



Pesticide-free arable cropping systems: performances, learnings, and technical lock-ins from a French long-term field trial

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Abstract

To ensure regular and high yields, current agriculture is based on intensive use of pesticides and fertilizers, which are detrimental to the environment and human health. Moreover, as pest resistance to pesticides increases, and more and more pesticides are taken off the market, national and European policies are becoming powerful drivers to deliver pesticide-free farming systems. Whereas numerous studies have compared organic versus conventional systems, our study assessed, for the first time, the performances of a pesticide-free arable cropping system (No-Pesticide), using synthetic fertilizers, specifically designed to produce high yields and meet environmental goals. This system was compared with an input-based cropping system designed with the same environmental targets (PHEP: productive with high environmental performances) in an 11-year field trial in France (Paris Basin). Banning pesticides did not result in a significant average yield gap (in GJ.ha⁻¹.year⁻¹ or in kg N.ha⁻¹.year⁻¹) calculated over the crop sequence. Yet, some crops' yields significantly decreased, due either to pest damages, or to limited nitrogen nutrition. In the No-Pesticide system, the mycotoxin content of cereal grains was lower than the regulatory threshold, and the average wheat protein content was higher than the required standard for baking. Indirect energy consumption, total greenhouse gas emissions, number of technical operations, nitrogen fertilizer amounts, and treatment frequency indexes were significantly lower compared to the PHEP system. Conversely, results showed significantly higher direct energy consumption, direct greenhouse gas emissions, and number of work hours for weed control. We identify highly effective agricultural strategies to avoid pesticide use (e.g., widely diverse and long crop sequence; introduction of hemp) and pinpoint several technical lock-ins hampering steady production in pesticide-free systems. We argue that more experiments should be undertaken to deliver technical knowledge for managing major or orphan species within pesticide-free systems, and to provide supplementary results, including economic and social performances.

Keywords Agroecology · Greenhouse gas emissions · Energy consumption · Yield · Grain quality · Field assessment · Integrated pest management · Agricultural practices

1 Introduction

Current conventional agriculture systems, based on intensive use of pesticides, chemical fertilizers, water, and fossil fuels, have largely contributed to ensure regular and high productivity in industrialized countries (Tilman et al. 2002). Yet, after decades of such input-intensive farming, many negative effects of pesticides are evident: contamination of ground-water and rivers (Patinha et al. 2018), air pollution (ANSES 2020), human health problems (Weber et al. 2019), and loss

of biodiversity (Cadillo-Benalcazar et al. 2020). Moreover, the efficiency of these intensive agricultural practices has decreased due to the increase of pest resistances (Aves et al. 2020), fast pathogen adaptations (Leroux and Walker 2011), and resistance breakdown of highly resistant cultivars sown on large areas (de Vallavieille-Pope et al. 2012). Currently farmers have to face the removal of numerous pesticides from the market, due to environmental and health risks recently reconsidered. This is leading to the development of alternative farming systems (organic, biodynamic, low input, or highly diversified) where pest control partly relies on preventive non-chemical techniques (Aubertot et al. 2005; Jacquet et al. 2022). Many papers analyze the benefits and difficulties of such alternative systems, mostly comparing organic to conventional systems. In these studies, organic

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systems generally show lower greenhouse gas emissions (Wittwer et al. 2021), reduced fossil energy use (Ramankutty et al. 2019), higher soil organic matter levels, and larger soil biodiversity, specifically macro- and microbiota (Wittwer et al. 2021).

However, the implementation of organic systems raises issues (Cadillo-Benalcazar et al. 2020) regarding weed management (Turner et al. 2007), soil erosion due to increased soil tillage (Trewavas 2001), and greater labor amount (Pimentel et al. 2005). Another major difficulty affecting yields concerns the management of organic fertilizers, due to the uneasy difficulty of synchronizing nitrogen nutrient availability with crop requirements (Chmelikova et al. 2021). Moreover, high nitrogen availability may increase disease pressure (Olesen et al. 2003) and has controversial effects on weed growth and weed-crop competition (Little et al. 2021). Ultimately, the major drawback of organic systems is their lower productivity. Many studies have quantified crop yield gaps between organic and conventional systems, relying on trial measurements (USA: Mäder et al. 2002; Switzerland: Wittwer et al. 2021; France: Hossard et al. 2016; Denmark: Pullens et al. 2021), survey analyses (USA: Kniss et al. 2016), and meta-analyses (de Ponti et al. 2012; Seufert et al. 2012). The decrease of individual crop yields in organic systems, compared to conventional systems, ranged from 21 to 29%, with a high standard deviation (21%), depending on crop species (de Ponti et al. 2012; Seufert et al. 2012) or pedoclimatic conditions (de Ponti et al. 2012). Yield gaps were due either to disease damages (Shah et al. 2017), or weed growth (Salonen et al. 2011), or difficulties to meet crop nitrogen requirements (Knapp and van der Heijden 2018; Wittwer et al. 2021). For example, the relative winter wheat yield of organic to conventional systems ranged from 60 to 75% (Ponisio et al. 2015; Kniss et al. 2016). Yet, in a few studies, yields in organic and conventional systems were not significantly different (Pimentel et al. 2005), and the estimated food supply was similar in magnitude in both systems (Badgley et al. 2007).

To overcome these frequent problems, Foley et al. (2011) and Chmelikova et al. (2021) proposed to design farming systems combining both organic and conventional techniques, where pesticide-free farming, allowing nitrogen fertilizer, could present some of the benefits of organic farming without their limitations. With carefully tailored crop management, the allowed use of chemical fertilizers is assumed to result in better growth and thus in higher yields. Yet, the ambivalent effects of nitrogen nutrients on pest development (i.e., increase of several disease impacts and controversial effects on weeds) have to be carefully considered through optimal nitrogen management. Such new systems should rely on the exclusion of natural products, such as copper, which are not environment friendly, even if they are used in organic systems. Pesticide-free systems

should not only succeed in controlling pests through biological regulation but also meet agronomic, environmental, and health challenges (i.e., reduce all forms of pollution such as nitrogen leaching, maintain soil fertility, strengthen biodiversity, and decrease greenhouse gas emissions, Pellerin et al. 2017). Until now, very few studies have designed such pesticide-free arable cropping systems and assessed their performances (Jacquet et al. 2022).

The objectives of this paper are to quantify the performances and to identify the effective strategies, difficulties, learnings, and technical lock-ins of an arable pesticide-free cropping system. This system was designed to reach high yields and multiple environmental targets, (i) such as low nitrate losses, environmental pesticide pollutions, and energy consumption; (ii) to maintain soil fertility; and (iii) to involve high crop diversity (Fig. 1). Results were collected from a long-term 11-year field trial located in the Paris Basin (France).

2 Materials and methods

2.1 Experimental trial

Four innovative arable cropping systems were assessed in a long-term (2009–2019) field trial located at the AgroParisTech experimental farm within the Paris Basin (France, N 48.84°, E 1.95°; Fig. 1). In this paper, we focus on two of these systems: the pesticide-free (No-Pesticide) system and the “productive with high environmental performances” (PHEP) system. The experimental design has already been precisely described in Colnenne-David et al. (2017, 2021), and some details are given in the “Supplementary materials (Fig. S1, Table S1).”

2.2 General description of the no-pesticide and the PHEP cropping systems

The PHEP system was designed to minimize environmental impacts compared to current local cropping systems, i.e., to reduce nitrate and pesticide pollutions, to limit energy consumption, to preserve soil fertility, and to enhance crop diversity, and then to reach the maximum possible yield. This cropping system was used as the reference system for comparisons with the No-Pesticide system. The No-Pesticide system was designed to meet an additional constraint, the banning of pesticide use. Unlike organic farming systems, natural products such as acetic acid were not allowed, but chemical fertilizers could be used. The two cropping systems, varying in crop sequence and crop management, were extensively described by Colnenne-David and Doré (2015) and Colnenne-David et al. (2017, 2021). These two systems were very different from the current dominant arable

Fig. 1 High crop diversity (hemp, mustard cover crop, spring faba bean: photographs from C. Colnenne-David) sown within the No-Pesticide system, and the experimental field trial (satellite image Google 2018).



cropping systems in the area where the trial is located (the Versailles Plain) and which were used for further comparisons (Table 1).

2.3 Measurements in the field trial

Measurements and observations were collected over an 11-year period (2009–2019).

2.3.1 Crops

For each crop, yield values ($t \cdot ha^{-1}$, 0% moisture) were calculated as the mean of six samples (each from an area of 75 to 140 m^2 , depending on the species) collected from each plot at maturity with a combine harvester. The harvested products were grains for each species, every year, and the straw for the winter wheat in 2016 (linked with weed control) and for the hemp every year. Energy content ($Gj \cdot ha^{-1}$) of the harvested products was calculated each year, based on calorific values collected from GESTIM (2019) for winter wheat, faba bean, triticale, and maize, and from Kraszkiewicz et al. (2019) and Marrot et al. (2022) for hemp straws. Dry biomass and nitrogen content were measured at maturity (stage 8.0 for winter rape, as recommended by Sylvester-Bradley et al. 1984), from nine to twelve samples of above-ground plants, collected from an area of 0.25 m^2 to 2 m^2 ,

depending on the species. Dry biomass (BM) and nitrogen content (N) of grains (g) and above-ground vegetative parts (vp) were analyzed separately for all crops except winter rape for which grains and vegetative parts were mixed. After separation of the corresponding organs, each sample was oven dried at 80 °C for 48 h. Nitrogen content (% of dry biomass) was analyzed, based on the Dumas combustion method (Jung et al. 2003). At maturity, the total plant nitrogen amount was calculated as $(BMg * Ng) + (BMvp * Nvp)$, and protein content of grains as $Ng * 5.7$. Mycotoxin (the deoxynivalenol (or DON) and zearalenone) content was analyzed using LC-MS/MS with procedures adapted from previously published methods (Sørensen et al. 2008), except from 2009 to 2012.

Agricultural practices and time required for each technical operation, including hand weeding, were recorded.

2.3.2 Pests

Pests were measured for each crop as detailed in “Supplementary material (Table S2).” Some years, due to time constraints, only global observations were performed to estimate pest pressures or damages: two or more trained technicians walked across the plot area to identify and assess pest abundances or damages through visual estimations at plot scale.

Table 1 Main agricultural practices and pest control strategies of the No-Pesticide and PHEP systems. Description of the current dominant cropping system practices on the Versailles Plain (78) near the area of the field trial in 2015. Details given for winter wheat. S, spring; W, winter; Cc, catch crop; SI, Simpson index; GHG, greenhouse gas.

Arable cropping system	No-Pesticide (no pesticide system)	PHEP (productive with high environmental performances system)	Current dominant systems on the Versailles Plain 3 main cropping system types
Crop sequence	6 years cc, maize, W wheat, cc, S faba bean, W wheat, cc, hemp, triticale SI = 0.35—wide diversity of species	5 years W faba bean, W wheat, W rape, W wheat, cc, S barley SI = 0.42—wide diversity of species	3, 4, or 5 years - W rape, W wheat, W wheat. SI: 0.56 - W rape, W wheat, W wheat, S barley. SI: 0.63 - W rape, W wheat, W wheat, maize, W wheat. SI: 0.68
Sowing date	Systematic alternative winter and spring-summer sowing periods to reduce weed specialization from year to year	One sowing in spring every 5 years	SI > 0.50—medium to low diversity of species 0, 1, and 1 sowing in spring every 3, 4, and 5 years, respectively
Sowing density	Delay of autumn sowing to avoid aphid pressures (e.g., beginning of November for W wheat) High sowing density to assume plant losses due to mechanical weeding (W wheat: 350 seeds.m ⁻²) Large row spacing to allow for the use of mechanical weeding and decrease pathogen propagations (W wheat: row spacing: 20 cm)	Current date of sowing (W wheat: mid-October) Current sowing density (W wheat: 220 seeds.m ⁻² and row spacing: 12.5 cm)	Current date of sowing (W wheat: mid-October) Current sowing density (W wheat: 220 seeds.m ⁻² and row spacing: 12.5 cm)
Species - Variety	Wide diversity of species to reduce pest pressures Resistant species to pests: hems, triticale, maize Species with rapid shoot growth to increase the competitiveness of the crop with respect to weeds: hemp, triticale Resistant varieties or mixtures of resistant varieties (W wheat) to diseases	Diversity of species to reduce pest pressures	Productive species
Nitrogen fertilization	Low nitrogen fertilization based on low targeted yields, leading to decrease disease pressures, weed growth, nitrogen pollutions, energy consumptions, and GHG emissions	Resistant varieties or mixtures of resistant varieties (W wheat) to diseases Low nitrogen fertilization based on low targeted yields, leading to decrease in pest pressures, nitrogen pollution, energy consumptions, and GHG emissions Depending on decision rules	Highly productive varieties High level of nitrogen fertilization to reach high yields
Pesticide	None	Depending on decision rules	Systematic, following advised current programs
W wheat yield target (0% moisture)	4.7 t.ha ⁻¹	6.7 t.ha ⁻¹	8.1 t.ha ⁻¹ and 7.2 t.ha ⁻¹ for the 1st and 2nd W wheat within the crop sequence, respectively Organic system in the Paris Basin (2015-2020) = 3.5 +/- 1.1 t.ha ⁻¹ https://www.bioledefrance.fr/documents/2021-observatoire-web.pdf (2021)

Due to a lack of people, no pest measurements were performed in 2012.

No pest results were detailed for the years with very low pests: winter wheat in 2010, 2011, 2012, and 2015; triticale in 2012, 2013, 2018, and 2019; spring faba bean in 2009 and 2010.

2.4 Calculation of indicators for environmental performances

The environmental performances of the cropping systems were assessed considering the real practices implemented on the field trial. Each performance was calculated over the 2009–2019 period and expressed on a per hectare and per year basis. The Criter® software (V4.0), based on the Indigo® method (Bockstaller et al. 2009), was used to calculate the working hours corresponding to the real practices implemented and specific parameters for each farm machine. Time spent on hand weeding was directly recorded. The treatment frequency index (Gravesen 2003), widely used to assess pesticide use in cropping systems in France (Jacquet et al. 2011), was calculated.

In this analysis, energy indicators and greenhouse gas performance calculations were updated using the GESTIM database 2019 and calorific values for hemp from Kraszkiewicz et al. (2019) and Marrot et al. (2022). The soil carbon sequestration was assessed with the latest version of the AMG model (Clivot et al. 2019), with the crop root carbon content calculations being improved. Energy consumption was expressed in $\text{MJ}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$, and greenhouse gas emissions in $\text{kg CO}_2\text{eq}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$. Carbon balance ($\text{kg CO}_2\text{eq}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) was calculated taking into account both carbon sequestration in the soil and total greenhouse gas emissions. These indicators were defined by Colnenne-David et al. (2017).

Compared to the previous results described in Colnenne-David et al. (2017), this assessment covered two crop sequences, and the practices of the second ones were slightly modified based on learnings from problems occurring during the first crop sequence.

2.5 Comparisons of cropping system performances

First, yields of the No-Pesticide and PHEP systems were compared over the 2009–2019 period, using two different units to take into account the wide diversity of crops grown ($\text{Gj}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ and $\text{kg N}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$).

Second, for winter wheat, yields ($\text{t}\cdot\text{ha}^{-1}$), grain protein contents (% of dry biomass), and nitrogen outputs ($\text{kg N}\cdot\text{ha}^{-1}$) were compared between the No-Pesticide and the PHEP systems. All these comparisons were carried out over the same years to take into account the climate inter-annual variability. Two comparisons between the no-pesticide and the PHEP systems were possible in the same year when the winter wheat was sown in two replicates within the same

system (in 2010, 2016, and 2018). Yields ($\text{t}\cdot\text{ha}^{-1}$) of triticale, maize, and spring faba bean were measured within the no-pesticide system. No comparison was performed, as these crops were not grown within the PHEP system.

Finally, environmental performances of the No-Pesticide and PHEP systems were also compared with averages of the current dominant cropping systems located on the Versailles Plain (where the innovative systems were implemented), defined on the basis of the data collected in 2016 (Agreste 2020–2021, <https://agreste.agriculture.gouv.fr>).

2.6 Statistical analysis

Yields over 11 years of the No-Pesticide and PHEP systems were analyzed by comparing means and carrying out analysis of variance (ANOVA, $p < 0.05$).

Winter wheat yields were compared using a mixed model (nlme package) assuming the systems as fixed effect and the years as random effect, allowing for a comparison over the entire period (2009–2019). For winter wheat specifically, an additional variance analysis (ANOVA, $p < 0.05$) was performed annually between the no-pesticide and the PHEP system yields.

Multi-year environmental performances were compared by analyzing variance (ANOVA, $p < 0.05$). When the variance was zero (e.g., the treatment frequency index values of all replicates of the No-Pesticide system were zero), only the confidence intervals ($p < 0.05$) were calculated and compared to the 0 value.

R statistical core software (R Core Team 2014) was used for all statistical analyses.

3 Results

3.1 Yield comparisons between the No-Pesticide and the PHEP systems

Yield differences between the No-Pesticide and the PHEP systems were not significant in average over 11 years (No-Pesticide = $101.96 \pm 6.20 \text{ GJ}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$; PHEP = $107.89 \pm 16.23 \text{ GJ}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$). The higher standard deviation for the PHEP system resulted from the winter wheat straws removal from the plot in 2016 (straw dry biomass: $12.3 \text{ t}\cdot\text{ha}^{-1}$), as the calculation included their energy output, whereas they were left in the field the other years. This straw management, unusual in a farming system managed without livestock production, was linked to the high weed pressure observed in this plot in 2016 (Table 2) and was decided to prevent weed dissemination on the plot over the following years. Without including the winter wheat straws harvested in 2016, the average yield of the PHEP system was $101.30 \pm 8.34 \text{ GJ}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$, very close to those of the No-Pesticide system.

Table 2 Mean annual yields ($t. ha^{-1}$; 0% moisture), and the highest damages and pressures of pests from 2009 to 2019, for winter wheat, in the No-Pesticide and PHEP systems. Yield differences between the No-Pesticide and the PHEP systems for winter wheat. Cropping systems: No-Pesticide (no pesticide use), PHEP (productive with high environmental performances). sd, yield standard deviation; s, significant; ns, not significant.

Year	Average yield ($t. ha^{-1}$; sd)		Yield gap ($t. ha^{-1}$)	Animal pest damages and pressures. Slugs and autumn aphids (global observation)		Disease damages and pressures. Leaf: <i>Septoria</i> , brown and yellow rust (% of leaf area covered by diseases). Ear: fusariose. Root: take-all		Weed pressures (% of soil covered by weeds)	
	No-Pesticide	PHEP		No-Pesticide	PHEP	No-Pesticide	PHEP	No-Pesticide	PHEP
2009	5.07 (0.63)	6.13 (0.43)	- 1.05 (s)	No slug, no autumn aphid damage	No slug, no autumn aphid damage	32%: <i>Septoria</i> 10% harvest area with take-all	28%: <i>Septoria</i> low take-all damages	0	0
2014	6.09 (0.55)	7.06 (0.32)	- 0.97 (s)	No slug damage no autumn aphid pressure	No slug damage medium autumn aphid pressure	33%: <i>Septoria</i> and brown rust	44%: <i>Septoria</i> and brown rust	5	0
2015	6.99 (0.66)	9.36 (0.15)	- 2.37 (s)	No slug damage no autumn aphid pressure	No slug damage low autumn aphid pressure	8.8%: <i>Septoria</i> and brown rust	6.8%: <i>Septoria</i> and brown rust	5	0
2016.1	3.98 (0.33)	4.31 (0.32)	- 0.33 (ns)	No slug damage no autumn aphid pressure	No slug damage low autumn aphid pressure	35%: <i>Septoria</i> and brown rust Fusariose: 2.0	40%: <i>Septoria</i> and brown rust Fusariose: 2.0	14	0
2016.2	3.32 (0.21)	4.31 (0.32)	- 0.99 (s)	No slug damage no autumn aphid pressure	No slug damage low autumn aphid pressure	41%: <i>Septoria</i> and brown rust Fusariose: 1.2	40%: <i>Septoria</i> and brown rust Fusariose: 2.0	50	0
2017	4.95 (0.72)	7.56 (1.00)	- 2.61 (s)	No slug damage no autumn aphid pressure	No slug damage low autumn aphid pressure	4.2%: <i>Septoria</i> and yellow rust	6.7%: <i>Septoria</i> and yellow rust	50	0
2018.1	4.73 (0.42)	7.45 (0.50)	- 2.72 (s)	No slug damage no autumn aphid pressure	No slug damage medium autumn aphid pressure	75%: <i>Septoria</i> and brown rust	39%: <i>Septoria</i> and brown rust	21	0
2018.2	4.73 (0.42)	8.66 (0.21)	- 3.93 (s)	No slug damage no autumn aphid pressure	No slug damage medium autumn aphid pressure	75%: <i>Septoria</i> and brown rust	20%: <i>Septoria</i> and brown rust	21	0

Expressed in nitrogen outputs, the yield drop (-17.5% ; $-20.1 \text{ kg N}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) of the No-Pesticide system, compared to the PHEP system, was not significant (No-Pesticide = $94.8 \pm 6.5 \text{ kg N}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$; PHEP = $114.9 \pm 19.8 \text{ kg N}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$). The lower value in No-Pesticide is explained by (i) the low nitrogen uptake of winter wheat in the No-Pesticide system (No-Pesticide = $111.4 \text{ kg N}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$; PHEP = $132.5 \text{ kg N}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$), (ii) the failure of the spring faba bean in 2011 and 2016 (nitrogen outputs were $13.6 \text{ kg N}\cdot\text{ha}^{-1}$ and $0.0 \text{ kg N}\cdot\text{ha}^{-1}$, respectively), and (iii) the replacement of hemp (due to its failure) by a buckwheat in 2018 (nitrogen output = $39.8 \text{ kg N}\cdot\text{ha}^{-1}$).

Winter wheat grain yields were significantly lower in the No-Pesticide system compared to the PHEP system, expressed both in $\text{t}\cdot\text{ha}^{-1}$ ($5.59 \pm 1.35 \text{ t}\cdot\text{ha}^{-1}$ and $7.17 \pm 1.60 \text{ t}\cdot\text{ha}^{-1}$, respectively) and in $\text{kg N}\cdot\text{ha}^{-1}$ ($111.4 \pm 26.7 \text{ kg N}\cdot\text{ha}^{-1}$ and $132.5 \pm 32.34 \text{ kg N}\cdot\text{ha}^{-1}$, respectively). For wheat, the lowest yield was measured in the No-Pesticide system in 2016 ($3.32 \text{ t}\cdot\text{ha}^{-1}$).

Banning pesticide use also resulted in severe yield drops for triticale in 2014; for spring faba bean in 2011, 2015, and 2016; and for maize in 2009 and 2015, compared with other years (Fig. 2).

3.2 Influence of pests on yield drops, for each species, within the No-Pesticide system

The No-Pesticide regularly faced pest pressures and damages over the eleven years (Fig. 2; Tables 2 and 3), on each crop within the trial, except for winter wheat in 2010.1, 2010.2, and 2011; for triticale in 2013; and for spring faba bean in 2009 and 2010. Due to the lack of pest measurements in 2012 for winter wheat and triticale, we used information on pest pressures in the region, indicating that it was very low this year (<http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal>).

3.2.1 Winter wheat

Ten times out of twelve, wheat yields of the No-Pesticide system were significantly lower than those of the PHEP system (Fig. 2; Table 2). In five cases, there were higher pest pressures in the No-Pesticide system: (i) in 2009, more root disease damage (take-all); (ii) in 2016.2 and 2017, more weed competition; and (iii) in 2018.1 and 2018.2, more foliar disease damage (*Septoria* and brown rust) and weed pressure. In four cases, significant yield gaps were not explained by greater pest

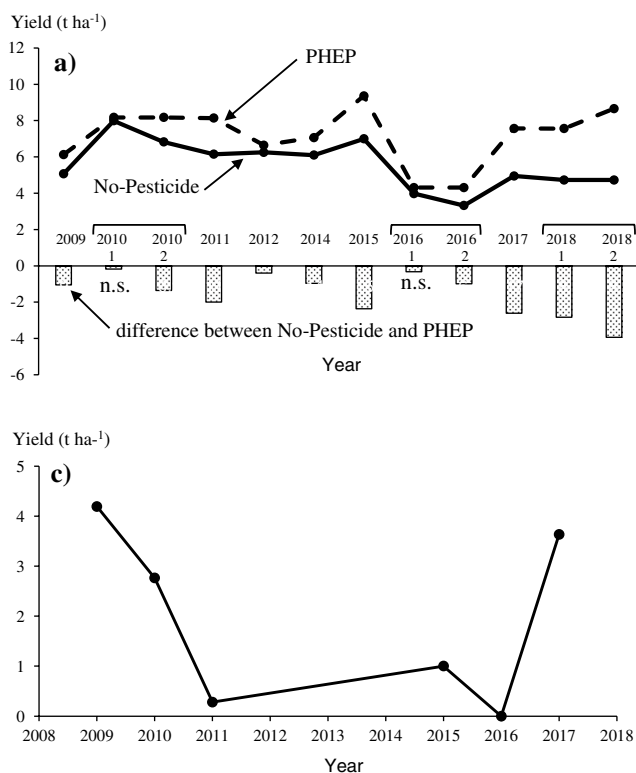
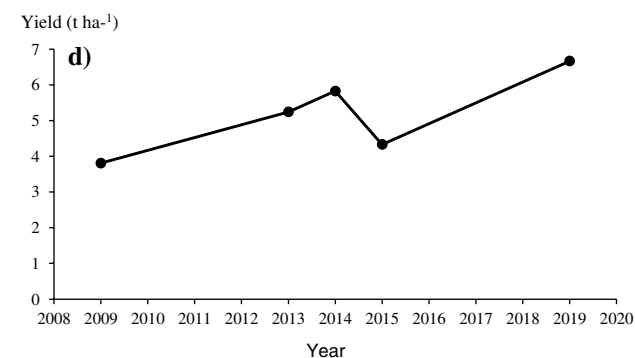
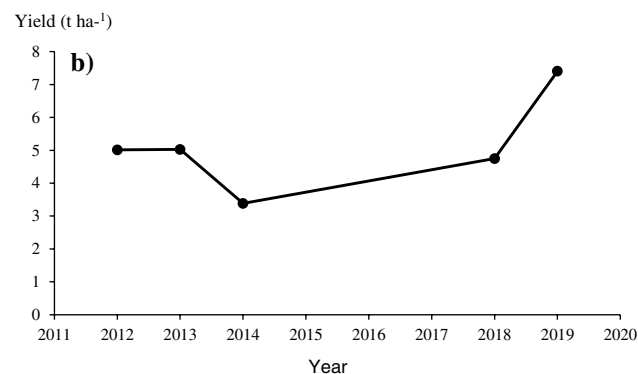


Fig. 2 Mean annual yields ($\text{t}\cdot\text{ha}^{-1}$; 0% moisture), from 2009 to 2019, for winter wheat (a), triticale (b), spring faba bean (c), and maize (d) of the No-Pesticide system, and for winter wheat of the PHEP system. Winter wheat yield differences were calculated between the No-



Pesticide and the PHEP systems. Cropping systems: No-Pesticide (no pesticide use), PHEP (productive with high environmental performances). In winter wheat sub-figure: 2010.1 and 2010.2 denote for two comparisons in 2010; n.s., non-significant difference in yield.

Table 3 Mean annual yields (t. ha⁻¹; 0% moisture), and the highest damages and pressures of pests from 2009 to 2019, for triticale, spring faba bean, and maize in the No-Pesticide system. sd, yield standard deviation.

Species	Year	Average yield (t. ha ⁻¹ , sd)	Animal pest damages and pressures	Disease damages and pressures	Weed
Triticale			Slugs autumn aphids (global observation)	Leaf: brown and yellow rust, <i>Septoria</i> , <i>Rhynchosporium</i> . (% of plants affected by diseases)	Pressures (% of soil covered by weeds)
	2014	3.38 (0.46)	No slug damage; no autumn aphids pressure	occasional but regular yellow rust (global observation); 68%: brown rust	5
	2018	4.75 (0.21)	No slug damage; no autumn aphid pressure	9%: <i>Septoria</i> and <i>Rhynchosporium</i>	20
Spring faba bean			Slug damages. Weevils (global observation), spring aphid pressures (% of plants affected by pests)	Leaf: brown rust, mildew, <i>Botrytis</i> (% of plants affected by diseases)	Pressures (% of soil covered by weeds)
	2011	0.28 (0.06)	100%: weevil damages 100%: spring aphid damages	100%: brown rust	Many weeds (global observation)
	2015	1.00 (0.15)	100%: weevil damages 18%: spring aphid damages	100%: mildew	100
	2016	0.00 (0.00)	100%: weevil damages	100%: <i>Botrytis</i>	100
	2017	3.63 (0.12)	100%: weevil damages	No disease	50
Maize			Birds (global observation), slug damages. Corn borer, <i>Geomyza</i> pressures	Leaf, cob: <i>Ustilago</i>	Pressures (% of soil covered by weeds)
	2009	3.81 (1.02)	High bird damages; corn borer (missing data)	No disease	100
	2013	5.24 (1.20)	High bird damages: 100% loss plants	No disease	100
	2014	5.83 (0.15)	High slug damages 100% loss plants; low bird damages	No disease	20
	2015	4.33 (1.85)	High <i>Geomyza</i> damages (global observation) 13% cobs affected by corn borer	No disease	90
	2019	6.67 (0.41)	9% cobs, 8% stems affected by corn borer	5% cobs affected by <i>Ustilago</i>	50

pressures: (i) in 2010.2, 2011, 2012, and 2015, pest damages were low in both systems (data not shown); (ii) in 2014, similar medium disease damages were observed in both systems. Yield gaps were not significant in 2010.1, and 2016.1.

3.2.2 Triticale

The highest yield drop in 2014 (Fig. 2; Table 3) resulted from disease damage occurring during tillering (yellow rust) and during the grain filling period (brown rust). In 2012 and 2013, there were low pest pressures leading to medium yields. In 2018, despite the high disease pressure, the yield drop was very low compared to those measured in 2012 and 2013. In 2019, due to the lack of disease pressure, and resulting from fulfilled nitrogen requirements (data not shown) yield was the highest.

3.2.3 Spring faba bean

This crop has been affected by large yield drops three years out of six (Fig. 2; Table 3). In 2011, 2015, and 2016, weevil pressures were high at crop emergence, thus weakening the plants. Later, either great aphid attacks (in 2011) or heavy disease pressures (mildew in 2015; *Botrytis* in 2016) led to plant damages and low plant growth, thus favoring weed development. In 2017, weevil attacks occurred on tall and old plants, due to the earlier sowing date, resulting in low damages (Table 3). In addition the same year, the disease pressure was low in the region (<http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal>), resulting in limited plant damages, thus enabling better crop competition against weeds. In 2009 and 2010, the slight yield decreases were consistent with the low pest damages observed.

3.2.4 Maize

Yields increased regularly over time, until the highest value in 2019 (Fig. 2; Table 3). Damages from birds (in 2009, 2013, and 2014) and slugs (in 2014) limited plant growth in the early stages, resulting in intensive weed development and weed competition. In 2015 and 2019, during the first growth steps, large weeds were highly competitive due to large development. Either *Geomyza* (in 2015) or *Ustilago* (in 2019) consequently weakened plants. Over these two years, additional corn borer damages also occurred. In 2019, corn borer pressure and summer drought did not limit yield.

For all species, yields were highly variable across years.

3.3 Nitrogen nutrition as a limiting factor for winter wheat yield in the No-Pesticide system

In five cases, significant yield gaps occurred between the No-Pesticide and the PHEP systems despite their comparable pest damages (i.e., no damage in 2010.2, 2011, 2012, and 2015; moderate damages in 2014). In all these situations, at maturity, the systematically lower plant nitrogen output in the No-Pesticide system (154 ± 14 kg N.ha⁻¹) than in the PHEP system (202 ± 21 kg N.ha⁻¹) contributed to yield gaps. In 2011 and 2012, the lack of nitrogen fertilization in the No-Pesticide system compared to the PHEP system (i.e., nitrogen fertilizer amount difference: 70 kg N.ha⁻¹ over the 2 years) led to a nitrogen deficiency throughout the crop growth (data not shown) resulting in a lower plant nitrogen outputs at maturity and significant lower yields: -1.99 t.ha⁻¹ and -0.39 t.ha⁻¹, respectively. In 2014 and 2015, the significant lower yields in the No-Pesticide system compared to the PHEP system (-0.97 t.ha⁻¹ and -2.37 t.ha⁻¹, respectively) were explained by several factors: sowing problems in the No-Pesticide plots (i.e., low seed quality in 2014; inappropriate seeding depth in 2015) leading to low plant densities (data not shown), combined with low nitrogen availability (low output measured at maturity), due to low amounts of nitrogen fertilizer (70 kg N.ha⁻¹ and 80 kg N.ha⁻¹ in 2014 and 2015, respectively). In 2010.2, the absence of nitrogen fertilization and the occurrence of a drought stress during grain filling explained the low nitrogen output at maturity in the No-Pesticide system, resulting in a significant yield gap compared to the PHEP system (-1.35 t.ha⁻¹).

3.4 Effectiveness and evolutions of pest-control strategies in the No-Pesticide system

3.4.1 Pest-control strategies managed at the crop sequence scale

The lack of perennial weeds such as thistle (*Silybum marianum*) or ryegrass (*Lolium perenne*) (data not shown), as

well as the effective weed control on all the plots during the 11 years of the experiment (Tables 2 and 3), highlighted the effectiveness of the weed control strategies at both crop sequence and crop scales (Table 4), which interacted with one another. At both scales, due to fast growth and high aerial biomass (data not shown), hemp has proven to be a very efficient weed competitor for light (i.e., very few weeds at flowering stage, data not shown, and 0% of soil covered by weeds at maturity each year; in 2014 and 2018, low percentage of soil covered by weeds at maturity in triticale, the following crop, Table 3).

The absence of take-all disease in winter wheat over time resulted from the sowing of non-cereal species as previous crops (Table 2), except in 2009 where the take-all damages in the No-Pesticide and PHEP systems resulted from the preceding winter barley sown in 2008 (before the trial).

3.4.2 Pest-control strategies managed at crop level

Specific pest control strategies were managed according to each species-pest couple. The effectiveness varied among species and pests and, based on regular diagnosis and learnings, some of them improved over time (Table 4).

Winter wheat and triticale Despite the autumn aphid pressures in 2014 and 2018, no symptom of virus diseases on either winter wheat or triticale (Tables 2 and 3) validated the effectiveness of the delayed sowing date, which clearly contributed to avoid autumn aphid attacks (Table 4). Similar results were found in 2015, 2016, and 2017 with low autumn aphid pressures.

No damage by slugs was measured on winter wheat and triticale in 2014, 2015, and 2016 despite intensive slug pressures in October (Tables 2 and 3). The delay in the cereal sowing date in the No-Pesticide system (i.e., almost 15 days after the local sowing period of cereals) appeared effective to escape slugs, while in the PHEP system molluscicides had to be spread (data not shown) on the winter wheat sown in mid-October, to reduce slug impacts in 2015 and 2016 (Table 2).

For the winter wheat, the plant disease damages in the No-Pesticide system (Table 2) were regularly in the same order of magnitude as those of the PHEP system, in which fungicides were systematically applied (i.e., treatment frequency index for fungicides (TFIF) from 0 to 1.3 according to the disease pressure of the year). These results, achieved with a nearly similar resistance index of the cultivars or cultivar mixtures sown in both systems, corroborated the effectiveness of the overall strategy of controlling diseases in the No-Pesticide system (Table 4), over the years with high disease pressures.

For *Septoria* and brown rust in 2014 and 2016.1, the use of the cultivar Atlass, in the No-Pesticide system, with a

Table 4 Technical strategies implemented to tackle each pest, and main adjustments to decision rules to decision rules to manage pests, from 2009 to 2019 at the crop sequence scale, and for each crop of the No-Pesticide system.

Species	Years	Animal pest management strategy (solution)	Disease management strategy (solution)	Weed management strategy (solution)
Crop sequence	2009 to 2019	Long crop sequence with high-diversity of species	Long crop sequence with wide diversity of species. Resistant species (hemp, triticale, maize). No cereal preceding winter wheat to avoid take-all. Decrease of nitrogen fertilization*	Long crop sequence with high diversity of species Systematic alternative winter and spring-summer sowing date Species with rapid shoot growth (hemp, triticale) Decrease of nitrogen fertilization*
Winter wheat	2009	Sowing date delay to avoid autumn aphid pressures (04/11)	High-resistance cultivar to <i>Septoria</i> and brown rust (Atlass)	Sowing date delay to manage false seedbed practice (04/11) High sowing density to offset plant losses due to late sowing and mechanical weeding (328 seeds.m ⁻²) Double-row density sowing to reduce weed competition on the row- high inter-row enable for mechanical weeding
	2010.1: post maize		Plowing to reduce fusariose pressure Mixture of high-resistance cultivars to <i>Septoria</i> , brown rust, fusariose (Premio, Renan, Atlass)	Plowing Mechanical weeding: curative decision rules (1 hoeing)
	2010.2: post spring faba bean			False seedbed practice (2 tillage) Mechanical weeding: curative decision rules (1 hoeing)
	2011, 2012: post spring faba bean			Mechanical weeding: new hoes; early implementation (1; 1 hoeing)
	2014, 2015, 2016.1: post maize		High-resistance cultivar to <i>Septoria</i> and brown rust (Atlass)	Mechanical weeding: new hoes; from curative decision rules to earlier and more numerous implementations (1; 1; 2 hoeing)
	2016.2: post spring faba bean		Mixture of high-resistance cultivars to <i>Septoria</i> , brown rust and fusariose (Skерzзо, Renan, Atlass)	Mechanical weeding: new hoes; from curative decision rules to earlier and more numerous implementations (2 hoeing)
	2017: post spring faba bean		Mixture of high-resistance cultivars to <i>Septoria</i> and brown rust (Atlass, Angelus, Venezia)	Mechanical weeding: early implementation (1 hoeing)
	2018: post spring faba bean		Mixture of high-resistance cultivars to <i>Septoria</i> , brown rust and fusariose (Atlass, Renan, Skерzзо)	Mechanical weeding: early and more numerous implementations (2 hoeing)

Table 4 (continued)

Species	Years	Animal pest management strategy (solution)	Disease management strategy (solution)	Weed management strategy (solution)
Triticale	2012, 2013, 2014	Sowing date delay to avoid autumn aphid pressures (2/11; 8/11; 30/10)	High-resistance cultivar to brown and yellow rusts (Kortego)	Sowing date delay (2/11; 8/11; 30/10) associated with false seedbed practice (3; 1; 2 tillage) High sowing density to offset plant losses due to late sowing and mechanical weeding (300; 357; 300 seeds.m ⁻²) Double-row density sowing to reduce weed competition on the row- high inter-row enable for mechanical weeding Mechanical weeding: transition from curative decision rules to earlier and more numerous implementations (0; 1; 1 hoeing) Mechanical weeding: earlier implementation (1; 0 hoeing) Cover crop to reduce weed growth over winter period Plowing and false seedbed practice (1 tillage) Current local sowing date (03/03) High sowing density to offset plant losses due to mechanical weeding (226 seeds.m ⁻²) Plowing, and false seedbed practice (decision rule: tillage every 3 weeks, 2; 1; tillage) Higher sowing density to offset plant losses due to mechanical weeding (316; 397 seeds.m ⁻²) Mechanical weeding: new hoes; early implementation (1; 1 hoeing)
Spring faba bean	2018, 2019 2010, 2011	High sowing density to avoid weevil pressures (462; 424 seeds.m ⁻²)	High-resistance cultivar to brown and yellow rusts (Kereon) Resistant cultivar to brown rust (Lady)	Resistant cultivar to brown rust (Espresso, Fanfare)
	2015, 2016	High sowing density to avoid weevil pressures (462; 424 seeds.m ⁻²)	Resistant cultivar to brown rust (Espresso, Fanfare)	Higher sowing density to offset plant losses due to mechanical weeding (462; 424 seeds.m ⁻²) Mechanical weeding: from curative decision rules to earlier and more numerous implementations (2; 2 hoeing) Mechanical weeding: early and numerous implementations (2 hoeing)
	2017	Early sowing date to avoid weevil pressures (21/02), decrease of sowing density (318 seeds.m ⁻²)		

Table 4 (continued)

Species	Years	Animal pest management strategy (solution)	Disease management strategy (solution)	Weed management strategy (solution)
Maize	2009	High sowing density to offset bird pressures (1.9 units of 50,000 seeds); current local sowing date (mid-end of April); <i>Trichogramma</i> against corn borer		Cover crop to reduce weed growth over winter period Plowing before sowing High sowing density to offset plant losses due to mechanical weeding (1.9 units of 50,000 seeds) Mechanical weeding: curative decision rules (1 hoeing) False seedbed practice (1 tillage) Mechanical weeding: new hoes; from curative decision rules to earlier and more numerous implementations (2 hoeing) False seedbed practice (decision rule: tillage every 3 weeks: 2 tillage) Higher sowing density to reduce weed competition on the row (2.5 units of 50,000 seeds) Mechanical weeding: new hoe; more numerous implementations (3 hoeing) Mechanical weeding: new harrow; more numerous implementations (1 harrow; 3 hoeing)
	2013			
	2014	High sowing density to offset bird pressures (2.5 units of 50,000 seeds)		
	2015			

* The reduction of the nitrogen fertilizer amount applied in the no-pesticide system was calculated on the basis of lower yield targets in the No-Pesticide system (defined by experts) than those of the PHEP system (Table 1), for winter wheat, triticale, maize. These decreases led to a reduced nitrogen availability (i) to crop growth resulting in low disease propagation, and (ii) for weeds, thus limiting their development and growth

resistance (index of disease resistance to *Septoria* = 7, and to brown rust = 6–7) similar to those of the variety mixtures of the PHEP system (“Premio, Mercato, Rubisko, and Barok” in 2014, and “Cellule, Rubisko, Koreli, and Boregar” in 2016.1) resulted in a medium level of both diseases across years (Table 2), whereas the PHEP plots had fungicide treatments in addition (TFIF of PHEP system were 1.3 and 0.5, respectively, in 2014 and 2016.1). In 2016.2, whereas TFIF was 0.5 in the PHEP system, the variety mixtures “Atlass, Skerzo, and Renan” and “Cellule, Rubisko, Koreli, and Boregar,” in the No-Pesticide and the PHEP systems, respectively, with a similar resistance index (average disease resistance index to *Septoria* = 7 and to brown rust = 6–7), resulted in the same low level of those diseases (Table 2). The strategies against diseases were especially effective for both comparisons in 2016, a year with very high pressures from these diseases.

In 2018, the crop management against diseases was less effective within the No-Pesticide plots. In 2018.1 and 2018.2, despite the use of variety mixtures with nearly similar resistance in both systems (“Atlass, Skerzo, and Renan” and “Cellule, Rubisko, Koreli, and Boregar” in the No-Pesticide and PHEP systems, respectively; Table 4), the damages were greater in the No-Pesticide system than in the PHEP system (Table 2). This highlighted the efficient use of fungicide (FTIF: 1 in the PHEP system) to control *Septoria*, whereas the level of resistance against this disease in the registered cultivars was low. Against the wide fusariose pressure in 2016, the highly resistant cultivar choice was clearly effective in the No-Pesticide system. In 2016.2, based on the comparison between plots with the same preceding crop (i.e., faba bean), the use in the No-Pesticide system of the Renan variety with a high disease resistance index (6.5) was more efficient than the use of a mixture of genotypes, in the PHEP system, with a lower global crop resistance to this disease (less than 5.5 for “Cellule, Rubisko, Koreli, and Boregar”; Tables 2 and 4).

Over time, weeds were more numerous in winter wheat plots (Table 2: 0% and 50% of soil covered by weeds at maturity in 2009 and 2017, respectively) in the No-Pesticide system compared to the PHEP one. Competition from weeds increased despite the continuous improvement of the decision rules over time to limit weeds. Due to this recurring weed increase, the curative protection strategy was modified and systematic mechanical weeding was carried out as soon as it became possible (Table 4). The weed threshold to trigger mechanical weeding consequently decreased over time, resulting in an earlier first weeding and a higher number of implementations (Table 4). As a result of frequent applications of livestock manure before the trial implementation, a high number of *Rumex crispus* appeared specifically in the replicate 3. Controlled with herbicides in the PHEP system (data not shown), hand weeding was exceptionally required

in the No-Pesticide system in 2018, leading to a drop in the weed population (Table 2). In the triticale crop, due to its fast growth (data not shown), and to the stiff competition and allelopathic effects from the preceding hemp, weed pressures were low (Table 3: 5% and 20%, respectively, in 2014 and 2018).

No data indicated effects of the nitrogen amount decrease on pest pressure (diseases and weeds). However, some winter wheat yield losses in the No-Pesticide system compared to the PHEP system resulted from detrimental crop nitrogen deficiencies.

Spring faba bean To deal with the recurrent pest pressures (weevils, rust, mildew, *Botrytis*, and weeds), practices were adjusted year after year (Table 4). In 2017, the earlier sowing date appeared ineffective against the weevil attacks (Table 4). Moreover, as we did not know any technical strategy to protect plants against spring faba aphids, the crop was totally destroyed in 2011 (Table 3).

Disease damages were regularly very high due to pressures from various pathogens (Table 3). To limit these impacts, varieties were frequently changed (Table 4), but few multi-resistant cultivars were listed in the national catalog of varieties. Moreover, cultivars, available in local market, presented low resistance to the diseases occurring in our region. Lady (medium brown rust resistant cultivar), Espresso (mildew disease resistance index = 4), and Fanfare (no specific resistance to *Botrytis*) were totally destroyed by various diseases: brown rust in 2011, mildew in 2015, and *Botrytis* in 2016.

From 2011, weed competition appeared (Table 3) despite winter plowing, several false seedbed operations before the sowing in mid-March, and curative mechanical weeding throughout the crop cycle. Continuous changes of mechanical weeding decision rules were consequently taken until 2016, resulting in a gradual transition from curative protection strategy to earlier and more numerous mechanical weeding implementations (Table 4). Despite these changes, the percentage of soil covered by weeds at maturity remained very high (Table 3). In 2017, the combination of weed control techniques with earlier sowing appeared moderately effective (i.e., 50% of soil covered by weeds at maturity in 2017 instead of 100% the previous years, Table 3). Due to early sowing (Table 4), the weevil attacks, occurring on stronger plants, resulted in little damage and led to an enhanced crop competitiveness against weeds.

Maize From 2009 to 2014, bird attacks regularly occurred in no-pesticide, due to the lack of chemical protection of the seeds (Table 3). To mitigate the damages, sowing density was modified over time (Table 4). Moreover, an earlier or a later plant emergence than those of the neighboring maize

plots led to an increase of plant damages. Thus, the maize sowing date in our trial had to be close to those of the local maize plots, from middle to end of April (Table 4). These strategies resulted in little bird damages over time (Table 3).

To limit weed pressure (Table 3), the combinations of techniques were modified over time. Winter plowing, combined with an increase of false seedbed operations before sowing, along with changes in the mechanical weeding decision rule, leading from a curative protection strategy to earlier and more frequent weeding (Table 4), resulted in a lower percentage of soil covered by weeds at maturity (Table 3). Moreover, the increase in sowing density (Table 4) contributed to reduce weed pressure on the rows (data not shown). However, in 2015, an unexpected development of *Solanum nigrum*, *Fallopia convulus*, and *Mercurialis annua*, the most numerous weeds in the plot required an unusual hand weeding with low success (Table 3).

The weeds and birds required antagonistic strategies in terms of sowing date. Delaying the sowing date allowed a higher number of false seedbed operations to decrease weed pressure, but led to greater bird damages due to later plant emergence than those of the local plots. In our trial, we prioritized protection from birds (i.e., similar sowing date as those of the neighboring plots) to foster the development of a maximum number of plants and further mobilized various mechanical weeding technics to mitigate the emerged weeds.

Due to the low disease sensitivity of maize (Table 3), no specific strategy was applied (Table 4).

For each crop, the strategy efficiencies against pests resulted from technical practice combinations (Table 4) which were known (or assumed) to interact with one another, and with those defined at crop sequence scale.

3.5 Grain quality in the No-Pesticide and the PHEP systems

3.5.1 Mycotoxin content of winter wheat, triticale, and maize grains

To reduce mycotoxin risks for winter wheat, fusariose-resistant varieties were sown, and plowing was systematic before the wheat grown after maize (Table 4). Toxicity levels were thus successfully reduced below the regulatory toxicity threshold. For triticale, only fusariose-resistant cultivars were used. No specific technique was applied for maize. From 2013 to 2019, the mycotoxin contents of the winter wheat, triticale, and maize grain samples, in the No-Pesticide system, were lower than the toxicity thresholds for deoxynivalenol and zearalenone contents.

Before 2013, there were neither fusariose symptoms nor damages on winter wheat (2009, 2010.1, 2010.2, 2011) and

maize (2009) (Table 4). No field measurements were available on winter wheat and triticale plots in 2012.

3.5.2 Protein content of winter wheat grains

The average protein content of winter wheat grains in the No-Pesticide system (10.8% \pm 1.6) was higher than the standard defined for baking bread (10.5%); this threshold being exceeded for 55% of the batches. It was not significantly different from that of the PHEP system: mean grain protein content was 10.9% (\pm 1.2), and 62% of the PHEP system batches were higher than the baking standard. Variability of the protein content was higher in the No-Pesticide system compared to the PHEP system, and the lowest contents were found within the No-Pesticide system samples (8.1 % in 2017).

3.6 Environmental performances of the No-Pesticide and the PHEP systems

Compared to the PHEP system, the No-Pesticide system resulted in significantly lower indirect energy consumption (reduced herbicide and nitrogen fertilizer use), lower total, direct and indirect greenhouse gas emissions (lower nitrogen fertilizer rates; fewer technical operations, less nitrogen and pesticide applications, and despite more mechanical weeding operations) (Table 5). Crop diversity was significantly higher within the No-Pesticide system compared to the systems using pesticides (Table 5). The No-Pesticide system management induced significantly higher consumption of direct energy due to more plowing and tillage (Table 5) and more working hours to manage weeds than in the PHEP system (3.5 h. ha⁻¹. year⁻¹ \pm 0.2 and 2.5 h. ha⁻¹. year⁻¹ \pm 0.2, respectively; i.e., more frequent plowing, tillage, and mechanical weeding). A peak of working hours occurred in the No-Pesticide system when hand weeding was required in specific circumstances (e.g., in 2015, 60 h. ha⁻¹ was needed to pull out weeds in replicate 1 in maize; in 2018, 24 h. ha⁻¹ was spent to export rumex (*Oxalis crispus*) in replicate 3 in winter wheat; Table 5). Both soil carbon sequestration and carbon balance were not significantly different between the two systems (Table 5) despite the systematic removal of hemp straw within the No-Pesticide system occurring every 6 years. The environmental performances of the two innovative systems were better than those of the current cropping systems in the Versailles Plain, excepted for (1) the direct energy consumption and the number of work hours of the No-Pesticide system due to a higher use of tillage and hand weeding, respectively, and (2) the soil carbon sequestration, resulting from low amount of buried crop residues (see above explanations on straw removal).

Table 5 Environmental performances of the No-Pesticide, the PHEP, and the current dominant cropping system on the Versailles Plain: energy (EN) consumption (indirect, direct: MJ. ha⁻¹. year⁻¹), greenhouse gas (GHG) emissions (total, indirect, direct: kg CO₂eq. ha⁻¹. year⁻¹), nitrogen fertilizer amount (kgN. ha⁻¹. year⁻¹), number of technical operations (ha⁻¹. year⁻¹), number of work hours without and with hand weeding (h. ha⁻¹. year⁻¹), treatment frequency index (TFI), diversity index (Simpson index: SI), soil carbon sequestration (kg CO₂eq. ha⁻¹. year⁻¹), and carbon balance (kg CO₂eq. ha⁻¹. year⁻¹). The values correspond to annual means and standard deviations. ns, not significant (*p* < 0.05); s, significant (*p* < 0.05). For TFI, the values in brackets are the confidence intervals (*p* < 0.05) for the three replicate. In bold and in italics, performances of the no-pesticide system is better and lower than those of the PHEP system, respectively. Cropping systems: No-Pesticide (no pesticide use), PHEP (productive with high environmental performances), VP (current dominant cropping systems in the Versailles Plain).

System	Indirect EN consumption (MJ. ha ⁻¹ . year ⁻¹)	Direct EN consumption (MJ. ha ⁻¹ . year ⁻¹)	Total GHG emissions (kg CO ₂ eq. ha ⁻¹ . year ⁻¹)	Indirect GHG emissions (kg CO ₂ eq. ha ⁻¹ . year ⁻¹)	Direct GHG emissions (kg CO ₂ eq. ha ⁻¹ . year ⁻¹)	Nitrogen fertilization (kg. ha ⁻¹ . year ⁻¹)	Number of technical operations (ha ⁻¹ . year ⁻¹)	Number of work hours without and with hand-weeding (h. ha ⁻¹ . year ⁻¹)	TFI (ha ⁻¹ . year ⁻¹)	Diversity index (SI)	Soil carbon sequestration (kg CO ₂ eq. ha ⁻¹ . year ⁻¹)	Carbon balance (kg CO ₂ eq. ha ⁻¹ . year ⁻¹)
No-Pesticide	3969 +/- 223 (s)	4849 +/- 44 (s)	1012 +/- 101 (s)	372 +/- 51 (s)	640 +/- 51 (s)	37 +/- 9 (s)	8.0 +/- 0.1 (s)	3.5 +/- 0.2 (s)	0.0	0.35 +/- 0.01 (s)	-92 +/- 108 (ns)	920 +/- 136 (ns)
PHEP	4866 +/- 231 (s)	4294 +/- 133 (s)	1269 +/- 53 (s)	534 +/- 26 (s)	735 +/- 29 (s)	67 +/- 4 (s)	8.8 +/- 0.2 (s)	2.5 +/- 0.2 (s)	[2.0 ; 2.8] (s)	0.42 +/- 0.03 (s)	179 +/- 175 (ns)	1078 +/- 171 (ns)
VP	9774 +/- 643	4936 +/- 104	2573 +/- 169	1159 +/- 86	1414 +/- 84	195 +/- 15	11.0 +/- 0.6	No hand weeding 3.3 +/- 0.1 No hand weeding	[3.2 ; 5.2]	0.62 +/- 0.06	377 +/- 90	2196 +/- 116

4 Discussion

This paper is the first to quantify the effects of a pesticide-free arable cropping system, designed to reach both high productivity and environmental targets, from a long-term field trial. We identified effective strategies and technical difficulties to design and to implement pesticide-free arable cropping systems, as well as several technical lock-ins limiting the performances, and thus the scaling of such innovative systems.

4.1 Implementing pesticide-free systems targeting high environmental performances requires a systemic approach

From 2009 to 2019, the field assessment demonstrated that the No-Pesticide system was highly productive, led to low environmental pollution (pesticides and nitrogen), reduced global warming potential and indirect energy consumption, and had no evident drawback regarding other environmental and commercial performances. This is linked to the systemic approach we implemented in 2008, when designing the system, leading to deep and coherent changes compared to the current cropping systems in the agricultural area, such as a new crop sequence and innovative practice combinations.

One of the effective practices consists in sowing a wide diversity of crops and a large range of sowing dates; this strategy being chosen for its ability to decrease the pool of pathogenic fungi and weeds (Aubertot et al. 2005). This diversity also reduced the dependence of the overall production to one species, thus lowering the vulnerability of the system to pest and climatic hazards occurring on one species. The contributions of the main crops to the total production (percentage expressed in $\text{GJ}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) were, for winter wheat and hemp in the no-pesticide system, 35% and 29%, respectively, while winter wheat accounted for 59% in the PHEP system. Within the current cropping systems in the Versailles Plain, winter wheat accounts for 80%, 61%, and 65% of total production for the crop sequence lengths of 3, 4, and 5 years, respectively (Table 1).

The high production in the No-Pesticide system was also due to the introduction of hemp. This species, belonging to the *Cannabaceae* family, scarcely sown in the local current systems, is unsusceptible to diseases. Hemp is also an effective strategic agronomic pillar to control weeds, at both crop and sequence scales, due to its allelopathic effects and high competitive ability. Moreover, its late sowing date (mid-May) allowed for numerous false seedbed operations in the spring, resulting in a weed decline, as described by Chikowo et al. (2009). Furthermore, the low nitrogen requirements of this species contributed to improve the environmental impacts of the crop sequence (indirect energy consumption; total greenhouse gas emissions).

4.2 Annual yield drops in the No-Pesticide system may be offset at the crop sequence scale

From 2009 to 2019, the field assessment demonstrated that the average yield, over the multi-annual No-Pesticide system, was not significantly reduced (expressed in $\text{GJ}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ and in $\text{kg N}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) compared to the PHEP system. This is an unusual result, regarding the literature on pesticide-free systems (de Ponti et al. 2012; Seufert et al. 2012; Knapp and van der Heijden 2018). However, results were different when considering each species separately. The significant decrease of winter wheat yields (-22%) between the No-Pesticide and the PHEP systems was low compared to yield differences between organic and conventional cropping systems given in the literature (de Ponti et al. 2012; Seufert et al. 2012; Kniss et al. 2016). For other species sown within the No-Pesticide system, yields were regularly lower in the pesticide-free system than the average ones of the Yvelines district where the trial was located: 4 years out of 5 for the triticale, 5 years out of 6 for the spring faba bean, and 4 years out of 5 for the maize (data not shown). Indeed, climate and pest pressures could be considered similar, every year, between our experimental conditions and the general conditions in the Yvelines district. Conversely, soil characteristics vary largely within this area, and it was difficult to compare yields more precisely as the soil type where these crops are grown in the district were not precisely accessible. We regularly measured a large inter-annual yield variability in the No-Pesticide system for all species, pinpointing the low yield stability of the pesticide-free system. Due to the ban of all pesticides, yield drops occurred for some species, despite our special attention to pest control when designing the system. We also showed that yield losses resulted not only from pest pressure, but sometimes from difficulties to manage nitrogen fertilization.

4.3 Tailored practices and learnings were required to control pests

Whereas most prevailing cropping systems can be managed with routine decision rules, the ban on pesticides makes it necessary to tailor the best techniques to each situation, every year, to anticipate and control a diversity of pests by prophylactic means. Moreover, appropriate indicators to measure pest pressures and therefore adopt better practices are poorly disseminated (Duru et al. 2015). In our long-term trial, observations and diagnosis were performed to improve the management and performances of the No-Pesticide system in a continuous learning loop (as described by Meynard et al. (2012) and Duru et al. (2015)), such as mechanical weeding management for each species or sowing dates for maize. The pest control resulted in a systemic management, continuously adjusted to optimize technical practices within the specific context of our field trial, as Toffolini et al. (2017)

proposed. In such an experimental system designed to reach specific performances, the year-after-year improvement of practices, based on learnings, is crucial, as innovative farmers point out (Chantre and Cardona 2014).

4.4 Technical difficulties still exist and tradeoffs between targets are needed

As Meynard et al. (2018) argued, due to scarce quantified references on the effects of crop rotations or nature-based protection methods under unconventional systems, several technical lock-ins are real impediments to the design of successful pesticide-free arable cropping systems. Among them, due to its ambivalent effects on pest development, nitrogen fertilization adds complexity to the management of such systems. Based on the literature, nitrogen management has been shown to have antagonist effects on pest control: crop growth is stimulated by nitrogen nutrients, resulting in higher aerial biomass and stiffer competition against weeds, but also higher moisture within the canopy which fosters disease propagations (Olesen et al. 2003). Likewise, analyses in the literature of weed growth and competition show that the nitrogen fertilizer impacts can be variable, depending on the time and amount of available nitrogen in the soil, with various consequences in terms of crop and weed growth: more fertilization induces higher yields with slow weed growth (Gallandt et al. 1998) or, conversely, stimulates weeds, resulting in decreasing yields (Olesen et al. 2009; Salonen et al. 2011). This highlights the variable interactions between nitrogen fertilizer and weed management within systems (Little et al. 2021). Based on our results, we could not prove that the reduction of the nitrogen applied in the No-Pesticide system (average of 37 kg N.ha⁻¹.year⁻¹ instead of 67 kg N.ha⁻¹.year⁻¹ in the PHEP system) may have contributed to lower disease damages over the years with high pest pressures. However, over the years with low pests, we showed that the lower winter wheat yields than those of the PHEP system partly resulted from nitrogen deficiencies. Moreover, weeds were more numerous over time in the No-Pesticide system. These results show that we do not know precisely how to manage nitrogen fertilization in pesticide-free systems—one more example of an agronomic knowledge gap in non-conventional systems.

In organic systems, improving nitrogen fertilization was identified as one of the key practices to enhance yields (Chmelikova et al. 2021) or yield stability (Knapp and van der Heijden 2018). Organic systems with livestock have the potential to supply a large amount of nitrogen to crops. However, organic fertilizers, whose mineralization depends on weather and soil conditions, generally result in delayed availability of nutrients, and in a mismatch between nutrient availability and plant requirements (Pang and Letey 2000), with possible high nitrogen loss (via nitrate leaching, Olesen

et al. 2009; via ammonia, Chmelikova et al. 2021). In the No-Pesticide system, the use of mineral nitrogen, which is more quickly assimilated by plants, and the easier synchronization of nitrogen applications with crop nitrogen needs, limited such risks. Moreover, in our trial, when the nitrogen fertilizer amount exceeded 80 kg N.ha⁻¹.year⁻¹ (e.g., for winter wheat), splitting the dose made it possible to fit the nitrogen availability dynamics to the crop requirement kinetics, leading to high yields and reduced nitrogen losses. In the no-pesticide plots, average soil nitrogen was very low (25 kg N. ha⁻¹) after winter wheat harvest.

Already mentioned by Pimentel et al. (2005) and Cadillo-Benalcazar et al. (2020), our results showed significantly higher labor hours in the no-pesticide system. In such systems, efficient weed control was achieved only with regular plowing, frequent tillage or false seedbeds, and intensive mechanical weeding. In our trial, this higher time was mainly due to hand weeding to control the numerous weeds developed over 3 specific years. This extra-time has been possible as the trial was managed in an experimental station, but farmers would have managed this problem in another way. We also found that additional time was needed to find new solutions to pest problems or to learn new techniques.

4.5 Long-term experiments are necessary to generate robust results for pesticide-free systems

To enhance the development of pesticide-free systems, more system experiments, assessed in a wide range of pedoclimatic conditions in France, are required to confirm their performances and enlarge the technical solutions to be implemented. Such experiments should also produce agronomic knowledge, regarding agroecosystem services provided, or conditions for successful innovative practices. References must, however, be interpreted in relation to the diversity of pest pressures, as noted by Pullens et al. (2021), and of socio-economic contexts (farm equipment or market outlets for orphan species).

Robust results need long-term field trial assessments. In our trial, from the experimental results of the first crop sequence, a further 5-year period (from 2015 to 2019) allowed to assess the No-Pesticide system under a wider range of environmental conditions (e.g., high unusual pest pressures in 2016; hot summer in 2019), thus enriching the previous conclusions based on results collected over the first period assessment (i.e., from 2009 to 2014; Colnenne-David et al 2017). Increasing the assessment duration also allowed to measure some environmental characteristics more accurately depending on slow processes such as weed population development or soil carbon sequestration. In the No-Pesticide system, weeds proliferated on winter wheat plots over the 2015–2019 period, contrary to the first crop sequence. Consequently, due to more tillage and intensive hand weeding

over the second crop sequence, the number of work hours was significantly higher over the 11-year assessment than the one calculated over the first crop sequence. Similarly, in the pesticide-free system, high yields for triticale and maize in 2019 induced changes in soil carbon sequestration across years (i.e., there was no significant difference in soil carbon sequestration between the No-Pesticide and the PHEP systems, while there was a significant decrease when considering the first 6-year period; Colnenne-David et al. 2017). Finally, learnings over the first period assessment led to improved management options over the second one, resulting in best performances (e.g., the sowing date of maize).

4.6 Genetic and market locks still have to be overcome

Several yield drops highlighted a high sensitivity of some species to pests, which could not be overcome with the agronomic techniques chosen. Regular low productivity of spring faba bean resulted from poor resistant cultivar availability for this minor species and underscored genetic locks, as described by Meynard et al. (2018). Additionally, there is a real need to develop and breed new species that are still rarely grown, such as hemp whose characteristics are quite suitable for such systems, to enhance the diversification required in pesticide-free systems (Knapp and van der Heijden 2018; Meynard et al. 2018; Jacquet et al. 2022). A deep change in breeding programs, consistent with the dominant input-based conventional systems, is also required (Meynard et al. 2018). As Jacquet et al. (2022) suggested, new breeding objectives have to take into account pesticide-free systems to deliver new cultivars suitable to such systems.

From the market point of view, due to the low regional hemp production, we had to deal with both the absence of a company able to harvest this crop and the difficulties to sell straw and seeds to the cooperative, whose strategies are based on major crops. Similarly, there were no local markets for faba beans, which were given to a local livestock farm. As Meynard et al. (2018) showed, the agricultural market is based on major crops and does not promote crop biodiversity needed for pesticide-free systems. Moreover, current manufacturing processes require specific qualities (e.g., a specific protein content threshold for baking), which could not be regularly provided by pesticide-free systems. There is a great need for evolving quality standards to the environment-friendly farming systems.

4.7 Adding economic value to pesticide-free system products is required

Among the difficulties encountered in managing a pesticide-free system, economic aspects should also be considered. Currently, the high prices of organic products allow higher economic results in organic systems compared to

conventional ones (Wittwer et al. 2021). For example, the winter wheat market price dated 03/05/2021 (Rouen, France) for conventional and organic products were 238 €·t⁻¹ and 454 €·t⁻¹, respectively. For pesticide-free systems using chemical fertilizers, such price discrepancies are not applied, because of the lack of a specific label. As Knapp and van der Heijden (2018), we argue that the high performances of the pesticide-free systems should be rewarded with higher product prices. Based on calculations (data not shown), the economic performances of the No-Pesticide and the PHEP systems should be close with an increase of 100 €·t⁻¹ applied to wheat grains produced within the No-Pesticide system compared to that of the PHEP system. In the current state of knowledge, further studies are required to quantify economic performances when considering the output prices of all crops sown within the No-Pesticide system. Further analysis will be required to define the potential prices of such products in line with awareness of environmental issues and consumers' capacity to buy more expensive products.

5 Conclusion

A pesticide-free cropping system, designed to reach high production and multiple environmental goals, was assessed in a long-term field trial (2009–2019) in the Paris Basin (France). To reach these goals, a systemic approach was required during the design process, and diverse pest-control strategies were combined both at the crop and crop sequence scales. Comparisons with arable cropping systems using pesticides highlighted the advantages of the pesticide-free systems: no significant average yield loss, no lower grain quality in terms of both mycotoxin and protein contents of winter wheat grains, lower indirect energy consumption, lower total greenhouse gas emissions, fewer technical operations, lower amount of nitrogen fertilizer, and no pesticide pollution. However, annual yield drops were regularly measured on some crops, resulting in a low stability of the production. We identified effective pest control strategies, such as the lengthening of the crop sequence and increased crop biodiversity with the introduction of hemp. Such systems should be tailored to pedoclimatic and socio-economic contexts, but their adjustment is hampered by important knowledge gap. Therefore, our analysis pointed out learning requirements to limit pest propagations. We also identified difficulties to manage such pesticide-free systems, thus shedding light on future research topics (nitrogen fertilization management or orphan species). To this end, it would be useful to collect, analyze, and widely disseminate information on new system experiments or farmers' experiences in a wide range of pedoclimatic conditions. In terms of plant breeding, due to limited pools of pest-resistant varieties and species, we also call for new breeding programs suitable to pesticide-free system conditions. To foster

pesticide-free systems, we also propose that minor crops be promoted throughout the innovative agricultural value chains. Further analyses of the performances of pesticide-free systems, including economic and social issues, are also needed to complement existing production and environmental studies.

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Authors' contributions Thierry Doré proposed and initiated the experiment. Caroline Colnenne-David and Gilles Grandeau were in charge of the system design and the implementation of the field trial. Caroline Colnenne-David performed the data processing. Caroline Colnenne-David, Marie-Hélène Jeuffroy, and Thierry Doré contributed to the conception of the article and reviewed the entire article. Caroline Colnenne-David coordinated the writing process and wrote the general parts of the manuscript, and was in charge of editing the article.

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Data availability All data are all available, while several trial and method descriptions are available within “Supplementary materials.”

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

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Conflict of interest The authors declare that they have no conflict of interest.

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