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Reducing pesticide use while preserving crop productivity and profitability on arable farms

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Achieving sustainable crop production while feeding an increasing world population is one of the most ambitious challenges of this century[1]. Meeting this challenge will necessarily imply a drastic reduction of adverse environmental effects arising from agricultural activities[2]. The reduction of pesticide use is one of the critical drivers to preserve the environment and human health. Pesticide use could be reduced through the adoption of new production strategies[3–5]; however, whether substantial reductions of pesticide use are possible without impacting crop productivity and profitability is debatable[6–17]. Here, we demonstrated that low pesticide use rarely decreases productivity and profitability in arable farms. We analysed the potential conflicts between pesticide use and productivity or profitability with data from 946 non-organic arable commercial farms showing contrasting levels of pesticide use and covering a wide range of production situations in France. We failed to detect any conflict between low pesticide use and both high productivity and high profitability in 77% of the farms. We estimated that total pesticide use could be reduced by 42% without any negative effects on both productivity and profitability in 59% of farms from our national network. This corresponded to an average reduction of 37, 47 and 60% of herbicide, fungicide and insecticide use, respectively. The potential for reducing pesticide use appeared higher in farms with currently high pesticide use than in farms with low pesticide use. Our results demonstrate that pesticide reduction is already accessible to farmers in most production situations. This would imply profound changes in market organization and trade balance.

Pesticide use in agriculture is increasingly reported to generate environmental disruptions[18] and health hazards, particularly for people directly exposed[19]. In temperate climates, agriculture is dominated by intensive farming systems, with highly specialized crop production and a heavy reliance on pesticides and mineral fertilizers[2]. France is the sixth biggest European consumer of pesticides per unit of agricultural area[5]. In 2013, 7% of the population had been supplied, at least once, with drinking water that was over the maximum authorized pesticide concentration[20]. Based on these considerations, the ECOPHYTO national action plan has set a target of a 50% decrease in pesticide use, initially to be reached by the year 2018. French agriculture is currently far from achieving this goal, and the end of the initial plan was recently postponed to 2025. Pesticide use has even increased over the last few years[5].

Concurrently, the principles of agroecology are promoted by the French government, advocating integrated management of pests for a reduction of pesticide reliance[3–5]. The general adoption of these management principles may involve a deep redesign of current cropping systems[21]. Although many studies have focused on the assessment of the sustainability of conventional versus innovative farming strategies[6,7,9,13,14,16,17], whether agriculture with less pesticide would be as productive and profitable as current agriculture practices remains controversial. Some studies mention that pesticides are essential for controlling pests and for ensuring a high level of food security[8], and that a reduction of pesticide use may lead to drastic yield and profit losses[10,12,15]. Other studies claim that pesticides threaten agricultural sustainability[19], and that a significant reduction of pesticide use can be conciliated with high levels of performance, including crop productivity and farm profitability[11,16].

We used data from a network of 946 non-organic arable French demonstration farms with contrasting levels of pesticide use (Supplementary Fig. 1), covering a diversity of production situations and displaying a wide range of strategies for pest management. The levels of pesticide use were assessed by computing the treatment frequency index (TFI). This indicator quantifies the number of recommended doses applied to each unit of cropped area, averaged across the crop sequence[22] (see Methods and Supplementary Information). TFI is the sum of four components corresponding to herbicide TFI, fungicide TFI, insecticide TFI and TFI for other pesticides (growth regulators, molluscicides, rodenticides, and so on). Throughout the whole farm network, total TFI was on average equal to 3.1 (s.e.m. = 0.05), and herbicide, fungicide and insecticide TFI represented about 49% (mean = 1.5, s.e.m. = 0.02), 27% (mean = 0.8, s.e.m. = 0.02) and 15% (mean = 0.5, s.e.m. = 0.02) of total pesticide use respectively (Supplementary Fig. 2). Other pesticides represented 9% of total pesticide use (mean = 0.3, s.e.m. = 0.01).

Crop productivity was calculated by converting yields into amount of energy produced per surface unit (GJ ha^{-1} yr^{-1}) based on the energy content of each given crop product, estimated by the higher heating value[23]. Profitability (€ ha^{-1} yr^{-1}) was computed with ten price scenarios for crop products and farm inputs between 2005 and 2015[24] (Methods).

Twenty-two variables were used to describe the biophysical and socio-economic contexts for each farm (Supplementary Table 1). These variables were included in regression models relating productivity and profitability to TFI, as they could affect productivity and profitability either directly or on interactions with TFI (Methods). Regression models were fitted to data using the Lasso[25,26] (least absolute shrinkage and selection operator) method to select a subset of the variables rather than using all of them and to improve prediction accuracy. The fitted models were then used to compute the marginal TFI effects on productivity and on profitability, which corresponded to the changes in productivity or profitability resulting from a one-unit increase in TFI. Estimated interaction effects were used to adjust TFI effects to biophysical and socio-economic contexts. Confidence intervals were computed by bootstrapping to assess uncertainty in the estimated values of marginal TFI effects (Methods).

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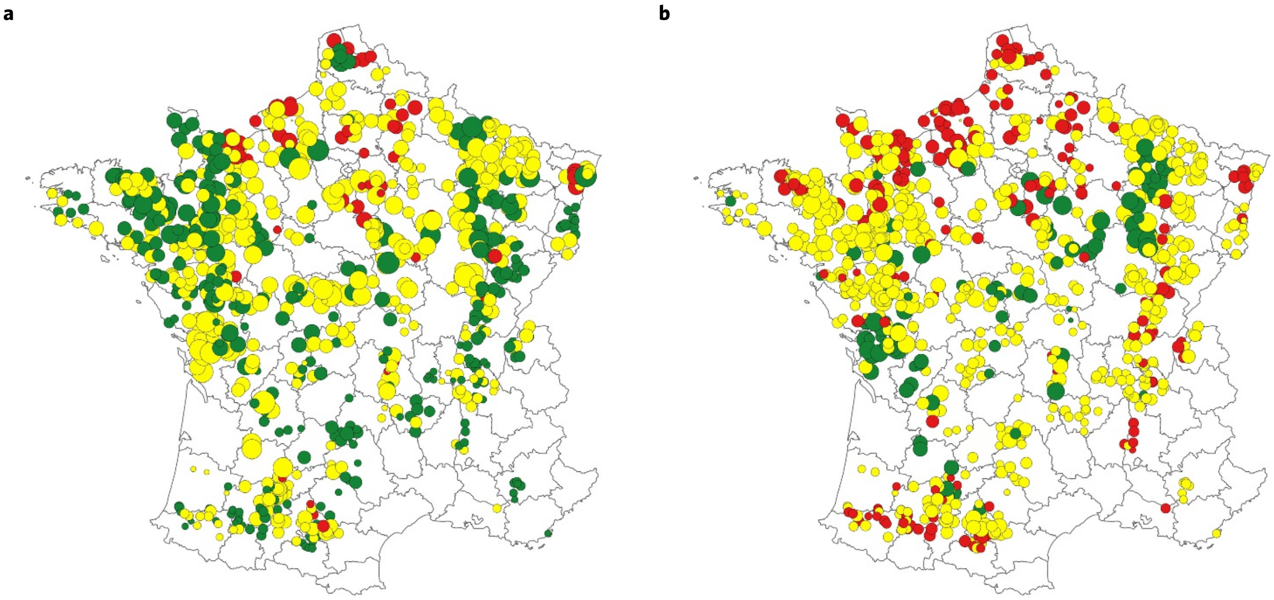


Figure 1 | Marginal effects of the total TFI. a,b, Marginal effects of the total TFI on crop productivity (**a**) and profitability (**b**). Each point corresponds to a single farm (number of farms, 946). Green indicates negative marginal TFI effects (concordance), yellow indicates non-significant marginal TFI effects and red indicates positive marginal TFI effects (conflict). The size of the points is proportional to the accuracy of the estimated TFI effect. Estimations of marginal TFI effect were performed with Lasso regression analysis.

Table 1 | Mean TFI over the whole farm sample (standard errors between brackets) by category of pesticide, and proportions of farms with negative, non-significant and positive effects of different categories of TFI on productivity and profitability.

TFI category	Mean	Productivity			Profitability		
		Negative TFI effect (%)	Non-significant TFI effect (%)	Positive TFI effect (%)	Negative TFI effect (%)	Non-significant TFI effect (%)	Positive TFI effect (%)
TFI	3.1 (0.05)	38.8	55.0	6.2	11.1	66.6	22.3
Herbicide TFI	1.5 (0.02)	6.4	64.8	28.8	7.7	71.2	21.0
Fungicide TFI	0.8 (0.02)	39.2	56.4	4.3	0.0	65.5	34.5
Insecticide TFI	0.5 (0.02)	86.2	13.8	0.0	7.1	75.5	17.4

Only 59 farms (6% of the sample) displayed a significant positive total TFI effect on crop productivity, indicating a potential productivity loss associated with a reduction of pesticide use (Fig. 1a and Table 1). Compared with the total TFI, the percentage of farms characterized by a significant positive herbicide TFI effect on productivity was higher (29%), but lower for fungicide TFI (4%) and insecticide TFI (0%), when these types of pesticide were considered separately (Table 1 and Supplementary Fig. 3). Fifty-five per cent of farms did not show a significant TFI effect on crop productivity (65% for herbicide TFI, 56% for fungicide TFI and 14% for insecticide TFI). Thirty-nine per cent of farms displayed a significant negative TFI effect on crop productivity, highlighting a potential for reducing pesticide use while increasing crop productivity (6% for herbicide TFI, 39% for fungicide TFI and 86% for insecticide TFI). In the farms with significant negative total TFI effect, most of them (72%) were livestock producers and were mainly characterized by soils with low available water capacity (AWC), medium to high yield potentials and a substantial proportion of temporary grasslands and maize production (Table 2), particularly silage maize. These crops were generally associated with high productivity (Supplementary Fig. 4) along with low TFI (Supplementary Fig. 5). In situations associated with negative TFI effect on productivity, the proportion of maize and grassland at the farm level was positively correlated with productivity (Spearman correlation test, $\rho = 0.65$, $P < 0.001$) and negatively correlated with pesticide use ($\rho = -0.60$, $P < 0.001$). Conversely, the 6% of farms showing a positive TFI effect on crop productivity were rarely based on mixed crop–livestock farming and were characterized by a low proportion of maize and no temporary grassland. These farms corresponded to farms from northern France with high yield potentials (deep loamy soils with high AWC), where sugar beet and potato are commonly cultivated (Table 2).

We found that pesticide use could be reduced without a significant impact on profitability in 67% of the surveyed farms (71% for herbicide TFI, 66% for fungicide TFI and 76% for insecticide TFI) (Fig. 1b, Table 1 and Supplementary Fig. 6). In 11% of the farms, pesticide use reduction could even significantly increase profitability (negative total TFI effect). This percentage was equal to 8, 0 and 7% for herbicide, fungicide and insecticide TFI respectively. In 22% of the farms, the total TFI effect was significantly positive, indicating that lower pesticide use would be associated with reduced profitability. This percentage was similar for herbicide and insecticide TFI (21 and 17.4%, respectively), but higher for fungicide TFI (35%). Most of these farms were located in northern or southwestern France and were characterized by a high soil AWC and high yield potentials (Table 3). These farms dedicated large areas to the cultivation of industrial crops with high added value such as potato and sugar beet for northern farms and seed maize for southern farms (Table 3). These crops simultaneously displayed high levels of pesticide use along with high profitability (Supplementary Figs 5 and 7). Among the farms associated with positive TFI effect on profitability, the proportion of these crops in the crop sequences influenced positively pesticide use and profitability (Supplementary Fig. 8), and therefore contributed to explaining the positive relationship

Table 2 | Characteristics of the farms with negative, non-significant and positive effects of the total TFI on crop productivity (average values and standard errors).

	Negative TFI effect	Non-significant TFI effect	Positive TFI effect
Proportion of farms with loam texture soils (%)	70.3	63.5	88.1
Proportion of farms with high yield potential (%)	54.0	44.2	84.8
Proportion of farms associated to livestock breeding (%)	71.9	39.8	5.1
Average productivity (GJ ha^{-1})	149.8 (2.5) a	122.2 (1.9) b	159.0 (5.7) a
Average TFI	2.50 (0.068) c	3.30 (0.070) b	4.96 (0.260) a
Average temperature (°C)	11.77 (0.057) a	11.69 (0.046) a	11.43 (0.093) b
Average precipitation (mm yr^{-1})	858.41 (8.3) a	796.28 (5.5) b	731.90 (13.0) c
Average pH	6.65 (0.032) c	6.96 (0.029) b	7.16 (0.067) a
Average OMC (%)	2.91 (0.056) a	3.09 (0.081) a	2.24 (0.092) b
Average AWC (mm)	109.21 (2.4) b	121.84 (4.5) b	170.07 (8.6) a
Average % of straw cereal	38.56 (1.1) b	50.80 (0.8) a	48.97 (1.5) a
Average % of winter wheat	25.42 (0.93) c	32.71 (0.71) b	40.98 (1.60) a
Average % of oilseed rape	6.64 (0.57) b	13.60 (0.57) a	8.51 (1.20) b
Average % of maize	36.40 (1.6) a	16.55 (1.0) b	8.67 (2.3) c
Average % of grassland	12.22 (1.20) a	6.34 (0.78) b	0.00 (0.00) c
Average % of sunflower	2.51 (0.36) b	5.75 (0.51) a	3.65 (1.10) ab
Average % of grain legume	2.76 (0.41) c	3.52 (0.31) b	5.93 (1.10) a
Average % of sugar beet	0.21 (0.11) c	1.50 (0.23) b	14.72 (1.50) a
Average % of potato	0.04 (0.041) b	0.17 (0.081) b	3.33 (0.990) a
Average % of seed maize	1.40 (0.48) a	0.53 (0.25) a	1.13 (1.10) a

Letters indicate significant differences ($P < 0.05$) according to the rank comparison test using the Benjamini and Hochberg correction to the P value[31]. AWC, available water capacity; OMC, organic matter content.

Table 3 | Characteristics of the farms with negative, non-significant and positive effects of the total TFI on farm profitability (average values and standard errors).

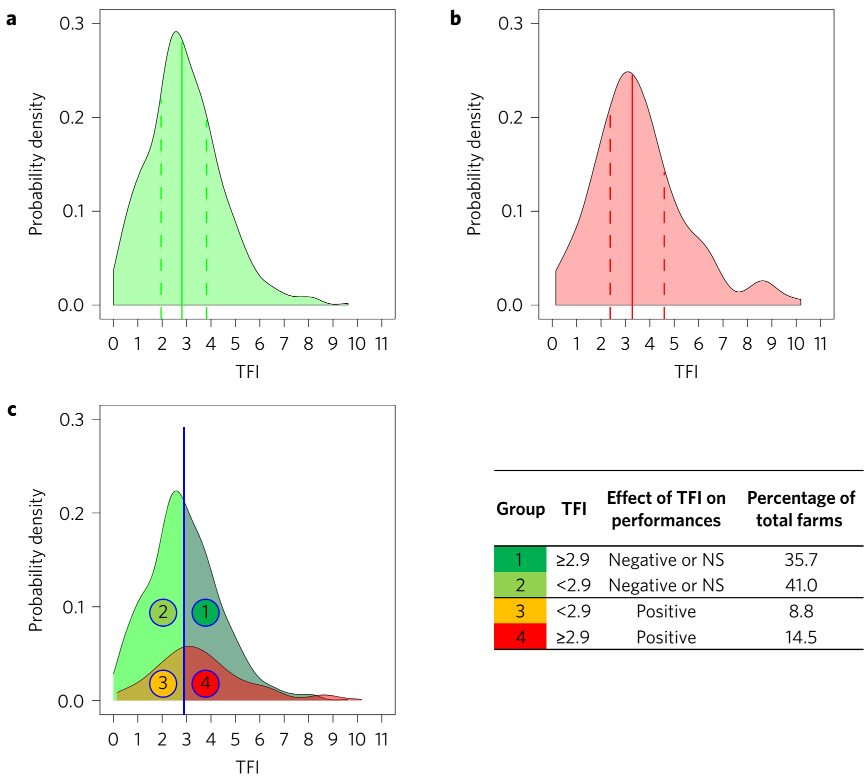
	Negative TFI effect	Non-significant TFI effect	Positive TFI effect
Proportion of farms with loam texture soils (%)	25.7	67.6	88.6
Proportion of farms with high yield potential (%)	2.9	43.5	95.2
Proportion of farms associated to livestock breeding (%)	6.7	55.2	56.4
Average profitability (€ ha^{-1})	433.93 (13.0) c	524.26 (8.4) b	795.05 (23.0) a
Average TFI	3.87 (0.170) a	2.80 (0.056) b	3.59 (0.130) a
Average temperature (°C)	11.71 (0.110) a	11.71 (0.042) a	11.70 (0.067) a
Average precipitation (mm yr^{-1})	803.18 (12.0) a	817.66 (5.8) a	819.09 (9.8) a
Average pH	7.25 (0.065) a	6.77 (0.025) c	6.90 (0.042) b
Average OMC (%)	3.61 (0.230) a	2.99 (0.061) b	2.60 (0.057) c
Average AWC (mm)	88.80 (2.5) c	116.60 (3.7) b	145.44 (4.5) a
Average % of straw cereal	58.90 (1.4) a	45.64 (0.8) b	40.37 (1.4) c
Average % of winter wheat	36.58 (1.30) a	29.18 (0.69) b	30.95 (1.30) ab
Average % of oilseed rape	19.12 (1.20) a	10.52 (0.51) b	6.52 (0.62) c
Average % of maize	4.50 (1.1) b	25.08 (1.1) a	29.40 (2.1) a
Average % of grassland	3.05 (1.30) b	9.66 (0.85) a	6.52 (1.20) a
Average % of sunflower	9.71 (1.30) a	4.35 (0.40) b	1.73 (0.38) c
Average % of grain legume	4.06 (0.73) ab	3.05 (0.29) b	4.02 (0.52) a
Average % of sugar beet	0.04 (0.042) b	0.42 (0.120) b	6.90 (0.710) a
Average % of potato	0.00 (0.000) b	0.02 (0.024) b	1.34 (0.350) a
Average % of seed maize	0.00 (0.000) b	0.12 (0.072) b	3.69 (1.000) a

Letters indicate significant differences ($P < 0.05$) according to the rank comparison test using Benjamini and Hochberg correction to the P value. AWC, available water capacity; OMC, organic matter content.

between pesticide use and profitability. In situations with high yield potential, we showed that farms cultivating these high added value industrial crops displayed profitability that was on average 45% higher (Mann–Whitney test, $P < 0.001$) and pesticide use that was on average 79% higher ($P < 0.001$) than the other farms. Conversely, the 11% of farms showing a negative TFI effect on farm profitability were mainly cereal farms associated with medium yield potentials and low soil AWC. These farms cultivated straw cereals, oilseed rape and sunflower, and they were on average less profitable than the other farms from the sample (Table 3).

Most farms showing a positive TFI effect on crop productivity (85%) also displayed a positive TFI effect on profitability. Distribution of the TFI values are compared in Fig. 2, distinguishing (1) the group of farms associated with a negative or non-significant TFI effect on both productivity and profitability (77% of the farms are in a non-conflicting situation for pesticide reduction) and (2) the group of farms showing a significantly positive effect of TFI on productivity and/or profitability (23% of the farms are in a conflicting situation for pesticide reduction). The median TFI value in the whole sample was 2.9. TFI was 22% higher (Mann–Whitney test, $P < 0.001$) in the farms in conflicting situations compared to non-conflicting situations (Fig. 2c); however, 47% of the farms in non-conflicting situations displayed high TFI values, above the sample median, suggesting that a drastic pesticide use reduction would be possible without any loss in productivity and profitability.

For each farm from non-conflicting situations we quantified the potential decrease in the TFI without any adverse impact on crop productivity or profitability by identifying a neighbourhood of farms sharing the same constraints and opportunities (Methods). The minimum TFI value among those farms in this neighbourhood defined a target TFI value for the considered farm, based on the assumption that each farm could adopt the farming systems of



Group	TFI	Effect of TFI on performances	Percentage of total farms
1	≥2.9	Negative or NS	35.7
2	<2.9	Negative or NS	41.0
3	<2.9	Positive	8.8
4	≥2.9	Positive	14.5

Figure 2 | Probability density of total TFI. a,**b**, The probability density of total TFI in farms where the TFI effect was negative/NS on both crop productivity and profitability (non-conflicting situations, **a**), and in farms where the TFI effect was positive (conflicting situations, **b**). The probability density was estimated with the Gaussian kernel method and describes the probability densities associated with TFI values in the range 0–10. Although the TFI in non-conflicting situations was lower than in conflicting ones, 47% of the farms in non-conflicting situations (35.7% of total farms) displayed a TFI higher than the median value on the whole farm sample (2.9). **c**, Categories (1–4) were defined as a function of the TFI effect (negative/NS versus positive) and TFI value (TFI < 2.9 versus TFI ≥ 2.9). Vertical solid lines correspond to median values (the solid blue line indicates the median value of the network). Vertical dashed lines indicate the 25th and 75th percentiles. NS, non-significant.

farms within its close neighbourhood, including the one associated with the lowest TFI. Provided that we considered only farms in non-conflicting situations, the difference between the current TFI value in this farm and the target TFI provided an estimate of the potential reduction in pesticide use achievable without negative impact on both productivity and profitability. Twenty-three per cent of the farms in non-conflicting situations were alone in their neighbourhood, and their potential pesticide use reduction could therefore not be computed. In other farms, the neighbourhoods were composed of 2–54 farms, with an average of 11 farms. Their potential pesticide use reduction was on average 42% (1.4 TFI units, s.e.m. = 0.05). This reduction potential was positively correlated with the current farm TFI (Spearman correlation test, $\rho = 0.27$, $P < 0.001$). For the farms with a TFI below the median (2.9), the reduction potential was on average 35% (0.7 TFI units, s.e.m. = 0.04), whereas it was 49% (2.1 TFI units, s.e.m. = 0.08) in farms with a TFI higher than the median (Supplementary Fig. 9). This potential reduction of total TFI corresponded to an average reduction of 37% for herbicide TFI (0.6 TFI units, s.e.m. = 0.03), 47% for fungicide TFI (0.4 TFI units, s.e.m. = 0.02), and 60% for insecticide TFI (0.3 TFI units, s.e.m. = 0.02). The proportion of herbicides in total TFI was thus higher when total pesticide use was decreased (see also Supplementary Fig. 2).

Our results suggest that pesticide use could be substantially reduced without any financial cost, but also without any financial interest, for most of the French arable farmers. We showed that 77% of farms from our national sample were in situations favourable to total pesticide reduction, and 23% of farms were in situations of conflict between pesticide reduction and productivity and/or profitability. These conflicting situations were associated with industrial crop characterized by both high pesticide use and high added value. In such a context, the proportion of industrial crops influences the relationship between pesticide use and profitability, so farmers reducing the frequency of these crops will hardly meet the objective of reducing their reliance on pesticide while maintaining their profitability. This finding emphasizes the need for further technical innovation for these crops to reduce their reliance on pesticide (for example, potato cultivars resistant to diseases and herbicide band-spraying combined with hoeing for the sugar beet).

The gradient of pesticide use observed in the farm network was related to a diversity of cropping systems, as farms differed not only for TFI, but also for crop rotation, soil tillage, cultivars, sowing dates and density, fertilization, and so on. Some agricultural practices used to control weeds, pests and diseases (for example, delaying cereal sowing dates, cultivars with low sensitivity to diseases but moderate yield potential, reduced nitrogen fertilization) may decrease the productivity, whereas other practices (for example, introduction of temporary grasslands or maize in rotation) may increase productivity. Compared with other categories of pesticides, reduction in herbicide use led to a higher risk of productivity loss. This is consistent with previous studies[27] that mentioned the difficulties for farmers to implement non-chemical weed management strategies. The implementation of such strategies predominantly tended to decrease productivity, particularly in northern, central and southern France (Supplementary Fig. 3). However, in central France, the productivity loss was offset by a decrease in production costs, and the frequency of conflicts between herbicide TFI and profitability was lower in this region than in others

(Supplementary Fig. 6). Conversely, non-chemical strategies to control fungal diseases predominantly tended to increase productivity and decrease profitability (Supplementary Figs 3 and 6), particularly in regions characterized by a high proportion of mixed farming with livestock breeding. In these regions, systems with low fungicide use presented high frequencies of silage maize and temporary grassland. Those two forage crops are associated with low fungicide requirements, high biomass productivity and low economic profitability (Supplementary Figs 4 and 7). The relationship between insecticide use and both productivity and profitability could be related to the frequency of oilseed rape in the crop sequence. Oilseed rape frequency appeared to be positively correlated with insecticide use (Spearman correlation test, $\rho = 0.60$, $P < 0.001$), negatively correlated with productivity (Spearman correlation test, $\rho = -0.49$, $P < 0.001$) and negatively correlated with profitability (Spearman correlation test, $\rho = -0.13$, $P < 0.001$). Farms with reduced area dedicated to oilseed rape tended to have low insecticide TFI, high productivity and similar or higher economic profitability than farms with high proportions of oilseed rape.

The adoption of low-pesticide management strategies might be challenging for farmers. Reducing pesticide use would increase the complexity of farming management and decision-making, creating technical hurdles and lock-ins that are likely to slow down the dynamic of change[27–29]. The transition towards low-pesticide farming strategies might be hampered by the uncertainty behind any deep change. Risk aversion may be a hindering factor because pesticide use reduction would not increase farm profitability in most situations, as shown from our results. The transition towards low-input systems will be fostered by identifying realistic targets of pesticide use reduction and by helping arable farmers to adapt their practices. According to the farming context and to the technical options available to compensate for a decreased chemical pest control, it might be easier to target specifically a decrease in herbicide, fungicide or insecticide use, or to distribute the lowering throughout all pesticide categories. This might affect the environmental benefits that arise from the decrease in pesticide use. TFI does not convey the entire information about such environmental benefits, and therefore it would be relevant to quantify them (for example, toxicity to specific non-target organisms, risk of groundwater contamination by pesticide residues). In addition, a wide-scale transition to low-pesticide farming systems would probably modify the agricultural landscape and the market organization, both for agricultural inputs and outlets. The whole agricultural sector may be thus impacted by a drastic reduction of pesticide use. A deeper analysis of these prospective evolutions would be wise.

Methods

Assessing pesticide use. The technical data, including pesticide application details, were collected for each farm between 2009 and 2011. We used the TFI as an indicator measuring pesticide reliance[22]. TFI can be calculated for all pesticide applications (total TFI) or each pesticide category considered separately (herbicide TFI, fungicide TFI, insecticide TFI, TFI for other pesticides). TFI was expressed at the farm level by averaging the crop TFI according to the proportion of each crop in the crop sequence (see Supplementary Information). TFI measures the reliance on pesticides, not the environmental impact of applied pesticides.

Assessing performance indicators: crop productivity and profitability at the farm level. Crop productivity was assessed using the higher heating value of crop products[23], which is the energy released as heat during the complete combustion with oxygen of the crop biomass in a bomb calorimeter. Profitability was assessed taking into account the variability of price context. To this end, we used a national database providing monthly variations of the selling and purchase prices, respectively, for crop products and farming inputs between 2005 and 2015[24]. Based on these price variations, we constructed ten contrasting price scenarios (see Supplementary Information) and we averaged farm profitabilities over these ten price scenarios.

Factors characterizing the production situation. For each farm from the DEPHY network, we collected data characterizing the production situation, that is the biophysical and socio-economic contexts. These data mainly refer to soil and climate factors as well as to factors describing the available crop outlets for the farmer. The detailed list of these factors and calculation details are provided in the Supplementary Table 1. For the whole dataset, 6% of production situation data were not available and was replaced by the median value or the mode for quantitative or qualitative variables respectively.

Estimating the marginal TFI effect. We estimated the marginal TFI effect using the Lasso regression analysis[25], a method based on variable selection and regularization, to enhance the prediction accuracy of the model. This method enables selection from complex models (models including many explanatory factors) of sub-models that find the best trade-off between the explanatory power of the model and the number of explanatory factors retained (for which coefficient estimates do not equal 0). The selectivity of the Lasso is determined by a regularization parameter λ (also called the tuning parameter), whose value directly determines the penalty on the number of explanatory factors retained in the sub-model[26] (see Supplementary Information). Two models were fitted, one for each performance indicator (crop productivity and profitability), to assess the marginal TFI effect on productivity and profitability. In addition to the direct effect of TFI on performance, the models included the direct effect of production situation factors and the two-way interactions between production situation factors and TFI. Each performance indicator was expressed as

$$\text{Performance} = \beta_1 \text{TFI} + \sum_{j=1}^{n} \beta_{j+1} \text{PS}_j + \sum_{j=1}^{n} \beta_{n+j+1} \text{PS}_j \text{TFI} + \beta_0 \tag{1}$$

and the marginal TFI effect was then calculated as

$$\text{Marginal TFI effect} = \beta_1 + \sum_{j=1}^{n} \beta_{n+j+1} \text{PS}_j \tag{2}$$

where PS_j, $j = 1, \ldots, n$, are the n variables characterizing the production situation and β_0 and β_i are the estimated intercept and regression coefficients for the $2n + 1$ explanatory factors, respectively. Lasso regression analysis was performed with the cv.glmnet function of the glmnet package (https://cran.r-project.org/web/packages/glmnet/glmnet.pdf) in R v3.1.2 (ref. 30). The regularization parameter λ was selected to minimize leave-one-out cross-validation error (LOO-XVE). We used the bootstrapping method (with 1,000 independent estimations of TFI effect) to assess confidence intervals on marginal TFI effect estimations. The marginal TFI effect was significantly positive or negative when the 95% confidence interval was strictly positive or negative, respectively.

Mapping and comparison of TFI effect categories. Marginal TFI effects were plotted on a map of the French territory using QGIS 2.6.1 software. The colour and point size were fixed for each farm according to the sign of the marginal effect of TFI and the accuracy of the TFI effect estimation, respectively (Fig. 1). We distinguished three categories of farms based on the marginal TFI effect (positive, negative or non-significant) and compared these sub-populations with a multiple non-parametric rank comparison test proposed by the kruskal function from the agricolae package (https://cran.r-project.org/web/packages/agricolae/agricolae.pdf) in R, using the Benjamini and Hochberg correction to the P-value[31].

Estimating potential pesticide use reduction in non-conflicting situations. We computed the gap in pesticide use between each farm and a 'target farm' with lower pesticide use in a similar context for crop production. This analysis was done in the group of farms with no significant positive effect of TFI on performance indicators, namely farms in non-conflicting situations between TFI reduction and both productivity and profitability. The target farms were identified using the Hill and Smith analysis[32] (see Supplementary Information). We calculated the difference between the current TFI of each farm and the TFI of its 'target farm'. These differences were used as indicators of the potential pesticide use reductions, assuming that each farm could adopt the farming systems of farms within its close neighbourhood, including the one associated with the lowest TFI.

Data availability. The data that support the findings of this study are available from the corresponding authors on request after acceptance by the French Ministry of Agriculture.

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Author contributions

N.M.J., D.M. and G.P. conceived the project; N.M.J. and G.P. contributed to data assembly; D.M. and F.D. contributed substantially to the methodology development; M.L. and F.D. analysed data; and M.L. wrote the paper, with substantial input from all authors.

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Competing interests

The authors declare no competing financial interests.