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ABSTRACT

A major path helping agriculture achieve the dual challenges of production and environmental preservation, consists of transitioning from the current, external input-based, conventional farming systems to a biodiversity-based agricultural system that rely more on ecosystem services. One lever of this transition consists of diversifying agri-food systems using practices such as rotation extension, intercropping (IC), multiple cropping or multi-services cover crops (MSCC) implementation. Here, we investigated to what extent the combination of diversification practices could contribute to the enhancement of the sustainability of current conventional cropping systems through an *ex ante* evaluation.

We compared the sustainability performances of five diversified (DIV) cropping systems from five major arable crop production regions of France to their local less diversified reference (REF) systems by calculating various criteria and implementing a multi-criteria decision aid model. 76 criteria assessing the three dimensions of sustainability were calculated (10, 17 and 49 criteria for the economic, social and environmental dimensions respectively).

Our analysis showed that the combination of diversification practices could improve the environmental performances while maintaining a priori economic and social performances at satisfactory levels according to the local expert working group. The DIV systems always had lower greenhouse gas (GHG) emissions compared to their REF systems and often improved air and water quality and above- and belowground biodiversity. However, diversification may also cause drawbacks for some indicators, as negative impacts were observed from, gross margin, NO_3 lixiviation, NH_3 volatilization or pesticide use, in some cases. Our analysis also suggested that the effect of a combination of diversification practices on an indicator can be either positive or negative according to the pedo-climatic context, the level of performance of the reference and compromises in the management of diversification practices in response to local objectives of performance.

1. Introduction

The large use of synthetic inputs (fertilizers and pesticides) combined with the simplification of agri-food systems has led to strong adverse impacts on the environment: soil degradation, water and air pollution, greenhouse gas emissions that contribute to climate change, and biodiversity erosion (e.g., birds and insects) (Campbell et al., 2017; COMIFER, 2017; Grunwald et al., 2011; Hallmann et al., 2017; IPCC, 2014; Laurance et al., 2014; Vermeulen et al., 2012). In addition, the constant growth of the world population and the increasing demand for meat in developing countries are challenging agriculture to continuously increase production. A major path to help agriculture face the dual

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challenges of production and environmental preservation consists of transitioning from the current external input-based conventional farming systems to biodiversity-based agricultural systems relying more on ecosystem services, also called agroecological intensification (Duru et al., 2015; HLPE, 2019; Therond et al., 2017; Tilman et al., 2002; Tittonell, 2014).

One important lever of this recommended transition by experts consists of diversifying agri-food systems in both time (rotation scale, i.e., all crops grown in a particular ordered sequence) and space (field scale) (Gaba et al., 2015; Pelzer et al., 2012; Watson et al., 2017). Diversification practices such as (i) rotation extension, (ii) intercropping (i.e., the simultaneous growth of two or more crops on the same land), (iii) multiple cropping (i.e., the growth of two or more cash crops on the same land and year and (iv) multi-services cover crop implementation (i.e., the growth of a non-harvested crop between two cash crops; Justes and Richard, 2017) have separately been shown to be able to increase both cash crop yields and yield stability, with reduced external inputs and environmental impacts (Bedoussac et al., 2014; Beillouin et al., 2019; Hunt et al., 2017, 2019, 2020; Meynard et al., 2015; Naudin et al., 2014; Raseduzzaman and Jensen, 2017).

Studies on diversification generally focus on a single diversification practice and its effect on a single service, e.g., yield or gross margin increase, N fertilization or soil C sequestration (Beillouin et al., 2019; Colnenne and Doré, 2014), which may limit the diffusion of the potential benefits of diversification. Indeed, in a meta-analysis, Beillouin et al. (2019) showed that cropping systems (CS) combining several diversification practices had higher productive performances than those using only one. However, studies assessing the performances of cropping systems combining diversification practices in real agricultural contexts are lacking, and this has been identified as one major issue hindering the development of diversification (Meynard et al., 2015). Additionally, several studies have suggested that interactions between diversification practices may not always be positive and could lead to trade-offs or antagonisms, i.e., ecosystem disservices (Martin et al., 2020; Palomo-Campesino et al., 2018) indicating that the performance assessment of cropping systems should be based on the three dimensions of sustainability (Deytieux et al., 2016), in order to avoid the creation of "solutions that create new problems".

Multi-attribute decision-aid methods (MADM) have been successfully implemented in the assessment of agricultural sustainability (Angevin et al., 2017; Sadok et al., 2008). The DEXiPM model from the DEXi® (Bohanec, 2015) software is a qualitative MADM method that has been used to evaluate *ex ante* and compare the performances of arable cropping systems by considering the economic, social and environmental dimensions of sustainability (Pelzer et al., 2012). Before their implementation in fields, innovative cropping systems, designed *in silico* can be assessed based on simulated performances (*ex ante* assessment) in order to confirm that the diversification objectives would be achievable given particular design constraints, e.g., increasing or maintaining the gross margin (Colnenne and Doré, 2014; Pelzer et al., 2012). This step can also help to identify sources of improvements and adapt cropping practices before an *ex post* assessment is conducted during the field experiment step. Consequently, the whole innovation process efficiency will be improved (Sadok et al., 2009).

Considering the current lack of knowledge on the effects of combining diversification practices on the sustainability of cropping systems, we decided to answer the following research question: to what extent could the combination of diversification practices contribute to enhancing of the sustainability of current conventional cropping systems? We hypothesized that the combination of diversification practices would lead to changes in cultivation operations, which would improve environmental performance while maintaining the economic and social performance of innovative conventional cropping systems at satisfactory levels for the local expert working groups. To achieve this, we performed *ex ante* evaluations of innovative cropping systems designed within a French network, grouping researchers, advisors and farmers, in the context of five main arable crop production regions of France with distinct economic and pedoclimatic contexts. This could highlight general trends and specificities regarding the combination of diversification practices and help the transition to biodiversity-based agricultural systems on a large scale.

2. Material and methods

2.1. Selected sites and design of diversified cropping systems

The Syppre network was created by a consortium of three French agricultural technical institutes, "Arvalis – Institut du Végétal", "Institut Français de la Betterave" and "Terres Inovia" to develop innovative arable cropping systems in the context of the agroecological transition launched by the French government (https://syppre.fr/). Innovative cropping systems of the network were designed to satisfy the following performances: (i) high productivity, to achieve higher needs for biomass to face an increasing demand for food, energy and proteins, (ii) high profitability for farmers, (iii) lower environmental impacts, measured by energy consumption (MJ ha^{-1}), GHG emissions (kg CO_2-eq ha^{-1}), N mineral (kg N ha^{-1}) and Treatment frequency index (TFI), which records the number of reference doses used per hectare during a crop year. To stay close to farmers issues and to preserve links with territorial specificities, the project included five locations representative of the main arable production regions of France: Béarn (BEA), southern France, deep clay humic soils, arable crop; Berry (BER), middle of France, shallow clay-limestone, arable crops; Champagne (CHA), northern France, deep chalky soils, highly-profitable standardized industrial productions (e.g., sugar-beet); Lauragais (LAU), southern France, steep hillside farmland, clay-limestone soils, arable crops; Picardie (PIC), northern France, deep loamy soils, highly-profitable standardized industrial productions (e.g., potato) (Fig. 1). The different locations would help to explore a large range of soil, climate and production system conditions, and thus a diversity of solutions to achieve the objectives of the network.

The methodology of '*de novo*' co-design of cropping systems (Meynard et al., 2012) was applied to reconcile global issues and local constraints. A local expert working group was set up with farmers, local advisors, researchers, crop specialists, and also grain collectors to include quality production issues and keep a view on new production opportunities, for each site. Each person within the local expert working group was chosen to balance the profiles, including experts in local issues and local knowledge, experts bringing good exploration knowledge and skills, and changes leaders (Reau et al., 2012). The design of the diversified cropping systems is detailed in Toqué et al. (2015).

Local expert working groups completed the objectives of the Syppre network, considering local agronomic, economic and social constraints, to be met by diversified (DIV) systems. The five local expert working groups had in common to search for an improvement of soil fertility as a solution to increase plant productivity and/or decrease dependency towards mineral fertilizers. In some cases (e.g., Lau), the improvement of soil organic matter content (SOM) was a key local objective to mitigate erosion risk of hillside farmland. Local expert working groups agreed on the cropping system to improve, i.e., one reference (REF), for each site (Fig. 1). The criteria for REF systems selection were a high representativeness of local farming practices, based on regional statistics and high technical and economic performances (i.e., mastered cropping practices and relatively high gross margin).

Several DIV systems were designed by each regional group by identifying candidate crops to introduce and suitable diversification strategies, based on their general knowledge and local expertise. *Ex ante* assessments of the sustainability performances of each REF and DIV systems were made using tools and models described in Section 2.2. Loop of improvements, including modification of cropping practices and/or addition or withdrawal of new crops, were made by the local expert working groups for the DIV systems until at least one could meet the national objectives and local issues (i.e., high productivity, high

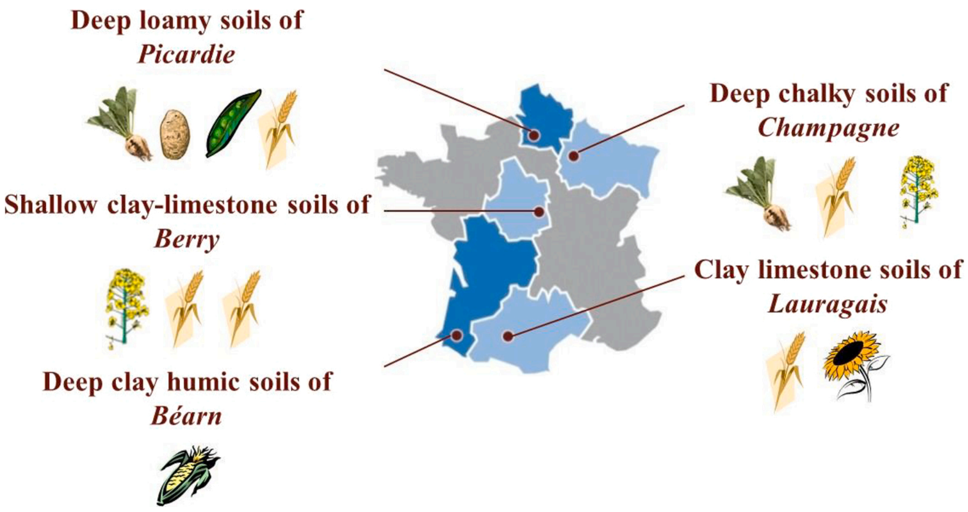

Fig. 1. The network of experimental sites. Italics indicates the name of the sites.; *Béarn*, southern France, deep clay humic soils, arable crop; *Berry*, shallow clay-limestone, arable crops; *Champagne*, chalky soils, industrial productions. *Lauragais*, southern France, clay-limestone, arable crops; *Picardie*, northern France, deep loamy soils, industrial productions; Pictures represent the main Cash Crops of the reference systems, adapted from (Cordoue et al., 2016). Crop sequences of both diversified and reference systems are presented in Table 1.

profitability and lower environmental impacts). At all sites, the most promising DIV system, according to the local expert working groups, was implemented on field trial along with its local low diversified REF system for comparisons of performances based on measurements (*ex post*). The field trials started in 2016 or 2017 according to the site. Note that all REF and DIV systems were rainfed so the use of irrigation was excluded in DIV systems.

This article will focus on the *ex ante* evaluation, i.e., based on estimated practices, performances of crops and prices, of the selected DIV systems performances compared to their local REF system in the same region. In contrast to system trials where *ex post* evaluations are made thanks to temporal replications (Lechenet et al., 2017), *ex ante* evaluations can be made on rotations even if the durations are different.

2.2. *Methods used for descriptor and indicator calculations and assessment of cropping systems performances*

2.2.1. *Diversification descriptors*

Diversification descriptors were calculated in order to characterize the use of diversification practices, i.e., rotation extension, intercropping, multiple cropping, introduction of multi-services cover crops (MSCC), and the botanical diversity and soil cover, of all REF and DIV systems. Calculations were based on the crop sequences of each cropping system (Table 1).

2.2.2. *Calculation of performance indicators, based on quantitative data*

The evaluation process of the cropping system performances started with the calculation of indicators based on quantitative data, whose values were estimated by local expert working groups (Fig. 2) which were transformed into qualitative data that were compatible with the multi-criteria assessment model DEXiPM. The calculations of the economic, social and environmental indicators for all DIV and REF systems were made using the following tools and models: Systerre® was used for economic, social, energy and greenhouse gases attributes (Cordoue et al., 2016; Jouy, 2011), DEXiSOL (Thibault et al., 2018) for attributes linked to soil physical quality and AMG (Clivot et al., 2019) for soil organic matter and carbon sequestration. Updated indicators of the INDIGO®, an environmental assessment method based on 8 composite indicators were also used: I-N 2.70 for nitrogen losses (NO_3, NH_3 and N_2O, Bockstaller et al., 2008) and I-Phy 2.05 for pesticide transfer (Lindahl and Bockstaller, 2012; Van Der Werf and Zimmer, 1998).

Systerre® is a performance assessment tool developed by the French agricultural institute “Arvalis- Institut du Végétal” (https://www.arvalis-infos.fr) which calculates scientifically-based performance indicators of cropping systems from an exhaustive description of their (i) cultivation practices including machinery and input use and (ii) outputs including grain yield and biomass production. The cultivations practices and crop yields of all REF systems used for calculations were based on local references of technically mastered rotations. Cultivations practices and crop yields of DIV systems were conceived and estimated by local expert working groups mentioned in section 2.1, (Supplementary material Table 6). Economical and technical parameters such as crop and fuel price were homogenized between REF and DIV systems at all sites. The descriptions of cropping system practices used in Systerre® were also used in the others tools and models listed above (Tables 2 and 3).

Table 1
Crop rotations of the reference and diversified cropping systems.

Cropping system	Crop rotation
Bea REF	MAG
Bea DIV	(RYE/FABA)-MAG-WB +SOY-WW + SOR
Ber REF	WOR-WW-WB
Ber DIV	WDW-WOR/(CLO/FABA/LEN)-(OAT/FABA/VET)-MAG-SUN-WW-WPEA + BUW-WW-(FABA/FENU)-WB-LEN
Cha REF	(MUS/VET)-SBEET-WW-WOR-WW-(VET)-SB
Cha DIV	WOR/(CLO/LEN)-WW-(PHA/VET)-SB-TRIT/(WPEA/VET) + SBEET-WW-(MUS)-WB/WPEA-(VET)-SUN-WW-OAT/(CLO/VET) + SBEET-SPEA
Lau REF	WDW-SUN
Lau DIV	(ALFA/CLO/LEN)-WOR-WDW-WB-TRIT/(VET) + SOR-WPEA + BUW-WDW-(FABA)-SUN-WW
Pic REF	(MUS)-SBEET-WW-(MUS)-POT-WW-WOR-(MUS)-SPEA-WW
Pic DIV	(CLO/MUS/RAD)-SBEET-WW-(PHA)-FABA-(CLO/VET/PHA)-SB-(CLO/PHA)-MAG (OAT/RYE)-SPEA-WOR-(CLO/VET/PHA)-POT-WW

Bea”, “Ber”, “Cha”, “Lau” and “Pic” indicate the Béarn, Berry, Champagne, Lauragais and Picardie sites, respectively. “REF” and “DIV” indicate reference and diversified cropping systems respectively. Brackets indicates non-harvested multi-services cover crops; “/” indicates intercrops; “ + ” indicates multiple cropping; “ALFA” = Alfalfa; “BUW” = Buckwheat; “CLO” = Clover; “FABA” = Faba bean; “FENU” = Fenugreek; “LEN” = Lentil; “MAG” = Grain maize; “MUS” = Mustard; “OAT” = Oat; “PHA” = Phacelia; “POT” = Potato; “RAD” = Radish; “RYE” = Rye; “SB” = Spring barley; “SBEET” = Sugar beet; “SOR” = Sorghum; “SOY” = Soybean; “SPEA” = Spring pea; “SUN” = Sunflower; “TRIT” = Triticale; “VET” = Vetch; “WB” = Winter barley; “WDW” = Winter durum wheat; “WOR” = Winter oil seed rape; “WPEA” = Winter pea; “WW” = Winter wheat.

2.2.3. *Multicriteria analysis via the DEXiPM® model, based on qualitative data*

Multi-criteria analysis was performed using an adapted version of the

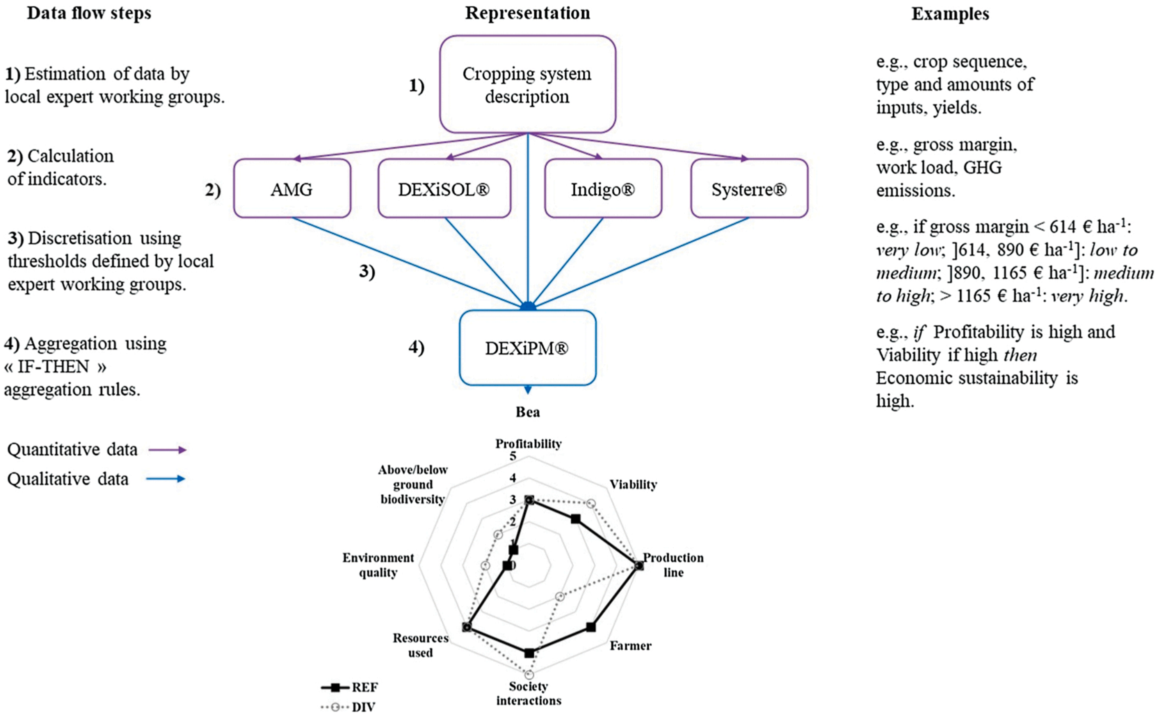

Fig. 2. Data flow used in this study. (1) Local expert working groups estimate quantitative and qualitative data based on their knowledge and the description of the cropping systems, e.g., crop sequence, type and amounts of inputs, yields, (2) Indicators are calculated using tools AMG, DEXiSOL®, Indigo® and Systerre®, e.g., gross margins, work load, GHG emissions, (3) Quantitative indicators are discretised, in order to be usable in DEXiPM, using thresholds defined by the local expert working groups. These thresholds can be common to all cropping systems or adapted to local constraints, e.g., if gross margin, <614 € ha^{-1}: *very low*;] 614, 890 € ha^{-1}]: *low to medium*;]890, 1165 € ha^{-1}]: *medium to high*; >1165 € ha^{-1}: *very high*, 4). Qualitative basic criterion obtained are then aggregated, using "IF-THEN" aggregation rules, to perform the multi-criteria analysis of the sustainability of the cropping systems, e.g., *IF* Profitability is high and Viability if high *THEN* Economic sustainability is high. The radar chart is an example of the outputs of the DEXiPM model. It represents the score of the second highest-ranking aggregated criteria in the DEXiPM model of the three dimensions of sustainability, of the reference (REF) and diversified (DIV) cropping system of Béarn "Bea". For all criteria, the lower the value for an indicator is, the lower the sustainability performance.

DEXiPM model (Angevin et al., 2017; Pelzer et al., 2012), (Supplementary material Figures 5, 6 and 7). This version was developed to use the economic, social and environmental indicators calculated from AMG, DEXiSOL®, INDIGO® and Systerre®, as input variables instead of agricultural practices. Such an approach, when possible, improves the sensitivity of this type of multi-criteria models (Carpani et al., 2012; Craheix et al., 2015). Quantitative indicators values described in Section 2.2.1, Tables 2 and 3 were transformed into qualitative variables, compatible with the DEXiPM model, by discretisation, using specific thresholds, defined by the local expert working groups, to fill in the basic criteria of the model. Thresholds used were always the same for the DIV and REF systems of a given site. It should be noted that some input data were directly based on qualitative data obtained from expert knowledge of local expert working groups in the Syppre network (Tables 2 and 3 and Fig. 2). The global sustainability of a cropping system is evaluated by aggregating the score of its economic, social and environmental dimensions with each dimension accounting for a third of the final global sustainability score (Craheix et al., 2015). The highest aggregated criteria in the hierarchy of the model for the economic sustainability assessment were "Profitability" and "Viability", both accounting for half the dimension score (Supplementary material Fig. 5). For the social dimension the highest-ranking criteria were production line, farmer and society interactions, accounting respectively for 45%, 45% and 10% of the dimension score (Supplementary material Fig. 5). Finally, for the environmental dimension, the highest-ranking criteria were "Resources used", Environment Quality" and "Above and below ground biodiversity", each accounting for a third of the dimension score (Supplementary material Fig. 6).

3. Results

3.1. Cropping system characterization

Rotation durations were always higher in DIV compared to in their respective REF systems (Table 4). The mean DIV system rotation duration was 7.8 ± 2.8 years, and the mean REF system rotation duration was 3.6 ± 2.4 years. For Bea DIV system, rotation duration, 3 years, was remarkably lower than those of the other DIV systems but was relatively important compared to the short rotation duration of its REF system (maize monoculture, Table 4).

The CCs in the REF systems had a low family-level botanical diversity with 4 sites growing not more than 3 botanical families (Table 4). In these systems, legumes (*Fabaceae*) were never grown as CCs, except in Pic, and the diversification practices, such as intercropping, multiple cropping and MSCC implementation, were almost always absent (Table 4). On the other hand, the botanical family diversity in DIV systems was always higher than or equal to their respective REFs, with 4 sites using 5 botanical families as CCs (Table 4).

MSCCs were introduced at all sites but were only legumes at Lau and only legumes and cereals (*Poaceae*) at Bea and Ber. Legumes *(Fabaceae)* were the only botanical family always present in the MSCCs of the DIV systems. The ratio of legume crops to the total number of crops greatly increased on average in DIV systems at all sites (7 ± 9% and 35 ± 8% of legume crops to the total number of crops for REF and DIV systems respectively, including CCs and MSCCs).

The share of intercropping in the DIV systems greatly differed according to the type of crop (CCs or MSCCs). The highest percentage of CC intercropped was 38% of the total number of CCs in the rotations but was 0 at 2 sites, while the percentage of MSCCs intercropped was never

Table 2
Methods used to evaluate all basic attributes of the economic and social dimensions of the DEXiPM model. “QT” stands for quantitative data obtained from cropping systems description and ‘QL” for qualitative data. All data used for calculation of basic criteria was obtained from local expert working group. Units of the reference method are presented between brackets when relevant. See DEXiPM model for calculation details.

Sustainability dimension	Basic criteria	Means used for basic criteria determination	Type of data	Reference method
Economic	Cropping system specialization	SYSTERRE	QT	Ratio of the main crop income to the total income (%). Main crop of a rotation is the crop whose contribution to the total rotation income is the highest
	Direct subventions to strategy	SYSTERRE	QT	Subventions given to specific cropping practices (€ ha^{-1}). “Medium” category affected to all systems at all sites
	Economic efficiency	SYSTERRE	QT	Ratio of semi-net margin to the sum of operating and mechanical costs (%)
	Financial security	SYSTERRE	QT	Difference between the gross operating income and the financial and salary expenses (€ ha^{-1})
	Investments need	SYSTERRE	QT	Additional costs to purchase new machinery. Investments needs are low by default for REF systems
	Pesticide expense	SYSTERRE	QT	Ratio of all pesticides expenses in a rotation to the total agricultural land (€ ha^{-1})
	Semi-net margin	SYSTERRE	QT	Ratio of semi-net margin considering subsidies and mechanical costs to the total agricultural land (€ ha^{-1}). REF and DIV subventions are equal at a given site
	Subvention independency	SYSTERRE	QT	Ratio of the total of subventions to semi-net margin (%)
	Turnover	SYSTERRE	QT	Ratio of the total gross product of all crops in a rotation to the total agricultural land (€ ha^{-1})
	Work load	SYSTERRE	QT	Ratio of the total of working hours dedicated to all cultivation operations of all crops in a rotation to the total agricultural land (h ha^{-1})
Social	Advisors access	DEXiPM	QL	“Low to Medium” category affected to all systems at all sites
	Certification requirements	DEXiPM	QL	“High” category affected to all systems at all sites
	Cropping system complexity	DEXiPM	QT	Ratio of the sum of the complexity coefficients to all crops in the rotation. The more technically difficult a crop is, the higher the complexity coefficient. The lower the indicator, the better
	Farming network access	DEXiPM	QL	“No” category affected to all systems at all sites
	Inputs access	DEXiPM	QL	“Easy” category affected to all systems at all sites
	Knowledge and technical skills	DEXiPM	QL	“Medium” category affected to all systems at all sites
	Landscape diversity	DEXiPM	QT	Simpson’s diversity index. The higher the indicator, the better
	Market flexibility	DEXiPM	QT	Sum of “Risky” crops in the rotation based on market outlets accessibility. “Risky” crops were designated by the local expert working groups. The lower the indicator, the better
	Non-sanitary qualitative requirements	DEXiPM	QL	“High” category affected to all systems at all sites
	Physical risks	DEXiPM	QT	Ratio of the sum of hand weeding operations to the rotation duration. The lower the indicator, the better
	Product acceptability by society	DEXiPM	QL	“High” category affected to all systems at all sites
		DEXiPM	QT	Ratio of the sum of all crop

(continued on next page)

Table 2 (*continued*)

Sustainability dimension	Basic criteria	Means used for basic criteria determination	Type of data	Reference method
	Risk of mycotoxin contamination			contamination risk index to the total number of crops in the rotation. The lower risk, the better
	Risk of pesticide residues contamination	DEXiPM	QL	"Low" category affected to all systems at all sites
	Risk of pestice use	DEXiPM	QT	Ratio of the number of spraying operations using harmful, toxic and very toxic pesticides to the rotation duration. The lower the indicator, the better
	Strategy acceptability by society	DEXiPM	QL	"Medium" and "High" categories affected to all REF and DIV systems respectively.
	Work balance	SYSTERRE-DEXiPM	QT	Calculation based on the number of work peak periods and their intensity.
	Work satisfaction	DEXiPM	QL	"Medium" category affected to all systems at all sites

below 80% (Table 4). CC intercrops were mostly legume/cereal intercrops or a CCs intercropped with a green manure containing at least one legume species (Table 1).

Multiple cropping was introduced at 4 sites but this diversification practice was less used compared to the other practices (Table 4), except at Bea. Unlike the CCs introduced via rotation extension and intercropping that were grown solely for food production, market outlets for the CC grown using multiple cropping were diverse, i.e., crops for grain (soybean, buckwheat) and crops for energy production, e.g., methanization, (sorghum, triticale) or silage (oat).

The percentage of bare soil over the total duration of the rotation was reduced at 4 sites (Table 4). The reduction was sometimes considerable, e.g., in Bea, where the percentage of bare soil fell from 48% to 7% between REF and DIV systems, respectively, indicating a major change in agronomic strategies (Table 4). Conversely, the percentage of bare soil was slightly increased at Ber in the DIV system (Table 4). This can partially be explained by the succession of two spring crops (grain maize and sunflower) without the implementation of an MSCC or the use of multiple cropping whereas the REF system only grew winter crops.

3.2. Impacts of diversification on main cultivation operations

Mineral N inputs at the rotation scale were reduced at all sites in the DIV compared to their respective REF systems (Fig. 3a). Four levers were used: (i) the introduction of CC with lower N requirements than the CC in the REF system (e.g., legumes, Supplementary material Figs. 8b, 9b, 10b, 11b and 12b), (ii) the introduction of reactive N in the rotation via legume fixation, through legumes grown as CCs (e.g., winter peas before winter wheat, Supplementary material Fig. 9a and 9b) or MSCCs (e.g., MSCC before grain maize, Supplementary material Fig. 8a and 8b), (iii) the use of intercrops with a legume as CCs (e.g., winter peas intercropped with barley, Supplementary material Fig. 10a and 10b) or as an MSCC (e.g., winter oil seed rape intercropped with frost sensitive legumes as green manure, Supplementary material Figs. 9a and 9b, 12a and 12b), and (iv) the substitution of mineral N with organic N inputs. In Lau, the introduction of 5 legume crops as MSCC and one as CC in DIV rotation (vs 0 in REF, Table 4) did not result in an important reduction in N fertilization at the rotation scale (-7 kg N ha^{-1} year^{-1}) mainly because the REF system contained sunflower which has relatively low N requirements in a short rotation (2 years, Table 1).

Similar to N mineral inputs, the reduction in P inputs (Fig. 3b) was due to the introduction of crops with lower P requirements than the crops in the REF system, which was combined with the use of MSCC (Supplementary material Figs. 8c, 8d, 9c, 9d, 11c, 11d, 12c, 12d) and intercropping (Supplementary material Figs. 10c, 10d, 12c, 12d). However, in Cha, the combination of diversification practices led to a high use intensity of P resources (e.g., multiple cropping of oats and sugar beets, Supplementary material Fig. 10c and 10d) which was compensated by a higher mineral P fertilization of sugar beets in the DIV system than in the REF system. At this site, the mineral P_2O_5 inputs of the DIV system were similar to that of the REF system ($+3$ kg P_2O_5 ha^{-1} year^{-1}).

The total TFI was reduced in the DIV systems with REF systems with the highest TFI values, i.e., Ber, Cha, Pic (−42%, −18%, −33% TFI for Ber, Cha, Pic, respectively, Fig. 3c). The reduction has two main causes: (i) the introduction of low TFI crops in the DIV system and ii) the reduction in pesticide requirements as a result of specific agronomic management strategies (integrated pest management) such as maximization of competition against weeds through intercropping and breaking pest cycles through rotation extension (Supplementary material Figs. 9e, 9f, 10e, 10f, 12e, 12f). Conversely, the total TFI was increased in DIV systems with REF systems with the lowest TFI, i.e., Bea and Lau, (+26% and +23% TFI for Bea and Lau respectively, Fig. 3c). In these cases, the increase was due to (i) the introduction of higher TFI crops in DIV systems (e.g., soybean in Bea and winter oil seed rape in Lau) compared to the REF systems that include maize or sunflower and (ii) the management of certain diversification strategies, e.g., chemical destruction of MSCC, which increased the TFI at the rotation scale (Supplementary material Figs. 8e, 8f, 11e and 11f). For the latter case, the local expert working group of Lau looked for a maximal soil cover duration and lowest soil tillage to reduce erosion which is a major local issue because of hillside farmland which led to the choice of the chemical destruction of MSCC. The multi-performances objective of DIV systems may sometimes lead to compromise between environmental performances.

The tillage fuel consumption (l ha^{-1}) at the rotation scale was reduced in all DIV systems (−19%, −27%, −49%, −73%, −31% for Bea, Ber, Cha, Lau and Pic respectively, Fig. 3d). This was the result of a strong reduction of tillage or even a suppression of ploughing, confirmed by the lower ploughing frequency (calculated as the total number of ploughs over the duration of the rotation) in the DIV systems than in the REF systems (not shown). The alternance of winter and spring crops, sowing delays and the introduction of MSCC were part of an integrated management of weeds in DIV systems of all sites, in response to the reduced tillage.

3.3. Impacts of diversification estimated via environmental performance indicators

All DIV systems consumed less primary energy than their respective REF systems (Fig. 4a–e and Supplementary material Fig. 13). There was a strong positive correlation between energy consumption and GHG emissions, i.e., the higher the energy consumption of a CS was, the higher its GHG emissions (Supplementary material Fig. 13). The decomposition of the total primary energy consumption per input category for the REF systems indicated that, on average, fertilizers and

Table 3
Methods used to evaluate all basic attributes of the environmental dimension of the DEXiPM model. "QT" stands for quantitative data obtained from cropping systems description and 'QL" for the qualitative data obtained from local expert working group expert knowledge.

Sustainability dimension	Basic criteria	Means used for basic criteria determination	Type of data	Reference method
Environmental	Climat effect	DEXiSOL	QT	See DEXiSOL model for calculation details
	Clod creation by tillage	DEXiSOL	QT	See DEXiSOL model for calculation details
	Compaction risk	DEXiSOL	QT	See DEXiSOL model for calculation details
	Crop effect on pollinisators	DEXiSOL	QT	See DEXiSOL model for calculation details
	Crop type	DEXiSOL	QT	See DEXiSOL model for calculation details
	Deep tillage	DEXiPM	QL	See DEXiPM model for calculation details
	Energy consumption	SYSTERRE	QT	Ratio of the energy consumption of all inputs related to their production (using life cycle analysis method) and use to the agricultural land (MJ ha^{-1})
	Energy efficiency	SYSTERRE	QT	Ratio of the gross energy production to the energy consumption (MJ ha^{-1}). Reference for crop energy content was "Table d'alimentation" INRA, 2007
	Equipment increasing contact surface	DEXiSOL	QT	See DEXiSOL model for calculation details
	Equipment lowering weight per surface unit	DEXiSOL	QT	See DEXiSOL model for calculation details
	Erosion risk	DEXiSOL	QT	See DEXiSOL model for calculation details
	Flora	DEXiSOL	QT	See DEXiSOL model for calculation details
	Flora quality of field borders	DEXiSOL	QT	See DEXiSOL model for calculation details
	GHG emissions	SYSTERRE	QT	Ratio of all direct (in situ) and indirect GHG emissions (related to production of all of inputs including machinery) of a rotation to the agricultural land (kg eq CO_2 ha^{-1}). Emissions of CO_2, CH_4, N_2O are weighted by their global warming potential. Methodology used is GES'TIM v1.2 following IPCC 2007 references
	Habitat management	DEXiSOL	QT	See DEXiSOL model for calculation details
	Habitat network	DEXiSOL	QT	See DEXiSOL model for calculation details
	Inversion tillage	DEXiSOL	QT	See DEXiSOL model for calculation details
	Irrigation	SYSTERRE	QT	Ratio of all water applied for all crops in a rotation to the agricultural land (m^3 ha^{-1}). "Low" category affected to all systems at all sites since irrigation was not possible
	K mineral use	SYSTERRE	QT	Ratio of all mineral K applied for all crops in a rotation to the agricultural land (kg K ha^{-1})
	Mechanical weeding	DEXiSOL	QT	See DEXiSOL model for calculation details
	N mineral use	SYSTERRE	QT	Ratio of all mineral N applied for all crops in a rotation to the agricultural land (kg N ha^{-1})
	NH3 volatilization	INDIGO	QT	See INDIGO model V 2.70 for calculation details
	NO3 lixiviation	INDIGO	QT	See INDIGO model V 2.70 for calculation details
	Non herbicide TFI	SYSTERRE	QT	Ratio of the sum of all TFI non-herbicide TFI applied for all crops in a rotation to the agricultural land
	Non-cultivated area	DEXiSOL	QT	See DEXiSOL model for calculation details
	Organic matter content management	AMG	QT	See AMG model for calculation details
	P mineral use	SYSTERRE	QT	Ratio of all mineral P applied for all crops in a rotation to the agricultural land (kg P ha^{-1})
	P surplus	SYSTERRE-DEXiPM	QT	See DEXiSOL model for calculation details
	Pesticide runoff	INDIGO	QT	See INDIGO model V 2.70 for calculation details
	Pesticide lixiviation	INDIGO	QT	See INDIGO model V 2.70 for calculation details
	Pesticides volatilization	INDIGO	QT	See INDIGO model V 2.70 for calculation details
	Proportion of crops harvested in autumn	DEXiSOL	QT	See DEXiSOL model for calculation details
	Rain quantity during autumn harvest	DEXiSOL	QT	See DEXiSOL model for calculation details
	Root system diversity	DEXiSOL	QT	See DEXiSOL model for calculation details
	Slope	DEXiSOL	QT	See DEXiSOL model for calculation details
	Soil cover	DEXiSOL	QT	See DEXiSOL model for calculation details
	Soil coverage during pesticide application	DEXiSOL	QT	See DEXiSOL model for calculation details
	Soil coverage during risks period	DEXiSOL	QT	See DEXiSOL model for calculation details
	Soil propension to fissuration	DEXiSOL	QT	See DEXiSOL model for calculation details
	Soil sealing sensibility	DEXiSOL	QT	See DEXiSOL model for calculation details
	Soil use intensity	DEXiSOL	QT	See DEXiSOL model for calculation details
	Superficial tillage between crops	DEXiSOL	QT	See DEXiSOL model for calculation details
	TFI fungicide	SYSTERRE	QT	Ratio of all TFI fungicide applied for all crops in a rotation to the agricultural land
	TFI herbicide	SYSTERRE	QT	Ratio of all TFI herbicide applied for all crops in a rotation to the agricultural land
	TFI insecticide	SYSTERRE	QT	Ratio of all TFI insecticide applied for all crops in a rotation to the agricultural land
	Tillage effect on reducing soil tearing	DEXiSOL	QT	See DEXiSOL model for calculation details
	Total TFI pesticides	SYSTERRE	QT	Ratio of all TFI applied for all crops in a rotation to the agricultural land
	Water accessibility	DEXiPM	QL	See DEXiPM model for calculation details. "High" category affected to all systems at all sites
	Worm biomass	DEXiSOL	QT	See DEXiSOL model for calculation details

Table 4
Comparison of the reference (REF) and diversified (DIV) cropping systems according to various diversification descriptors.

Cropping system	Rotation duration (year)	CC botanical families	MSCC botanical families	Total legumes as CC	Total legumes as MSCC	CC intercropped over total CC ratio	MSCC intercropped over total MSCC ratio	Multiple Cropping	% Soil cover with MSCC	% Bare soil
Bea REF	1	1	0	0	0	0%	0%	0	0%	48%
Bea DIV	3	2	2	1	1	0%	100%	2	11%	7%
Ber REF	3	2	0	0	0	0%	0%	0	0%	22%
Ber DIV	9	5	2	2	7	10%	100%	1	8%	24%
Cha REF	5	3	2	0	2	0%	67%	0	11%	22%
Cha DIV	10	5	4	2	8	38%	80%	2	20%	17%
Lau REF	2	2	0	0	0	0%	0%	0	0%	43%
Lau DIV	8	5	1	1	5	10%	80%	2	10%	18%
Pic REF	7	5	0	1	0	0%	0%	0	10%	25%
Pic DIV	9	5	4	2	6	0%	93%	0	26%	19%

The cash crops (CC) and multi-services cover crops (MSCC) botanical families indicate the total number of botanical families grown as CCs and MSCCs respectively, in a rotation. The total legumes as CC and MSCC indicate the total number of legume species grown as CCs and MSCCs, respectively, in a rotation. CCs intercropped over the total CC ratio is the ratio of the total number of CC that are intercropped over the total number of CCs, in a rotation; for the ratio is similarly calculated for MSCC. Multiple cropping indicates the occurrence of multiple cropping at the rotation scale (see definition of multiple cropping in introduction section). The percentage (%) of soil cover with MSCC for a rotation was calculated as the sum of all MSCC growth durations over the duration of a rotation. The growth duration of an MSCC was calculated from its date of sowing until its date of chemical or mechanical destruction. The percentage (%) of bare soil was calculated as the sum of all periods without CC or MSCC growth over the duration of a rotation.

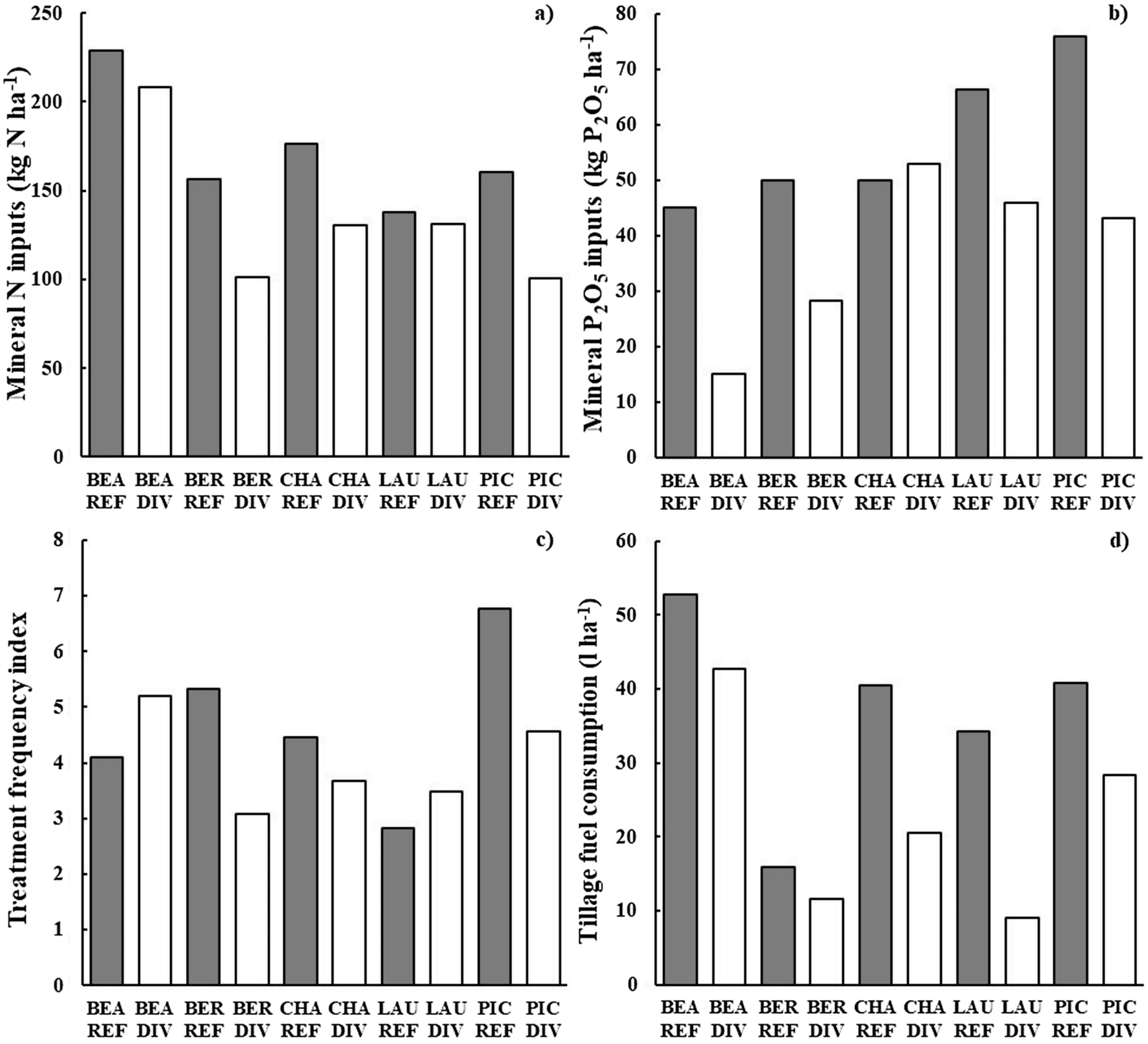

Fig. 3. Modification of cultivation operations as a result of diversification: (a) comparisons of the mineral N inputs (kg N ha^{-1}) between REFs and DIVs per site, (b) comparisons of mineral P_2O_5 inputs (kg P_2O_5 ha^{-1}) between REF and DIV per site, (c) comparisons of treatment frequency index between REFs and DIVs per site, (d) comparisons of the tillage fuel consumption (l ha^{-1}) between REF and DIV per site.

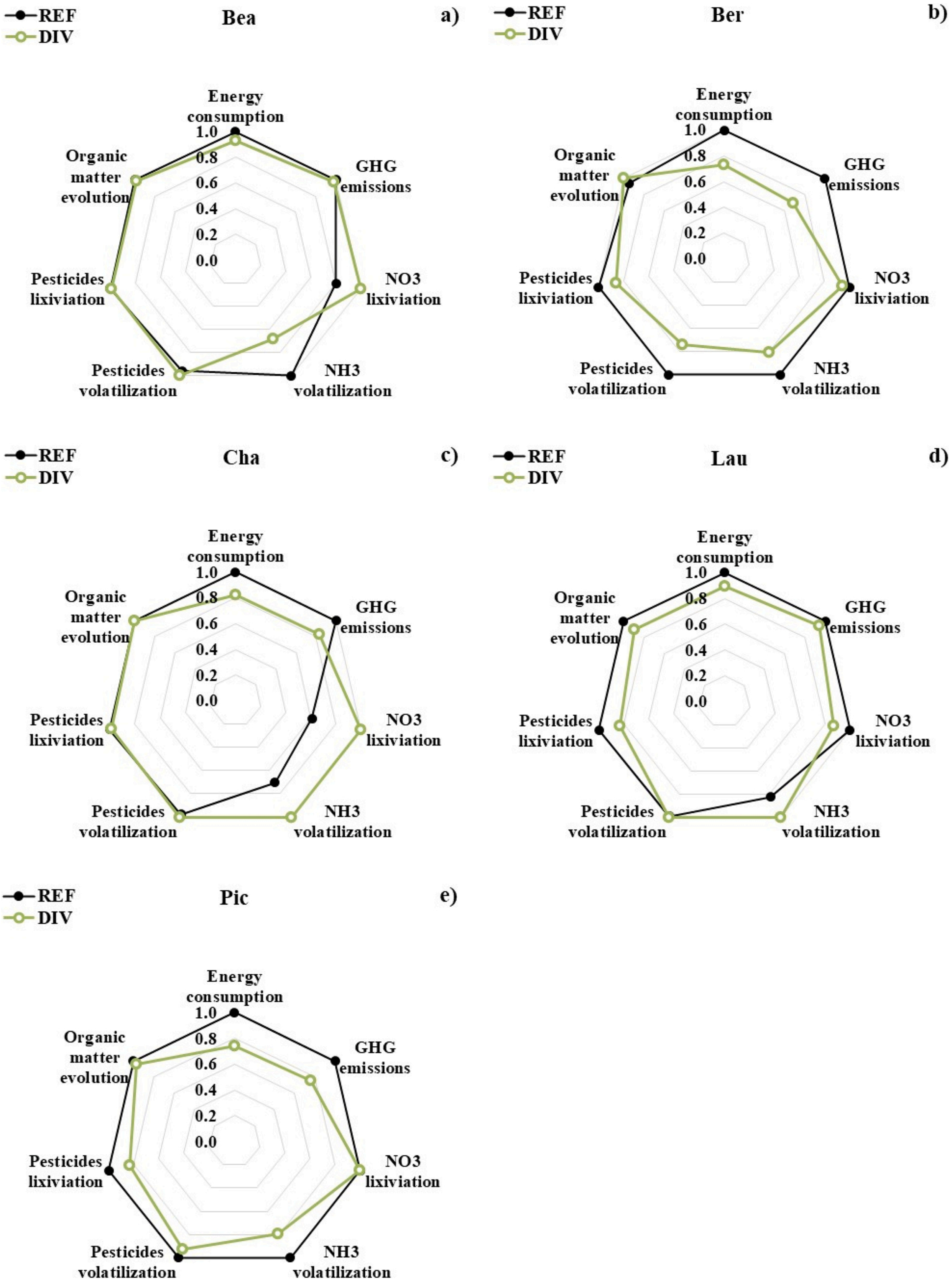

Fig. 4. Indicators of environmental performances of the reference (REF) and diversified (DIV) cropping systems for (a) Béarn “Bea”, (b) Berry “Ber”, (c) Champagne “Cha”, (d) Lauragais “Lau” and (e) Picardie “Pic”. Values are normalized on a 0–1 scale, with 1 representing the cropping system (REF or DIV system) with the highest absolute value for that indicator, i.e., the less favourable for the environmental performance. For all indicators, the lower the value for an indicator is, the better the performance.

fuel accounted for 66 ± 4% and 25 ± 5%, respectively, of the total primary energy consumption (Supplementary material Fig. 14). Other inputs, i.e., pesticides, seeds and machinery, on average, altogether, accounted for only 9 ± 3% of the total primary energy consumption. Comparable orders of magnitude were found in the DIV systems for each category of primary energy consumption (Supplementary material Fig. 14), despite the reduction of fertilizers and tillage use in these CSs (Fig. 3a and d). On average, GHG emissions were reduced by 16 ± 12% in DIV systems compared to the REF systems, but there were large discrepancies between sites; the lowest reduction was 2% at Bea and the highest was 31% at Ber. Sites with the largest reductions in GHG emissions (Ber and Pic) were those with the largest reductions of energy consumption related to mineral fertilizers use and vice versa. Ber and Pic reduced mineral fertilizers use by a relatively high introduction of legumes in both CCs and MSCCs while sites with lower reductions in GHG emissions, e.g., Bea, had a relatively lower uses of legumes. Additionally, in Bea, the high use frequency of multiple cropping (two times over a three-year long rotation) led to an increase in fuel consumption which partly erased the gain obtained by the reduction in mineral fertilizers.

NO_3 lixiviation was either similar or decreased at Pic, Ber and Lau (Fig. 4e, b and d). However, NO_3 lixiviation increased by 24% and 64% at Bea and Cha compared to in their respective REFs (Fig. 4a and c). The NO_3 lixiviation levels in Bea and Cha were far above the sustainable level of 10–15 kg NO_3 ha^{-1} $year^{-1}$ (Archambeaud and Thomas, 2016), (i.e., 56 and 36 kg NO_3 ha^{-1} $year^{-1}$ for the DIV systems in Bea and Cha, respectively). This could be explained by two main factors: (i) the absence of soil cover or presence of a crop in its early vegetative phase, during a high lixiviation risk period i.e., the late summer and/or early spring and (ii) the mineralization of low C/N residues by the introduced legumes.

NH_3 volatilization decreased by 32%, 19% and 21% at Bea, Ber and Pic respectively (Fig. 4a, b and e) but increased by 42% and 21% at Cha and Lau respectively (Fig. 4c and d), despite the reduction in mineral N fertilization (Fig. 3a). The increase in NH_3 volatilization in the DIV systems can be explained by a higher use of fertilizers with high urea content (50%) which generate more NH_3 volatilization than other forms of N fertilizers (e.g., ammonium nitrate) for an equal amount of N applied (COMIFER, 2017; Robert and Le Borgne, 2019). In those sites, many CC species introduced in DIV systems were cereals that are often fertilized using the high urea content fertilizers.

Pesticide volatilization was reduced at Ber and Pic (Fig. 4b and e), mostly due to a strong reduction in the TFI in these sites (Fig. 3c), but slightly increased at the other three sites (Fig. 4a, c and d). The pesticide lixiviation was reduced in DIV systems of all sites (Fig. 4a–e). Nevertheless, the introduction of new crops in the DIV systems can result in the use of pesticides with relatively high or low active ingredient toxicity compared to those present in the REF systems. This ultimately positively or negatively impacts air and water quality. Consequently, a decrease in TFI does not necessarily lead to lower pesticide volatilization or lixiviation and vice versa (Bockstaller and Girardin, 2008).

The organic matter evolution indicator calculated as the ratio of the estimated soil organic matter (SOM) content after 30 years over the initial SOM content was similar between DIV and REF systems for Bea, Cha and Pic (1 ± 1% difference in the indicator on average of the 3 sites; Fig. 4a, c and e) suggesting a low effect of diversification on SOM evolution in these sites. In Lau, the organic matter evolution indicator was higher in DIV than in the REF system (+11%; Fig. 4d) and superior to 1, suggesting a faster rate of SOM increase in the DIV than in the REF system. This would mainly be due to the incorporation of the biomass produced by the MSCCs of the DIV system, which were absent in the REF system. In Ber, the organic matter evolution indicator was lower in the DIV than in the REF system (−6%; Fig. 4b) and below 1, suggesting a faster rate of SOM decrease in the DIV than in the REF system. In that case, the lower biomass production of some introduced CC, e.g., winter pea or lentil, would not be compensated by the biomass production of others CC and MSCCs, which would lead to a decline trend in SOM content. Overall, the simulations of the AMG model suggest that the combination of diversification strategies, including an important diversification of CC and use of MSCC (Tables 1 and 4 would not necessarily lead to an increase in SOM content over time. However, these predictions should be verified by measurements in the field trials.

3.4. Multi-criteria analysis of diversified and reference cropping systems

The values of global, economic and social sustainability ranged from medium to very high when considering all REF systems. The environmental sustainability of the REF systems ranged from very low to medium and was always the lowest performing dimension among the three (Table 5).

In this ex ante assessment, global sustainability was higher in DIV systems compared to REF systems at Ber, Cha and Lau and similar at Bea and Pic (Table 5).

The economic sustainability was similar between the DIV and REF systems at four sites and increased at Bea (Table 5). The semi-net margins were higher at Ber and Lau (14% and 21% respectively), similar at Bea and Cha (3% and 2% respectively) and were lower at Pic (−22%) in the DIV systems compared to in their respective REF systems (data not shown). For the latter, this was the result of a lower proportion of highly profitable industrial crop, i.e., potato, in the rotation of the DIV system. Even though the semi-net margin reduction was important, the level of semi-net margin was still deemed “very high”, i.e., the highest rank for that attribute, in the DEXiPM model. The local expert working group decided to test this DIV system nonetheless considering the improvements of other performances.

Of all attributes of the economic dimension, the cropping system specialization (Table 2) was one most impacted by diversification. Indeed, cropping system specialization was strongly decreased in the DIV compared to in the REF systems (35 ± 8% vs 59 ± 26% on average for DIV and REF systems, respectively, for all sites; data not shown). This feature could contribute to a higher economic stability of DIV systems, since any major crops in DIV systems accounted for more than 50% of the total income, in contrast to that in the REF systems.

Social performances were increased or maintained at Pic, Cha and Ber and decreased at Bea and Lau (Table 5). The lower social performances of these sites were due to the higher technical complexity of the DIV systems compared to the simplified REF systems (Table 5) which was deemed a negative feature in the DEXiPM model because this requires the farmer to keep a high level of technical monitoring, which can be difficult for minor species. In the DIV systems, the workload was reduced at Ber, Cha and Lau (−14%, −12% and −22%), which was mainly due to the reduction in the time-consuming soil tillage operations. The workload remained similar at Pic (−2%) but increased at Bea (11%) because of the high use of MSCCs and multiple cropping in this system which increased the number of cultivation operations per year and consumed the time saved by the reduction in soil tillage. The increase in workload in the Bea DIV system could be a major issue as the absolute value was near the maximal physical capacity for one person. Nevertheless, the local expert working group decided to implement this DIV system due to its advantages in others criteria and dimensions of sustainability and given that cultivation operations efficiency could be improved during the field trial phase.

Environmental performances were always higher or similar (Pic) in the DIV systems compared to in their respective REF systems (Table 5). However, we observed many trade-offs during the aggregation of attributes that were positively and negatively affected by diversification. Indeed, as seen in 3.3, the modification of cultivation practices in the DIV systems did not always lead to the improvement of all environmental indicators at the same time. For instance, the “above-and below-ground biodiversity” aggregated indicator was improved in Bea and Lau, because of the beneficial effect of the reduction in soil tillage on fauna and flora, which compensated for the increase in TFI in these sites. Another example was that, in Pic, the value of the “resources used”

Table 5
Comparisons of the reference (REF) and diversified (DIV) cropping systems performances on global, economic, social and environmental sustainability using multi-criteria analysis performed by the DEXiPM model. Performances range from 1 (very low) to 5 (very high) in this model. Red, orange, light orange, green and blue colours stand for very low, low, medium, high and very high performances respectively.

Dimension	Bea		Ber		Cha		Lau		Pic	
	REF	DIV	REF	DIV	REF	DIV	REF	DIV	REF	DIV
Global	3	3	4	5	3	4	3	5	4	4
Economic	3	4	5	5	5	5	5	5	5	5
Social	5	4	4	4	4	4	5	4	4	4
Environmental	1	2	3	5	2	3	2	4	3	3

aggregated indicator was similar in the DIV and REF systems because the global reduction in energy consumption compensated for the increase in non-renewable mineral input (P and K) use in the DIV system. Globally, the strategy of reducing synthetic inputs and soil tillage while increasing the level of diversification seems to have a positive global impact on the environmental performances of conventional cropping systems, but one should also bear in mind that mechanisms of compensation between attributes can occur.

4. Discussion

4.1. Diversification as a mean to increase the sustainability of cropping systems

The multi-criteria analysis performed in this study indicated that diversification could improve the environmental sustainability of cropping systems (CSs) while maintaining economic and social dimensions at satisfactory levels, according to the local expert working groups and consequently improve the global sustainability of conventional arable CSs in France, as seen in other pedoclimatic contexts worldwide (Beillouin et al., 2019; Davis et al., 2012). Regarding the important issue of climate change, the combination of diversification practices appears to be a relevant mean to lower the GHG (considering CO_2, CH_4 and N_2O, Table 3) emissions of the agricultural sector (Pellerin et al., 2013). The reduction in the total primary energy consumption at the rotation scale in the diversified (DIV) systems was the main driver of the reduction in GHG emissions. Our results confirmed that the key to a low-carbon agriculture in conventional arable CSs lies in the reduction of fertilizers and fuel use (Colnenne and Doré, 2014; COMIFER, 2017), which can be compensated by a higher use of ecosystem services, as recommended by published studies and experts worldwide (Beillouin et al., 2019; Davis et al., 2012; FAO, 2018; HLPE, 2019). The environmental benefits associated with diversification in our study were also found for water and air quality and above- and below-ground biodiversity, which are important features of food safety, notably due to the provision of ecosystem services. It should be noted that the conception of innovative CSs in this study did not consider the management of landscape habitats (e.g., hedges or forests) because it cannot be tested afterwards in the long-term experiments conducted at field level. Nevertheless, the management of these types of habitats could contribute to reduce biodiversity losses of birds or pollinators and provide even more ecosystem services, e.g., on pest regulation, to diversified cropping systems (Duru et al., 2015; Martin et al., 2020; Sirami et al., 2019). Discussions among local expert working groups of the Syppre network identified landscape management as an avenue for future studies.

In spite of many positive effects on the sustainability performance, diversification showed also some drawbacks. The multi-criteria analysis (MCA) revealed that diversification did not improve all attributes of the environmental dimension at the same time and that trade-offs between performances occurred, confirming the importance of using MCA when assessing CS sustainability (Angevin et al., 2017; Colnenne-David et al., 2017). Indeed, in our *ex ante* analysis, NO_3 lixiviation, NH_3 volatilization, TFI and SOM evolution were sometimes worsened in DIV systems, as a result of diversification. For instance, the rotation extension in DIV systems could increase the frequency of spring crops in rotations, which potentially increased the occurrence of bare soil periods, if soil is not covered by a multiple cropping or a MSCC, or if the crop is its early vegetative phase (Colnenne-David et al., 2017). This may generate negative environmental impacts e.g., increased NO_3 lixiviation even though mineral N inputs were reduced at the rotation scale. In this case, cultivation operations could be adapted by following the decision rule to always cover the soil before growing a spring crop in order to lower bare soil duration and the associated environmental risks (Colnenne-David et al., 2017). The use of decision rules in the design of diversified cropping systems can be a great asset for the management of cultivation operations in order to maximize ecosystem services and to minimize ecosystem disservices (Debaeke et al., 2009).

Our results also demonstrated that the effect of a diversification practice on an indicator could depend on the REF value for that indicator. For instance, we observed two opposite trajectories regarding the evolution of TFI as a response to diversification. In the REF systems growing potatoes, sugar beets or oilseed rape, the three arable crops with the highest TFI values in France (TFI of 18.9, 6.5 and 5.2 respectively, Ministère de l'Agriculture de l'Agroalimentaire et de la Forêt, 2016), the introduction of new crops with much lower TFI values such as maize or sunflowers, mechanically led to a reduction in the TFI at the rotation scale. Conversely, we observed an increase in the TFI at sites with a REF system that used very low TFI crops (maize and sunflower), in very short rotations (1 and 2 years for Bea and Lau respectively; Table 4). Considering that about 3.6% of the French cultivated area uses monoculture systems (Toupet De Cordoue, personal communication) our results suggest that diversification could lead to a consequent TFI increase in a significant part of the French cultivation area. This confirms that the conception of diversified CS should be performed on a relatively small scale to answer specific agronomic issues from a given pedoclimatic and economic context, in order to lower the risk of trade-offs or antagonisms between performances (HLPE, 2019; Meynard et al., 2015). As stated by Tittonell (2014), "there is no single generalizable model of ecological intensification".

The performances of the DIV systems in this study depended on the assumptions made to evaluate potential yields used for the indicator calculations. The hypotheses were collectively made by local expert working groups of farmers, advisors and researchers to maximize the level of expertise. In our *ex ante* analysis, the results expressed the performances of systems with no CC or MSCC failure and mastering of innovative cultivation practices, which requires a very high level of technical expertise, which is not necessarily currently available for minor crops and all MSCCs. Nevertheless, the objective of the Syppre network is to create this technical expertise, which has been identified as a major factor hindering diversification development in France (Meynard et al., 2018), to reach the yield hypotheses used in this study. Beyond technical issues, other factors, such as climate, notably through water availability, lack of seed availability and breeding on minor crops, market outlets and selling price fluctuations, may negatively affect the performances of diversified cropping systems (Meynard et al., 2018). On the other hand, the economic performances of the DIV systems in this study are based on existing value chains. With increasing pressure to implement regulations to pay for the environmental cost of agricultural production (e.g., Green Deal, Farm 2 Fork, Biodiversity strategies), the economic performances of diversified cropping systems might improve relatively to that of the less diversified ones in the future.

The *ex post* evaluation is necessary to test whether the yield hypotheses, management strategies and economic parameters simulated in the *ex ante* analysis were validated in experiments using real farming conditions. The first two years of field trials of the Syppre network show positive trends in the environmental performances of the DIV systems but the achievement of the economic objective was sometimes not completed because of technical issues regarding management and unfavourable pedo-climatic conditions to new crops (Tauvel et al., 2019).

4.2. *Diversification and ecosystem services delivery*

The study of several highly diversified CSs, which was co-conceived with various actors, represents an original contribution by our article. In our study, the total number of crops (CC + MSCC) in the DIV systems was 17 ± 7 on average with $n = 5$ CSs, which was relatively high compared to those in the published literature on the effects of diversification on CS performances (8 ± 2 with $n = 20$ in Craheix et al., 2016, 9 ± 3 with $n = 4$ in Colnenne and Doré, 2014 and 5 ± 1 with n = 2 in Davis et al., 2012). Innovative CSs within the Syppre network used ecosystem services to lower the reliance on energy-consuming and pollution-producing external inputs (see above), as recommended by experts on sustainable agriculture (FAO, 2018; HLPE, 2019; Meynard et al., 2013). The combination of diversification practices showed an interesting potential for increasing the supply of ecosystem services and constitutes a relevant approach towards a biodiversity-based agriculture. Indeed, high species diversity within rotations could promote an important level of ecosystem service provision, especially for pest regulation (Harrison et al., 2014; Palomo-Campesino et al., 2018) however the relationship is not always as straightforward in scientific literature and is sometimes dependent on the scale considered (field, agroecosystem or landscape), (Balvanera et al., 2016). Also, a high reliance on ecosystem services in biodiversity-based cropping systems may introduce a high variability on all the sustainability dimensions performances because the services provided are highly dependent on the environmental conditions.

When comparing the level of botanical diversification in the CCs and MSCCs of the DIV systems, we observed that the botanical diversity of MSCCs was lower than that of CCs (Table 4) and that the ecosystem services expected from MSCCs were mainly nitrogen fixation and biomass production. Although the latter were key services to enhance sustainability of CS, other services such as the "biofumigation" provided *Brassicaceae* crops to mitigate pests and diseases (Couëdel et al., 2018), were sometimes unused even though they could help to further reduce TFI or tillage frequency. The lower botanical diversity in MSCCs could be explained by a low availability of seeds, lack of technical information, especially on destruction means of complex MSCC, or unfavourable pedoclimatic conditions. This also suggests that dissemination of scientific publications about the positive effects of botanical diversity in MSCCs may still be needed. Local solutions should be addressed to allow cultivation of diverse MSCCs to fully use their benefits at the rotation scale. Note that the botanic diversity of MSCC is increased at several sites in the ongoing *ex post* evaluation.

Multiple cropping was less used in comparison to the other diversification practices, except at Bea (Table 4). This practice has several assets, as it is a way to cover the soil before a spring crop, and unlike with MSCCs, the crops can be harvested to increase yield and economic performances at the rotation scale. However, in certain areas where precipitations in late spring are low, such as in Lau, multiple cropping could lower water availability at the sowing of the spring cash crop and impede its early development, which partially explains why the local expert working groups did not use multiple cropping as much as others diversification practices. Furthermore, multiple cropping can accelerate soil resource (mineral and organic) depletion over time, because the aboveground parts are exported, and should be compensated by the use of MSCC at some points in the rotation to maintain soil fertility (Archambeaud and Thomas, 2016). Consequently, it should not be overused in crop rotations.

Regarding intercropping, we observed that this practice was widely used in MSCCs as a way to enhance the provision of ecosystem services (Couëdel et al., 2018) but never exceeded 25% of the total number of CCs and was sometimes absent (Table 4). Many studies in France, in Europe and worldwide have shown the benefits of intercrops, even in conventional agriculture, to increase resource use efficiency, promote pest control, stabilize yields and increase gross margins (Barot et al., 2017; Carton et al., 2019; Martin-Guay et al., 2018; Raseduzzaman and Jensen, 2017). In our study, the most intercropped CCs were associated with a non-harvested green manure, and only one cereal/legume intercrop with both crops as CCs was implemented among all sites. Many legumes were introduced as sole crops, such as lentil, with a high lodging risk that could lead to crop failure (Colnenne-David et al., 2017; Viguier et al., 2018). In these cases, the introduction of legumes intercropped with cereals could be a way to reduce the risk for farmers. Additionally, the use of intercropping does not necessarily need to be constrained to new minor crops. Studies have shown the benefits of intercropping cereals that are usually main crops (maize or winter wheat) with legumes (Aziz et al., 2015; Brooker et al., 2014; Du et al., 2018). Nevertheless, it should be borne in mind that the number of legumes in the crop sequence should align with the minimum sequential break for each legume crop in the rotation in order to avoid phytosanitary issues (Reckling et al., 2016). This could be a factor limiting the proportion of intercrops with legumes in the rotation. In France, other main factors hindering the development of intercropping are the lack of local technical knowledge and sorting difficulties, i.e., separating grains of different species harvested together (Pelzer et al., 2015).

The Syppre network developed a "de-novo" approach towards diversification involving multiple actors of the agricultural sectors willing to make a transition from a chemical input-based model towards a biodiversity-based model of agriculture. The adoptability potential of the DIV systems was meant to be high, which explains why these systems could not completely break from their REF systems. As stated above, the relatively high level of diversification proposed in this network already represents a technical challenge at all sites.

A further increase in the diversification level might reach a critical level of feasibility given the existing lack of technical knowledge and threaten the performances of the systems in the *ex post* evaluation. The results of the field experiments in real farming conditions will surely provide directions for further necessary studies to take on the next step towards the agroecological transition of cropping systems.

5. Conclusion

The *ex ante* analysis performed in this study highlighted that a diversification strategy based on a combination of diversification practices could improve the environmental dimension of French conventional cropping systems while maintaining the economic and social dimensions at satisfactory levels according to the local expert working group. Diversification would always lead to a reduction in GHG emissions compared to those in the reference systems and would often lead to an improvement in air and water quality and above- and below-ground biodiversity. However, the choices of diversification strategies would not necessarily improve all environmental indicators at the same time, and negative impacts could sometimes occur on NO_3 lixiviation, NH_3 volatilization or treatment frequency index. In any case, the results obtained by the *ex ante* evaluation will have to be confirmed or rejected by an *in situ* evaluation of the field system experiments. Overall, the diversification level tested in this study was high compared to that in the published literature, but there is a potential to increase the ecosystem services provided by multi-services cover crops, intercrops, multiple cropping and rotation extension in the future to further improve the global performance of diversified cropping systems

Authors' contribution

Loïc Viguier: formal analysis, writing – original draft preparation, reviewing and editing.

Nicolas Cavan, Sophie Dubois: investigation, formal analysis.

Christian Bockstaller, Olivier Keichinger: methodology and formal analysis.

Stéphane Cadoux, Rémy Duval, Methodogy, Clotilde Toqué, Anne-Laure Toupet de Cordoue: investigation, resources.

Frédérique Angevin and Guénaëlle Corre-Hellou: conceptualiztion, methodology and funding acquisition.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at https://doi.org/10.1016/j.eja.2021.126279.

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