lenth, R., Lenth, M.R., 2018. Package 'lsmeans'. Am. Stat. 34, 216–221.
Li, C., Hoffland, E., Kuyper, T.W., Yu, Y., Zhang, C., Li, H., Zhang, F., van der Werf, W., 2020. Syndromes of production in intercropping impact yield gains. Nat. Plants 6, 653–660. https://doi.org/10.1038/s41477-020-0680-9.
Liu, H., Gao, X., Li, C., Cai, Y., Song, X., Zhao, X., 2025. Intercropping increases plant water availability and water use efficiency: a synthesis. Agric. Ecosyst. Environ. 379, 109360. https://doi.org/10.1016/j.agee.2024.109360.
Locke, M.A., Bryson, C.T., 1997. Herbicide-soil interactions in reduced tillage and plant residue management systems. Weed Sci. 45, 307–320. https://doi.org/10.1017/S0043174500092882.
Luo, C., Lv, J., Guo, Z., Dong, Y., 2022. Intercropping of Faba bean with wheat under different nitrogen levels reduces Faba bean rust and consequent yield loss. Plant Dis. 106, 2370–2379. https://doi.org/10.1094/PDIS-11-21-2451-RE.
Mahé, I., Gauvrit, C., Angevin, F., Chauvel, B., 2020. What Lessons Can Be Learned From the Atrazine Ban in the Context of the Future Withdrawal of Glyphosate?.

Mariotti, M., Masoni, A., Ercoli, L., Arduini, I., 2015. Nitrogen leaching and residual effect of barley/field bean intercropping. Plant Soil Environ. https://doi.org/10.17221/832/2014-PSE.
Meyer, N., Bergez, J.-E., Constantin, J., Justes, E., 2019. Cover crops reduce water drainage in temperate climates: a meta-analysis. Agron. Sustain. Dev. 39, 3. https://doi.org/10.1007/s13593-018-0546-y.
Meyer, N., Bergez, J.-E., Justes, E., Constantin, J., 2022. Influence of cover crop on water and nitrogen balances and cash crop yield in a temperate climate: a modelling approach using the STICS soil-crop model. Eur. J. Agron. 132, 126416.
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.
Nie, S., Eneji, A.E., Chen, Y., Sui, P., Huang, J., Huang, S., 2012. Nitrate leaching from maize intercropping systems with N fertilizer over-dose. J. Integr. Agric. 11, 1555–1565. https://doi.org/10.1016/S2095-3119(12)60156-7.
Nouri, A., Lukas, S., Singh, Shikha, Singh, Surendra, Machado, S., 2022. When do cover crops reduce nitrate leaching? A global meta-analysis. Glob. Chang. Biol. 28, 4736–4749. https://doi.org/10.1111/gcb.16269.
Osipitan, O.A., Dille, J.A., Assefa, Y., Knezevic, S.Z., 2018. Cover crop for early season weed suppression in crops: systematic review and meta-analysis. Agron. J. 110, 2211–2221. https://doi.org/10.2134/agronj2017.12.0752.
Peng, Y., Wang, L., Jacinthe, P.-A., Ren, W., 2024. Global synthesis of cover crop impacts on main crop yield. Field Crop Res. 310, 109343. https://doi.org/10.1016/j.fcr.2024.109343.
Plaza-Bonilla, D., Nolot, J.-M., Raffaillac, D., Justes, E., 2015. Cover crops mitigate nitrate leaching in cropping systems including grain legumes: field evidence and model simulations. Agric. Ecosyst. Environ. 212, 1–12.
Potter, T.L., Bosch, D.D., Joo, H., Schaffer, B., Muñoz-Carpena, R., 2007. Summer cover crops reduce atrazine leaching to shallow groundwater in southern Florida. J. Environ. Qual. 36, 1301–1309. https://doi.org/10.2134/jeq2006.0526.
R Core Team, 2024. R: A Language and Environment for Statistical Computing.
Rakotomalala, A.A.N.A., Ficiciyan, A.M., Tscharntke, T., 2023. Intercropping enhances beneficial arthropods and controls pests: a systematic review and meta-analysis. Agric. Ecosyst. Environ. 356, 108617. https://doi.org/10.1016/j.agee.2023.108617.
Robinson, R.A., Sutherland, W.J., 2002. Post-war changes in arable farming and biodiversity in Great Britain. J. Appl. Ecol. 39, 157–176. https://doi.org/10.1046/j.1365-2664.2002.00695.x.
Rodriguez, C., Carlsson, G., Englund, J.-E., Flöhr, A., Pelzer, E., Jeuffroy, M.-H., Makowski, D., Jensen, E.S., 2020. Grain legume-cereal intercropping enhances the use of soil-derived and biologically fixed nitrogen in temperate agroecosystems. A meta-analysis. Eur. J. Agron. 118, 126077. https://doi.org/10.1016/j.eja.2020.126077.
Silva, V., Mol, H.G., 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.
Stagnari, F., Maggio, A., Galieni, A., Pisante, M., 2017. Multiple benefits of legumes for agriculture sustainability: an overview. Chem. Biol. Technol. Agric. 4, 2. https://doi.org/10.1186/s40538-016-0085-1.
Steele, G.V., Johnson, H.M., Sandstrom, M.W., Capel, P.D., Barbash, J.E., 2008. Occurrence and fate of pesticides in four contrasting agricultural settings in the United States. J. Environ. Qual. 37, 1116–1132. https://doi.org/10.2134/jeq2007.0166.
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, eaba1715. 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, 206–210. https://doi.org/10.1038/s41561-021-00712-5.
Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112, 58–72.
Tribouillois, H., Cruz, P., Cohan, J.-P., Justes, É., 2015. Modelling agroecosystem nitrogen functions provided by cover crop species in bispecific mixtures using functional traits and environmental factors. Agric. Ecosyst. Environ. 207, 218–228.
Tribouillois, H., Cohan, J.-P., Justes, E., 2016. Cover crop mixtures including legume produce ecosystem services of nitrate capture and green manuring: assessment combining experimentation and modelling. Plant Soil 401, 347–364. https://doi.org/10.1007/s11104-015-2734-8.
Vinther, F.P., Brinch, U.C., Elsgaard, L., Fredslund, L., Iversen, B.v., Torp, S., Jacobsen, C. S., 2008. Field-scale variation in microbial activity and soil properties in relation to mineralization and sorption of pesticides in a sandy soil. J. Environ. Qual. 37, 1710–1718. https://doi.org/10.2134/jeq2006.0201.
Wan, N.-F., Fu, L., Dainese, M., Hu, Y.-Q., Pødenphant Kiær, L., Isbell, F., Scherber, C., 2022. Plant genetic diversity affects multiple trophic levels and trophic interactions. Nat. Commun. 13, 7312. https://doi.org/10.1038/s41467-022-35087-7.
Wauchope, R.D., Yeh, S., Linders, J.B.H.J., Kloskowski, R., Tanaka, K., Rubin, B., Katayama, A., Kördel, W., Gerstl, Z., Lane, M., Unsworth, J.B., 2002. Pesticide soil sorption parameters: theory, measurement, uses, limitations and reliability. Pest Manag. Sci. 58, 419–445. https://doi.org/10.1002/ps.489.
White, P.M., Potter, T.L., Bosch, D.D., Joo, H., Schaffer, B., Muñoz-Carpena, R., 2009. Reduction in metolachlor and degradate concentrations in shallow groundwater through cover crop use. J. Agric. Food Chem. 57, 9658–9667. https://doi.org/10.1021/jf9021527.