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RESEARCH ARTICLE

Design and multicriteria assessment of low-input cropping systems based on plant diversification in southwestern France

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Abstract

Lengthening and diversifying crop rotations is an efficient strategy to reduce the use of fertilizers and pesticides, thereby improving the sustainability of cropping systems. To test this assumption, six innovative cropping system prototypes were designed, each introducing one or more agroecological practices, as alternatives to the 2-year sunflower (*Helianthus annuus* L.)–durum wheat (*Triticum turgidum* L. subsp. *durum*) rotation widespread in southwestern France. Two 3-year rotations were implemented at INRAE, Toulouse, from 2011 to 2016. The six prototypes were composed of two low-input cropping systems (with/without cover crops) and four very low-input cropping systems (including cultivar or species mixtures, each with/without cover crops). As compared to the sunflower–wheat rotation, the prototypes aimed at reducing the use of N fertilizers by 25% (low-input) and 50% (very low-input) and pesticides by 50%. A set of agronomic, environmental, technical, and socio-economic indicators was calculated to assess the different components of sustainability. The introduction of agroecological principles resulted in a clear reduction of the use of synthetic inputs as compared to the sunflower–wheat rotation. The treatment frequency index was decreased by 56, 18 and 39% for the low-input cropping systems, very low-input cropping systems with cultivar mixtures, and very low-input cropping systems with species mixtures, respectively. However, the profitability decreased with the diversification of cropping systems as the semi-net margin decreased for the three previous cropping systems (745, 696, and 438 €·ha^{-1}, respectively, vs. 963 €·ha^{-1} for the sunflower-wheat rotation). Despite the costs of inputs, the short rotation remained the most profitable. Agroecological practices succeeded in reducing the dependence of cropping systems on synthetic inputs, but their implementation needs to be improved to achieve better economic performance, using both scientific knowledge and know-how of innovative farmers.

Keywords Species diversification · Input reduction · Crop rotation · Grain legume · Cover crop · Species mixture

1 Introduction

World food production raised by a factor of 2.5 from 1960 to 2000 due to an increase in the application of fertilizers, irrigation, and pesticides altogether with the use of improved cultivars and continued progress in agricultural machinery and technologies. Unfortunately, this intensification of agriculture resulted in a decrease in air and water quality, water shortages, soil erosion, resistance of weeds and pathogens to pesticides, and a decrease in plant and soil biodiversity (Kremen and Miles 2012). As a result, citizens and consumers' concern about human and environmental health issues related to intensive farming systems have grown increasingly. This has prompted policy makers to regulate input use and decrease negative impacts and has encouraged

The original online version of this article was revised: In Table 2 of this article, some of the data in the second column headed 'Description and/or calculation - Agro-economic output performance' were mistakenly listed under the first column headed 'Indicators – Agro-economic output performance'.

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agronomists to develop low-input farming systems based on diversifying cropped species (Duru et al. 2015).

Agroecology is widely recognized as a relevant systemic alternative based on ecological intensification that might be combined with Green Revolution technologies to move towards sustainable agriculture (Altieri et al. 2015). Agroecology requires a high degree of diversification in agricultural systems at the field, farm, and landscape scales to increase resource-use efficiency, intensify ecological processes to promote ecosystem services and resilience to external stresses, and therefore reduce the use of external inputs (Kremen and Miles 2012). Spatial and temporal diversification of cropping systems, a fundamental pillar of agroecology, can be achieved through several practices, such as diversifying crop rotations by growing more legumes, multi-service cover crops, cultivar mixtures, and species mixtures (Duru et al. 2015). Agronomists and farmers have long understood the principles of diversified crop rotations and how they can improve agricultural sustainability. However, they have been insufficiently implemented in conventional systems due to agronomic, organizational, economic, and market reasons, a lack of information, and technological lock-in (Magrini et al. 2016).

Introducing legumes to fix atmospheric nitrogen (N_2) and thus reduce application of N fertilizers in cereal-based crop rotations has been widely studied and experimentally demonstrated. Sowing multispecies cover crops to avoid bare soils between cash crops decreases N leaching and increases soil nutrient availability. When they contain cruciferous species, cover crops can function as natural biofumigants to reduce the inoculum of some soil-borne diseases (Couedel et al. 2018). Increasing intra-field crop diversity by growing mixtures of cultivars and/or species received increasing attention over the past two decades. Many benefits, such as increased resource use, complementary effects of legumes on crop N nutrition, and a smaller yield gap due to abiotic stresses, have been highlighted for species mixtures (Bedoussac et al. 2015) and cultivar mixtures (Creissen et al. 2016). In some agroecological systems, reduced tillage favors beneficial invertebrate macrofauna (e.g., carabids, earthworms) and decreases soil erosion by maintaining crop residues on the surface (Hobbs et al. 2008). Conservation agriculture combines reduced or no tillage with diversified crop rotations and a permanent soil cover (by living cover crops or residues), but it mostly fully depends on herbicide use, particularly glyphosate (Soane et al. 2012). Therefore, there is no general agreement on whether adopting widely conservation agriculture would reduce pesticide use.

Designing cropping systems to reduce drastically the use of pesticides and N fertilizers requires combining several diversification practices with a systemic approach. It also requires adapting farmers' decision rules to maximize their effects and provide ecosystem services for sustainable agriculture. Unfortunately, field experiments on such diversified cropping systems have not received much attention, and a few results are available on cropping systems' comparison and multicriteria assessment. Experiments on cropping systems are traditionally used to test disruptive or innovative systems or those that have not yet been adopted in practice and require rigorous evaluation at experimental stations (Debaeke et al. 2009). More results are needed to demonstrate the economic effectiveness of these types of cropping systems and their relevance for evaluating agroecological principles. Evaluating these low-input and diversified cropping systems must consider multiple criteria due to the many potential benefits of agronomic innovations and the expected trade-offs among agronomic, economic, environmental, ecological, and social objectives (Colnenne-David and Doré 2015).

The generic approach of prototyping was developed to design and evaluate cropping systems according to a set of objectives and constraints. Agronomic strategies were translated by the cropping system designer into decision rules (including thresholds for triggering cropping practices) for easy implementation by farmers and experimental evaluation (Lancon et al. 2007). Because of the learning process throughout the experiment, all agronomic strategies and decision rules can be revised according to continuous improvement loops, while the objectives and constraints of the cropping systems must remain fixed. The agronomic assessment has two parts (Debaeke et al. 2009): (i) overall multicriteria assessment, to determine whether the management system met the objectives based on the data collected at harvest or during the cropping year, and (ii) assessment of agronomic strategies, which consists of testing the validity of the assumptions made to design the innovative cropping system.

We adapted this methodological framework to design and evaluate prototypes of diversified cropping systems aiming at drastically reducing the use of pesticides and N fertilizers, as a way to lower agriculture's dependence on chemical inputs and fossil energy and to limit the environmental and human health impacts. The strategy of diversification was used to decrease the vulnerability of crops to diseases. These prototypes were designed to identify alternatives to the common 2-year rotation of sunflower (*Helianthus annuus* L.) and durum wheat (*Triticum turgidum* L. subsp. *durum*) currently practiced on rainfed farms in southwestern France. Although this cropping system is cost-effective and largely adopted, it has several agronomic disadvantages notably when practiced widely over a region (Debaeke et al. 2017), such as the following:

- Shallow tillage after sunflower harvest leads to unburied stalks that are sources of inoculum for fungal diseases (e.g., Phomopsis stem canker, Phoma black stem) in adjacent sunflower fields.

- Sunflower stalks release relatively little N and, due to their high C:N ratio, require more N in the soil than cruciferous or legume residues to decompose.
- The lack of cover crops on the steeply sloped clay soils of southwestern France leads to a high risk of soil erosion during the fallow period (i.e., more than 9 months from wheat harvest in July to sunflower sowing in April).
- Some weeds are difficult to control due to the short crop rotation, which prevents a large decrease in herbicide use.

Therefore, we assumed that a more diversified crop rotation that includes legumes, cover crops, species mixtures, and/or cultivar mixtures could improve the environmental performance of the cropping system while maintaining profitability and producing a similar amount of grain. Our study tested this assumption by designing and assessing six cropping system prototypes (Fig. 1) during 6 years in southwestern France. The objectives of this study were thus to (i) assess whether each prototype met the objectives based on three major indicators (N fertilizer use, pesticide use, and semi-net margin) and (ii) compare the prototypes using multicriteria assessment based on quantitative indicators that reflected the production factors applied and agro-economic performances.

2 Materials and methods

2.1 Soil and weather conditions of the study site

The study site was located at the INRAE (French National Research Institute for Agriculture, Food and Environment) experimental station in Auzeville, southwestern France (43° 31′ 38″ N, 1° 30′ 22″ E). The 6-year cropping system experiment was set up in 2010 on a deep silt–clay to clay soil (0–120 cm). The upper layer (0–30 cm) consisted of 27% clay, 36% silt (of which 65% was fine silt and 35% coarse silt) and 37% sand (of which 41% was fine sand and 59% coarse sand). The soil had a mean $CaCO_3$ content of 0.03%, organic matter content of 1.5%, and pH of 7.3.

The climate is altered oceanic, with mean annual precipitation of 648 mm and mean annual temperature of 13.8 °C (data from 1996 to 2016). Weather data were recorded throughout the experiment (Fig. 2) using a weather station (Cimel, 516i, INRAE) located on the experimental site. The experimental dataset was divided into two successive 3-year periods: the first period (2011–2013) from October 2010 to September 2013 and the second period (2014–2016) from October 2013 to September 2016. Subsequently, a cropping season was defined as the period from the burial of residues

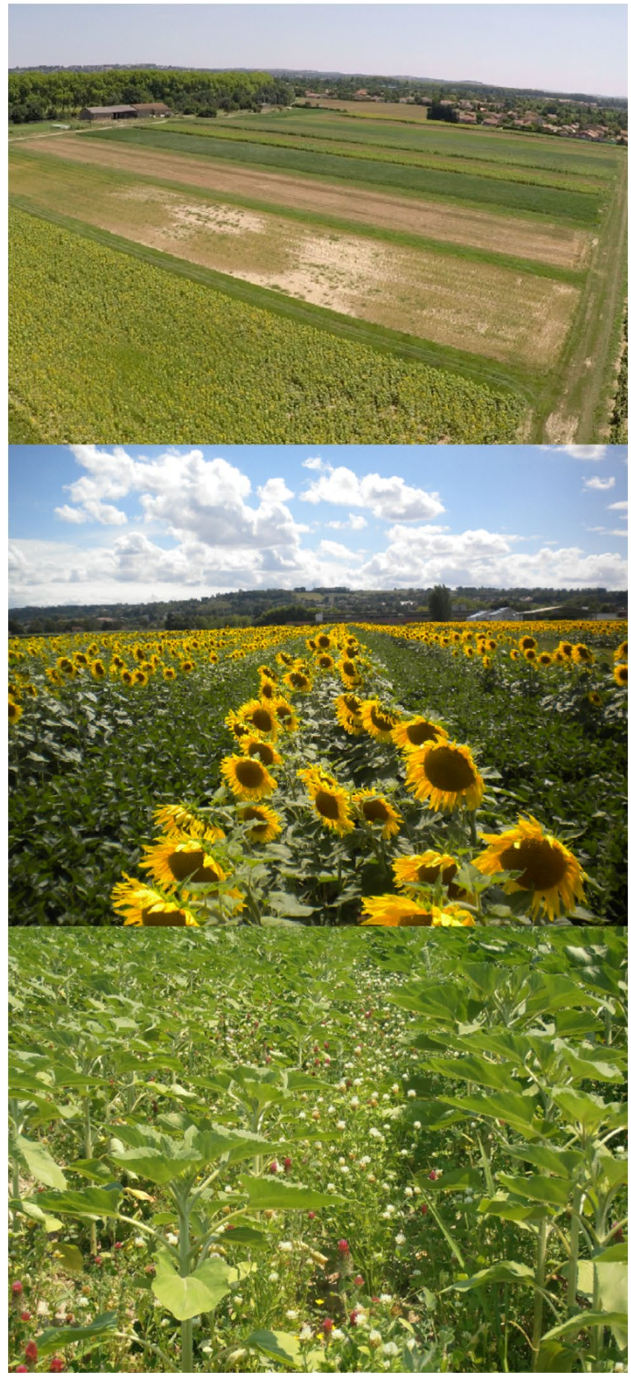

Fig. 1 Aerial view of the experimental site (top) located at the INRAE (French National Research Institute for Agriculture, Food and Environment) experimental station in Auzeville, southwestern France (43° 31′ 38″ N, 1° 30′ 22″ E), covering ca. 3.5 ha and consisting in nine plots (200 m × 30 m) separated by 6 m of grass buffer strips (credit: Rémy Marandel, INRAE, UEGC). Sunflower (Helianthus annuus L.)–soybean (Glycine max L.) mixture (middle) of the very low-input cropping system prototype (credit: Grégory Véricel, INRAE). Legumes cover crop (Berseem clover, Trifolium alexandrinum; Crimson clover, Trifolium incarnatum; and alfalfa, Medicago sativa) under sunflower cover (bottom) of the low-input cropping system prototype (credit: Didier Raffaillac, INRAE).

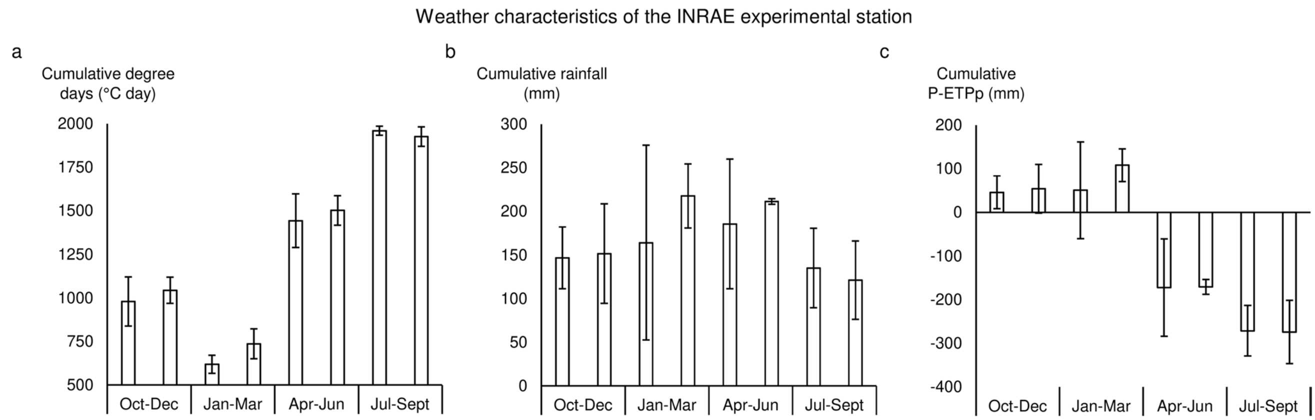

Fig. 2 Weather characteristics of the INRAE experimental station in Auzeville (43° 53′ N, 1° 51′ W) during the experimental period (2010–2016): **a** cumulative degree-days ± standard deviation (°C day) calculated quarterly as the sum of daily mean temperature on a 0 °C basis, **b** cumulative precipitation ± standard deviation (mm) calculated quarterly as the sum of precipitation, and **c** cumulative P-ETPp ± standard deviation (mm) calculated quarterly as the sum of cumulative precipitation (P) minus cumulative evapotranspiration (ETP—Penman method).

of the previous cash crop to the harvest of the current cash crop.

This region experiences substantial interannual weather variability, as illustrated by three dry years: 2010–2011 (609 mm), 2011–2012 (504 mm), and 2015–2016 (611 mm). Drought was particularly severe from December 2010 to June 2011 and October 2011 to March 2012 (275 and 174 mm of precipitation, respectively). Conversely, the spring of 2013 and the springs and summers of 2014 and 2015 were relatively rainy. During the first period (2011–2013), 18 months received less than 50 mm of precipitation, compared to 12 months during the second period (2014–2016). In addition, the second period had higher mean temperature (14.3 °C) than the first one (13.7 °C).

2.2 Cropping system design and description

2.2.1 Cropping system description

The cropping system prototypes were defined during co-design workshops, involving agronomic researchers, technicians, and agricultural engineers advising farmers. The experiment studied low-input cropping systems designed to reduce the use of chemical inputs (N fertilizers and pesticides) as alternatives to the common 2-year durum wheat/sunflower cropping system without irrigation (COM). The design of the cropping system prototypes had to comply with two main goals: (i) maintain durum wheat and sunflower in the crop rotation to limit the impacts on the current organization of the agrifood chain and (ii) assess the effect of cover crops, which are mandatory in nitrate-sensitive areas, by designing each cropping system both with cover crops during fallow periods and without them (i.e., bare soil). Consequently, six prototypes of three crop rotations were designed, all aiming at reducing the use of pesticides by 50%, but with additional objectives regarding N fertilizer and semi-net margin (Table 1):

- A low-input (LI) system based on a sunflower/durum wheat/sorghum (*Sorghum bicolor* (L.) Moench) crop rotation with cover crops (LI_CC) and without cover crops (LI). The objectives of LI(_CC) (i.e., LI and LI_CC) at the 3-year period scale were to reduce the use of N fertilizers by 25% (compared to the COM) and to achieve 100% of the COM semi-net margin.
- A very low-input system with cultivar mixtures (VLI_CM) based on a sunflower/faba bean (*Vicia faba* L.)/durum wheat crop rotation with cover crops (VLI_CM_CC) and without cover crops (VLI_CM). The objectives of VLI_CM(_CC) (i.e., VLI_CM and VLI_CM_CC) were to reduce the use of N fertilizers by 50% and to achieve 90% of the COM semi-net margin.
- A very low-input system with species mixtures (VLI_SM): sunflower–soybean (*Glycine max* (L.) Merr.)/triticale (*Triticosecale rimpaui* Wittm.)–faba bean/durum wheat–winter pea (*Pisum sativum* L.), with cover crops (VLI_SM_CC) or without cover crops (VLI_SM). For the second 3-year period, crop rotation's composition was modified according to the decision rules (Section 2.2.2), with durum wheat–winter pea introduced as the second mixture and soft wheat (*Triticum aestivum* L.)–faba bean as the third one. The objectives of VLI_SM(_CC) (i.e., VLI_SM and VLI_SM_CC) were to reduce the use of N fertilizers by 50% and to achieve 85% of the COM semi-net margin without seed treatments.

Table 1 Description of the objectives, main agronomic practices, and species for the common 2-year durum wheat/sunflower cropping system (COM) and the six prototypes designed according to an agro-ecological gradient. Legume species are in bold. LI (low-input prototype); LI_CC (LI with cover crops CC), VLI_CM (very low-input prototype with cultivar mixtures), VLI_CM_CC (VLI_CM with CC), VLI_SM (VLI with species mixtures), and VLI_SM_CC (VLI_SM with CC).

Cropping systems	COM	LI	LI_CC	VLI_CM	VLI_CM_CC	VLI_SM	VLI_SM_CC
Diversification gradient	0	1	2	3	4	5	6
Objectives (% of COM)							
Pesticide use	100%	50%		50%		50%	
Seed treatments	Yes	Yes		Yes		No	
N fertilizer use	100%	75%		50%		50%	
Semi-net margin	100%	100%		90%		85%	
Mouldboard plowing	100%; every 2 years	133%; 2 out of 3 years		67%; every 3 years		67%; every 3 years	
Main characteristics							
Rotation length	2 years	3 years		3 years		3 years	
Cultivar mixtures	No	No		Yes		No	
Species mixtures	No	No		No		Yes	
Legume cash crops	0	0		1		3	
Crop species richness	1,3	1,6		1,6		3,2	
Cash crop species							
2011–2013	Sunflower	Sunflower		Sunflower		Sunflower–soybean	
	Durum wheat	Durum wheat		**Faba bean**		Triticale–faba bean	
	Sunflower	Sorghum		Durum wheat		Durum wheat–**winter pea**	
2014–2016	Durum wheat	Sunflower		Sunflower		Sunflower–soybean	
	Sunflower	Durum wheat		**Faba bean**		Durum wheat–winter pea	
	Durum wheat	Sorghum		Durum wheat		Soft wheat–**faba bean**	
Cover crop species							
2011–2013	Bare soil (residues crushed and in mulch as soil cover) ×3	Bare soil ×3	**Egyptian clover**	Bare soil ×3	Oat	Bare soil ×3	Bare soil
			Vetch–phacelia		**Vetch**–mustard		**Vetch–mustard**
			Regrowth volunteers		**Vetch**–oat		Oat–phacelia
2014–2016	Bare soil (residues crushed and in mulch as soil cover) ×3	Bare soil ×3	**Legumes under cover**	Bare soil ×3	Forage sorghum–mustard	Bare soil ×3	Buckwheat
			Vetch–mustard		**Vetch**–mustard		**Vetch–mustard**
			Faba bean–clover–oat		**Vetch**–oat		Green foxtail–mustard

To preserve soil health and biodiversity, mouldboard plowing was limited to 1 out of 3 years for VLI_CM and VLI_SM, which corresponds to a mouldboard plowing before sunflower instead of (i) 1 out of 2 years for the COM, which corresponds to a mouldboard plowing before sunflower, and (ii) 2 out of 3 years for LI, which corresponds to a mouldboard plowing before sunflower and before sorghum.

These six prototypes (LI, LI_CC, VLI_CM, VLI_CM_CC, VLI_SM, and VLI_SM_CC) followed an agroecological gradient increasing from LI to VLI_SM_CC based on (i) expected decrease of pesticides use, (ii) expected decrease of N fertilizers use, (iii) increased diversity of crop species, (iv) increased number of cash crop legumes, (v) increased diversity of cultivars, (vi) use of cover crops, and (vi) decreased intensity of soil tillage.

2.2.2 Decision rules

Technical operations were performed to follow the objectives of the prototypes, which influenced the decision rules defined during the design process of the prototypes and applied for their daily management. The decision rules were based on several parameters, such as the presence or risk of pests, climatic conditions, or the N content in soil and crop residues. Thus, crop auxiliaries, animal pests, diseases, and weeds were monitored throughout the experiment to adapt farm management. Consequently, the technical operations differed by prototype and year, especially due to weather variability, as a consequence of the application of the formalized decision rules.

As a first decision rule, the sowing dates were determined to reduce the use of pesticides and avoid extreme weather events. For example, winter crops were sown later than those in conventional systems to avoid cereal aphids (*Rhopalosiphum padi*) and thus the use of insecticides. Spring crops were sown early to avoid water shortages and heat at the flowering stage, which is a critical period for seed set and final grain size. Mechanical weeding (false seedbed, tine harrow, rotary harrow, and hoeing) was performed during early crop stages to reduce herbicide use as much as possible.

The N-budget method derived from Rémy and Hébert (1977) was used to calculate N fertilization to apply as a function of yield targeted, initial soil N, and N mineralization expected from organic matter and crop residues. We assumed that atmospheric N inputs (non-symbiotic fixation, dry and wet deposition) compensated for gaseous losses (volatilization and denitrification), which can be considered an acceptable assumption in this agricultural context. Soil N mineralization was estimated using the equation from the STICS soil-crop model (Brisson et al. 2002).

The crop species used to diversify the common durum wheat/sunflower cropping system was chosen to maintain these two crops in each prototype and to include a third crop according to the objectives of each prototype. For LI(_CC) prototypes, grain sorghum was chosen because it was assumed to require few pesticides and moderate N fertilizer. For VLI_CM(_CC) prototypes, faba bean was chosen because it was assumed to require few pesticides and no N fertilization. For VLI_SM(_CC) prototypes, in order to decrease competition for N and thus reduce N fertilizer inputs, grain legumes were chosen for all mixtures: (i) pea with durum wheat, (ii) soybean with sunflower, and (iii) faba bean with a cereal crop. This changed in the second 3-year period because the soil N content was too low after the sunflower–soybean mixture to meet durum wheat yield and protein objectives. As a result, the durum wheat–winter pea mixture was postponed to the second year and was replaced in the third year by a soft wheat–winter pea mixture. Soft wheat was chosen instead of triticale due to its more consistent yield and higher selling price when sold for human consumption. All cultivars were chosen according to their agronomic performances and information on their disease tolerance.

2.3 Experimental design and measurements

2.3.1 Experimental design

The experiment covered ca. 3.5 ha and was composed of nine plots (200 m × 30 m) for the prototypes, which were separated by 6 m of grass buffer strips. Each plot was divided into two 200 m × 15 m subplots (one with cover crops and one without). The subplots were designed to enable the use of common agricultural machinery and thus conform to farmers' technical constraints. All cash crops in each cropping system prototype were grown each year and were randomly distributed in three spatial blocks of three plots each to consider soil heterogeneity. The COM consisted of sunflower and durum wheat in a 2-year rotation cultivated in two fields also located at the INRAE experimental station in Auzeville on a similar soil and managed by the INRAE Experimental Unit of Toulouse-Auzeville.

2.3.2 Plant measurements

At harvest, plants were sampled in two areas per subplot. In each sampling area, plants were harvested manually from a given area as a function of the density of the species grown (2.4 m^2 for durum wheat and cereal–legume mixtures and 3 m^2 for sunflower, faba bean, and the sunflower–soybean mixture). Aboveground biomass samples were divided into grain and vegetative parts and, in species mixtures, separated by species. The samples were dried at 80 °C for 48 h. N content in the grain and vegetative parts were determined using the Dumas combustion method with an elemental analyzer (LECO CNS-2000, LECO Corp., St. Joseph, Michigan, USA) from (i) a 10 × 20 cm area for cereals, winter pea, and faba bean and (ii) 20 plants for sunflower, soybean, and sorghum. The content of sunflower seed oil was measured from 125 achenes by nuclear magnetic resonance using a spectrometric analyzer (Minispec mq10, Bruker).

2.3.3 Soil measurements

The soil mineral N (ammonium and nitrate) content was measured during three key periods (after harvest, early winter, and late winter) in two sampling areas of each subplot. In each of the sampling area, six soil samples were collected on four soil layers (0–30, 30–60, 60–90, and 90–120 cm) which were then pooled per soil layer, homogenized, and stored at − 18 °C until their analyze with a continuous flow analyzer (Scan + +, SKALAR). NH_4^+ concentration was measured using Berthelot's method (Krom 1980; Searle 1984) and NO_3^- concentration according to the method developed by Navone (1964).

2.4 Criteria for assessing cropping systems

Agro-economic and socio-technical objectives were defined for each prototype relative to the COM. To assess whether these objectives were met and to compare the prototypes, indicators related to their agro-economic performance and the production factors applied were calculated (Table 2) to carry out a multicriteria evaluation of performances.

2.4.1 Characterizing the diversification gradient and soil tillage practices

Crop diversity of the prototypes was characterized by the cash crop species richness (Last et al. 2014) and the number of cash crop legumes in the crop rotation (Table 1). Soil tillage was assessed based on three indicators calculated at the 3-year period scale for each year, i.e., the mean number of (i) mouldboard plowings (30 cm deep), (ii) shallow tillage operations (< 15 cm deep), and (iii) mechanical weed control operations (< 10 cm deep).

2.4.2 Production factors for monitoring and meeting cropping system objectives

Several production factors (Table 2) were applied to meet the objectives of the cropping systems. The treatment frequency index (TFI) was used to assess pesticide pressure. To characterize the main type of pesticide pressure accurately, TFI was separated into three components according to the taxon (weed, fungal disease, or insect) targeted: $TFI_{Herbicide}$, $TFI_{Fungicide}$, and $TFI_{Insecticide}$. For each cropping system, toxicity of pesticides—the total number of applications of molecules registered as toxic to humans (i.e., corrosive, acutely toxic, harmful, an irritant, hazardous to health, carcinogenic, or mutagenic)—was quantified. Toxicity was defined based on the information provided by the material safety data sheet for each product. The amount of N fertilizer was quantified to verify the initial objectives of each prototype. Finally, labor time was calculated as a social indicator to assess the total time spent to produce crops.

2.4.3 Cropping system agro-economic assessment

The agro-economic performance of the cropping system prototypes was assessed by calculating the semi-net margin (Table 2). To understand the differences observed in this indicator, all of its components (i.e., gross income, operational costs, and mechanical costs) were also calculated. Mean crop price and subsidies of each cash crop were calculated over the 6 years of the two 3-year periods (Table 2) to eliminate the variability not directly related to the experiment. Species mixtures were considered to be sold as a feed grain mixture, except for sunflower–soybean, since each species in the mixture was harvested and sold separately.

Grain yield was assessed for durum wheat and sunflower, which were grown in all cropping systems, as well as grain quality (i.e., protein content for durum wheat and oil content for sunflower). For a given species, we distinguished (i) the grain yield at the crop scale, corresponding to the quantity produced on 1 ha cultivated with this species (or mixture), and (ii) the quantity of grain produced by this species on 1 ha of the cropping system, since each species represents only 33% of the surface area for the prototypes and 50% for the COM. Similarly, we distinguished (i) the protein and oil content of the grain and (ii) the amount of protein and oil produced on 1 ha of the cropping system.

For the COM, because of sample losses, the protein content of durum wheat grain was not measured in 2011, 2012, and 2014, nor was the oil content of sunflower grain in 2011 and 2012. Consequently, we used the mean contents of all prototypes for these missing data in order to consider the year effect on grain protein content and oil content. Moreover, according to the crop management of durum wheat and sunflower in the COM, the protein content and oil content are expected to be at least similar to the average of the prototypes and closed to the commercial quality standard since the agricultural cooperative that bought the grain did not modify the price greatly during this period nor deliver premiums or apply penalties for the range of qualities obtained in the experiment.

We used the commercial quality standard of 13% protein for durum wheat and 44% oil for sunflower as the threshold values for considering whether the grain quality of the cropping systems was acceptable. The price of durum wheat, soft wheat, and sunflower was considered constant regardless of the harvest quality (i.e., grain protein content for durum wheat and grain oil content for sunflower). Finally, energy efficiency, hereafter defined as the ratio of energy produced to energy consumed, was used to assess and compare the

Table 2 Indicators used to characterize the cropping systems. The indicators were calculated at the yearly scale, where "n" is the number of cash crops in the crop rotation (two for the common 2-year durum wheat/sunflower cropping system and three for the prototypes).

Indicators	Description and/or calculation	Unit
Crop diversity		
$Crop_{Species_{Richness}}$	$= 0.3 \times Number_{of_{species_{grown_{per_{rotation}}}}} + 0.7 \times$ Number_of_species_grown_per_year; Source: Last et al. (2014)	number of species grown
Fixed variables		
Mean_price_for_crop$_i$	$= \sum_{j=1}^{6} \frac{\text{Price for crop}_i \text{ for year}_j}{6}$; crop prices were 137 €·t^{-1} for sorghum, 167 €·t^{-1} for triticale/faba bean, 163 €·t^{-1} for soft wheat/faba bean, 174 €·t^{-1} for faba bean, 203 €·t^{-1} for durum wheat/pea, 234 €·t^{-1} for durum wheat, 332 €·t^{-1} for sunflower/soybean and 347 €·t^{-1} for sunflower	€·t^{-1}
Subsidies	$= \sum_{j=1}^{6} \frac{\text{Subsidies for crop}_i \text{ for year}_j}{6}$; subsidies were 273 €·ha^{-1} for sorghum, 296 € ha^{-1} for triticale/faba bean, 269 € ha^{-1} for soft wheat/faba bean, 402 €·ha^{-1} for faba bean, 279 €·ha^{-1} for durum wheat/pea, 306 €·ha^{-1} for durum wheat, 283 €·ha^{-1} for sunflower/soybean and 273 €·ha^{-1} for sunflower	€·ha^{-1}·year^{-1}
Soil tillage intensity		
Mean_plowing_for_year$_j$	$= \sum_{i=1}^{n} \frac{\text{Plowing for crop}_i \text{ for year}_j}{3\times n}$; plowing (depth = 30 cm) for crop$_i$ for year$_j$ corresponds to plowing that occurred between harvest of the previous crop and sowing of crop$_i$ in year$_j$	Number of plowing operations per year on 1 ha of a given cropping system
Mean_shallow_tillage_operations_for_year$_j$	shallow tillage operations (rotary harrow, mounted disk harrow, vibra-shank cultivator; depth < 15 cm) that occurred between harvest of the previous crop and harvest of crop$_i$ in year$_j$	Number of shallow tillage operations per year on 1 ha of a given cropping system
Mean_mechanical_weed_control_operations_for_year$_j$	mechanical weed-control operations (weed harrow, weeder, rotary harrow; depth < 10 cm) that occurred between harvest of the previous crop and harvest of crop$_i$ in year$_j$	Number of mechanical weed control operations per year on 1 ha of a given cropping system
Agro-economic output performance		
Mean_grain_yield_for_year$_j$	$= \sum_{i=1}^{n} \frac{\text{Grain yield for crop}_i \text{ for year}_j}{3\times n}$	t·ha^{-1}·year^{-1}
Mean_gross_proceeds_for_year$_j$	$= \sum_{i=1}^{n} \frac{\text{Grain yield for crop}_i \text{ for year}_j \times \text{Mean\_price\_for\_crop}_i}{3\times n}$	€·ha^{-1}·year^{-1}
Operational_costs	= Seed costs + Pesticide costs + Fertilizer costs	€·ha^{-1}·year^{-1}
Mechanical_costs	$= \sum_{i=1}^{n} Area_i \times (Tractor_cost_i + Equipment_cost_i + Fuel_costs)$where 'n' is the number of mechanical operations on a plot, 'i' is the area worked (in ha) and the costs of the tractor and equipment (in €.ha-1), which depend on the mechanical operation, correspond to wear, maintenance and amortization	€·ha^{-1}·year^{-1}
Semi_net_margin	=Gross_income+Subsidies-Operational_costs-Mechanical_costs	€·ha^{-1}·year^{-1}
Sunflower_seed_oil_content	measured by NMR spectroscopy	% of dry matter
Nitrogen_grain_content	determined using the Dumas combustion method	% of dry matter
Durum_wheat_grain_protein_content	= 5.7 × grain nitrogen content	% of dry matter
Energy_consumption	=Mechanical energy use + Energy used to produce fertilizers + Energy used to produce pesticides + Energy used to produce seeds; Source: ADEME (2011)	MJ·ha^{-1}

Table 2 (continued)

Indicators	Description and/or calculation	Unit
Calorie_content	= Grain yield for crop$_i$ for year$_j$ × calorie content of crop$_i$ where calorie contents were 16,700 MJ·t^{-1} for wheat, pea, and faba bean; 16,800 MJ·t^{-1} for sorghum; 16,900 MJ·t^{-1} for sunflower; 17,400 MJ·t^{-1} for triticale and 26,700 MJ·t^{-1} for soybean. Source: ADEME (2011)	MJ·ha^{-1}
Energy_efficiency	$= \frac{Energy\_consumption}{Calorie\_content}$	%
Input use		
Fertilizer_applied	$= \sum_{i=1}^{n}$ Fertilizer_applied$_i$	kg N·ha^{-1}·year^{-1}
Labor_time	labor time in and outside the field where labor time was set as a function of equipment width and tractor forward speed (h·ha^{-1})	h·ha^{-1}·year^{-1}
Toxicity to human health	$= \sum_{i=1}^{n}$ number of applications of toxic compounds applied during rotation$_i$	Number of applications of toxic compounds·ha^{-1}·yr^{-1}
TFI (treatment frequency index)	$= \sum_{i=1}^{n} \frac{rate\_applied_i \times treatment\_area_i}{approved\_rate_i \times plot\_area_i}$ where "i" is a given pesticide applied to a crop for given target organisms. The seed treatments used in the experiment were not included in this index since no standard rates exist for these products. TFI was divided into TFI$_{Herbicide}$, TFI$_{Fungicide}$ and TFI$_{Insecticide}$	Number of full pesticide treatments·ha^{-1}·year^{-1}

cropping systems on a standardized productivity scale using data from ADEME (2011).

2.5 Data analysis

Data were analyzed using R software (R Core Team 2018). Two-way analyses of variance (ANOVAs) were conducted to determine the effects of the 3-year period (2011–2013 vs. 2014–2016) and cropping system (COM, LI(_CC), VLI_CM(_CC), VLI_SM(_CC)) on production factors and agro-economic indicators. One-way ANOVAs were conducted to compare differences between cropping systems within a given 3-year period and differences between the two 3-year periods for a given cropping system. When significantly different ($p < 0.05$), means were compared using Tukey's range test. For all ANOVAs, normality of residuals was checked visually and the homogeneity of variances was tested using the Levene test.

3 Results

3.1 Performances of durum wheat and sunflower main cash crops

Sunflower and durum wheat were the two species present in the COM and all prototypes, although they were grown in a cultivar mixture in VLI_CM(_CC) or as components of species mixtures in VLI_SM(_CC).

Grain yields of sunflower and durum wheat for LI(_CC) and VLI_CM(_CC) did not differ significantly from that of the COM (Fig. 3a and b). Conversely, in VLI_SM(_CC), grain yields of sunflower and durum wheat (1.3 and 3.9 t·ha^{-1}·yr^{-1}, respectively) were significantly lower than that of the COM (3.0 and 6.3 t·ha^{-1}·yr^{-1}, respectively; Fig. 3a and b). The total amount of sunflower produced on 1 ha in the prototypes was significantly lower than that of the COM (0.8 vs. 1.5 t·ha^{-1}·yr $^{-1}$, respectively; Fig. 3c), and the same result was observed for durum wheat (1.7 vs. 3.2 t·ha^{-1}·yr $^{-1}$, respectively; Fig. 3d).

Sunflower grain oil content (Fig. 3e) did not differ significantly among all prototypes for a given 3-year period (47.9% and 44.4% for the first and the second periods, respectively). For the first period, sunflower grain oil content was higher than the commercial quality standard of 44%, regardless of the prototype. In the second period, grain oil content tended to decrease but remained higher than the commercial norm, except for VLI_SM (40.9%). Likewise, grain protein content of durum wheat (Fig. 3f) did not differ significantly among all prototypes for a given 3-year period or between the two periods (12.2%

and 12.1% for the first and the second 3-year periods, respectively) and was slightly lower than the commercial quality standard of 13%. However, the total amount of protein produced by durum wheat on 1 ha in the prototypes was lower than that in the COM (0.21 vs. 0.40 t·ha^{-1}·yr^{-1}, respectively; Fig. 3g), as was the total amount of oil produced by sunflower (0.39 vs. 0.67, respectively; Fig. 3h).

3.2 Production factors applied in the prototypes

The type of cropping system, which reflects effects of practices, influenced significantly all production factors and differently depending on prototypes and indicators considered (Fig. 4; Table 3). The 3-year period, which reflects mainly the effect of weather, influenced significantly all production factors except the amount of N fertilizer applied and labor time (Fig. 4; Table 3). The 3-year period had a greater effect than the prototype on TFI, $TFI_{Herbicide}$, $TFI_{Fungicide}$, and toxicity.

The effect of the 3-year period on TFI and TFIHerbicide concerned only the VLI_SM(_CC) prototypes, with values lower for the first 3-year period (0.86 and 0.19, respectively) than the second one (1.49 and 0.72, respectively). TFIFungicide did not differ between the first and the second 3-year period for any of the cropping systems (0.41 vs. 0.67, respectively). Insecticides were used only once in 2011 on durum wheat–winter pea mixture, against green aphids found on the peas.

TFI values of all prototypes did not differ significantly from that of the COM for the second 3-year period (1.44 vs. 2.08, respectively) but were significantly lower during the first 3-year period for LI(_CC) and VLI_SM_CC (1.75 vs. 0.76, respectively). Only VLI_CM_CC and VLI_SM(_CC) had a lower $TFI_{Herbicide}$ than the COM and only for the first 3-year period (0.31 vs. 1.24, respectively). $TFI_{Fungicide}$ of the prototypes did not differ significantly from that of the COM for both 3-year periods (0.52 vs. 0.65, respectively). Cover crops had no effect on TFI, $TFI_{Herbicide}$, or $TFI_{Fungicide}$, regardless of the cropping system.

N fertilizer inputs depended greatly on the prototype and did not differ significantly between the two 3-year periods for any of the cropping systems. Cover crops did not significantly reduce N fertilization. N fertilizer use was significantly lower in the VLI prototypes (49 and 51 kg N·ha^{-1}·yr^{-1} for VLI_CM(_CC) and VLI_SM(_CC), respectively, averaging the two 3-year periods) than in the LI prototypes, which did not differ significantly from the COM (98 and 99 kg N·ha^{-1}·yr^{-1}, respectively).

Toxicity to human health was significantly lower for all prototypes than that of the COM when averaging the two 3-year periods (0.75 vs. 1.29, respectively), except for VLI_CM(_CC), for which it was lower for the first 3-year period (0.67) than for the second one (1.22).

Labor time did not differ significantly between the two 3-year periods for any of the cropping systems. Averaging the two 3-year periods, labor time did not differ significantly between the COM and the prototypes without cover crops, but the inclusion of cover crops in the prototypes increased significantly labor time (+1.0, +2.2, and +1.6 h·ha^{-1}·yr^{-1} for LI_CC, VLI_CM_CC, and VLI_SM_CC, respectively). While the mean $TFI_{Herbicide}$ of all prototypes was significantly lower than that of the COM, mechanical weed control increased proportionally compared to that of the COM (+3.4, +3.4, and +1.6 h·ha^{-1}·yr^{-1} for LI(_CC), VLI_CM(_CC), and VLI_SM(_CC), respectively).

3.3 Agro-economic performance

The type of cropping system had a significant effect on all agro-economic performance indicators, except operational costs and energy efficiency (Fig. 4; Table 3). The 3-year period had a major effect on the semi-net margin, gross income, operational costs, and energy efficiency.

The semi-net margin decreased significantly between the first and the second 3-year periods only for VLI_SM(_CC) (545 and 332 €·ha^{-1}·yr^{-1}, respectively) due to the first 3-year period crop's combination of (i) higher grain yields (4.3 vs. 3.5 t·ha^{-1}·yr^{-1}, respectively), (ii) lower operational costs (306 vs. 339 €·ha^{-1}·yr^{-1}, respectively), and (iii) lower mechanical costs (321 vs. 346 €·ha^{-1}·yr^{-1}, respectively). The mean semi-net margin of both 3-year periods was significantly higher for the COM than for the VLI_CM_CC and VLI_SM(_CC), and it tended to decrease as the diversification of the prototypes increased. Except for LI_CC, prototypes with cover crops did not have a significantly lower semi-net margin than those without cover crops (675 vs. 578 €·ha^{-1}·yr^{-1}, respectively), because there was no effect on yield (4.3 vs. 4.2 t·ha^{-1}·yr^{-1}, respectively), even though mechanical costs were higher (292 vs. 344 €·ha^{-1}·yr^{-1}, respectively).

Operational costs did not differ significantly between all prototypes and the COM (310 vs. 348 €·ha^{-1}·yr^{-1}), nor between prototypes with or without cover crops (328 vs. 292 €·ha^{-1}·yr^{-1}, respectively). Conversely, mechanical costs were significantly lower for the COM than the prototypes (234 vs. 318 €·ha^{-1}·yr^{-1}, respectively), except for VLI_CM. For a given prototype, mechanical costs increased significantly with cover crops (+28, +76, and +54 €·ha^{-1}·yr^{-1} for LI_CC, VLI_CM_CC, and VLI_SM_CC, respectively), since they were destroyed mechanically.

Energy efficiency did not differ significantly between the two 3-year periods, except for VLI_SM. Unlike other indicators, energy efficiency did not differ significantly between all prototypes and the COM, and cover crops had no effect on it.

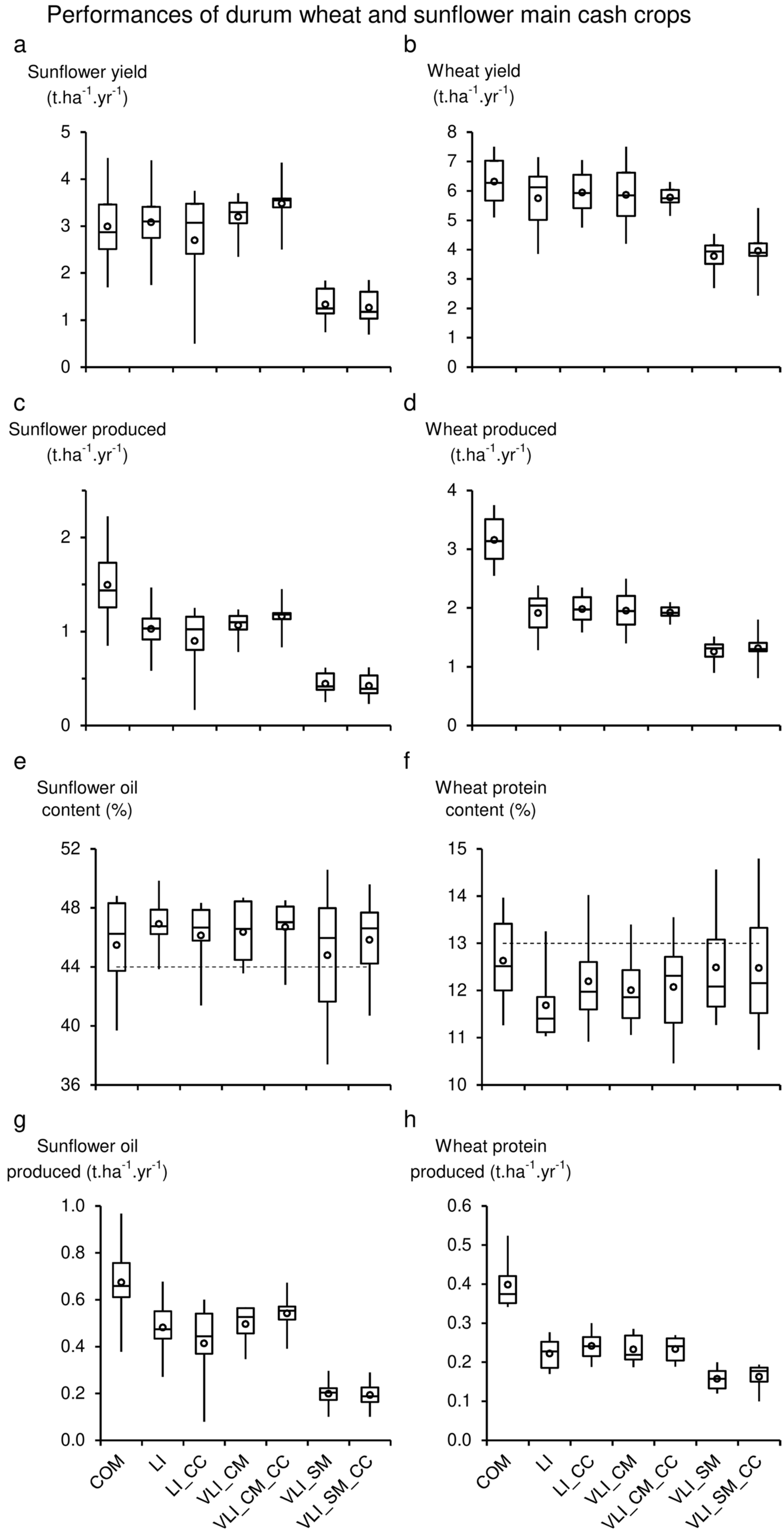

Fig. 3 Box plots for grain yield at 0% humidity of **a** sunflower and **b** durum wheat; grain produced at 0% humidity on 1 ha of the cropping system for **c** sunflower and **d** durum wheat; **e** sunflower grain oil content; **f** durum wheat grain protein content; **g** sunflower oil produced on 1 ha of the cropping system and **h** durum wheat grain protein produced on 1 ha of the cropping system of the six prototypes differing in their degree of diversification compared to the 2-year durum wheat/sunflower rotation (COM): LI (low-input prototype), LI_CC (LI with cover crops), VLI_CM (very low-input prototype with cultivar mixtures), VLI_CM_CC (VLI_CM with cover crops), VLI_SM (VLI with species mixtures), and VLI_SM_CC (VLI_SM with cover crops). The horizontal dashed line in **e** and **f** corresponds to the commercial quality norm of 44% and 13% for sunflower and durum wheat, respectively. The circle symbol in the box plots corresponds to the mean.

Fig. 4 Production factors applied (**a, c, e**) and agro-economic performances (**b, d, f**) of the six prototypes compared to the common sunflower/durum wheat rotation for the first 3-year period (2011–2013; **a, b**), the second 3-year period (2014–2016; **c, d**) and the mean of the two 3-year periods (**e, f**). Line color indicates the prototype, i.e. red: low-input prototype LI(_CC); blue: very low-input prototype with cultivar mixtures VLI_CM(_CC); green: very low-input prototype with species mixtures VLI_SM(_CC). Line filling indicates the use or not of cover crops (solid line, without cover crops; dashed line, with cover crops). The black horizontal line corresponds to the 2-year durum wheat/sunflower rotation (COM). TFI, treatment frequency index.

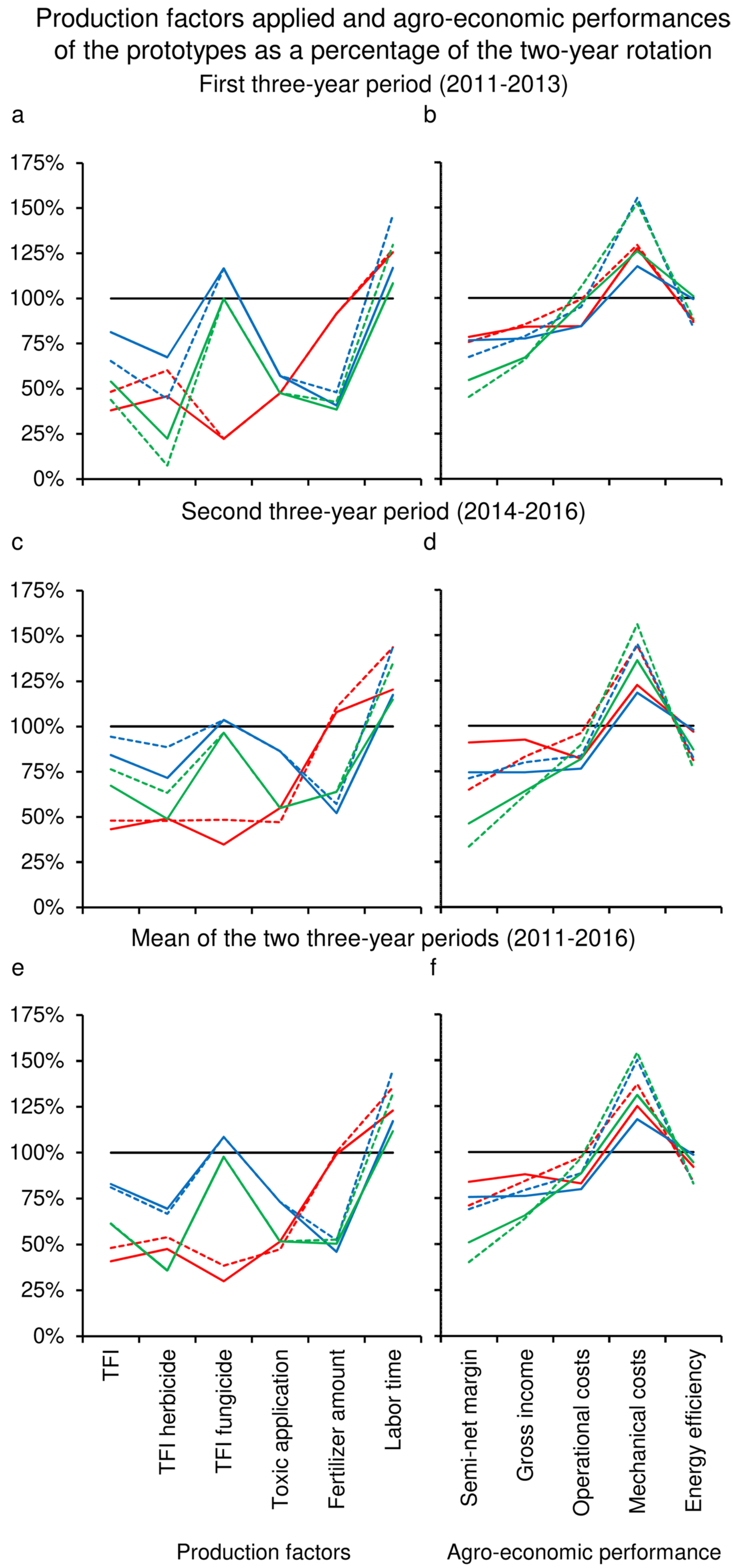

Table 3 Mean ± standard deviation of production factors applied and agro-economic performance of the six prototypes. Lower-case letters indicate a significant difference ($p < 0.05$) between cropping systems. *TFI* treatment frequency index. (LI, low-input prototype; LI_CC, LI with cover crops CC; VLI_CM, very low-input prototype with cultivar mixtures; VLI_CM_CC, VLI_CM with CC; VLI_SM, VLI with species mixtures; VLI_SM_CC, VLI_SM with CC) compared to the 2-year durum wheat/sunflower rotation (COM), averaged for two 3-year periods (2011–2013, 2014–2016).

Cropping systems	COM	LI	LI_CC	VLI_CM	VLI_CM_CC	VLI_SM	VLI_SM_CC	ANOVA
Production factors								
TFI (treatment·ha^{-1}·yr^{-1})	1.92 ± 1.11; a	0.78 ± 0.70; c	0.92 ± 0.81; bc	1.59 ± 1.07; ab	1.56 ± 1.30; ab	1.17 ± 0.87; abc	1.18 ± 0.97; abc	< 0.0001
TFI herbicide (treatment·ha^{-1}·yr^{-1})	1.26 ± 0.86; a	0.60 ± 0.70; b	0.68 ± 0.76; ab	0.88 ± 0.91; ab	0.84 ± 1.06; ab	0.45 ± 0.44; b	0.45 ± 0.63; b	0.001
TFI fungicide (treatment·ha^{-1}·yr^{-1})	0.65 ± 0.78; ab	0.20 ± 0.38; b	0.25 ± 0.54; ab	0.71 ± 0.75; a	0.71 ± 0.75; a	0.64 ± 0.73; ab	0.64 ± 0.73; ab	0.001
Toxicity (compounds·ha^{-1}·yr^{-1})	1.29 ± 0.75; a	0.67 ± 0.48; b	0.61 ± 0.60; b	0.94 ± 0.71; ab	0.94 ± 0.71; ab	0.67 ± 0.68; b	0.67 ± 0.68; b	0,0007
N fertilizer use (kg N·ha^{-1}·yr^{-1})	99 ± 76; a	98 ± 51; a	99 ± 52; a	45 ± 49; b	52 ± 58; b	50 ± 43; b	52 ± 43; b	< 0.0001
Labor time (h·ha^{-1}·yr^{-1})	8.0 ± 1.3; d	9.9 ± 2.6; abcd	10.9 ± 3.6; ab	9.4 ± 2.1; bcd	11.6 ± 1.5; a	8.9 ± 2.4; cd	10.6 ± 3.1; abc	< 0.0001
Agro-economic performance								
Semi-net margin (€·ha^{-1}·yr^{-1})	963 ± 356; a	807 ± 427; ab	683 ± 514; abc	728 ± 355; abc	664 ± 323; bc	491 ± 308; cd	386 ± 321; d	< 0.0001
Gross income (€·ha^{-1}·yr^{-1})	1256 ± 361; a	1105 ± 374; ab	1059 ± 412; abc	955 ± 479; bc	997 ± 453; abc	824 ± 247; c	803 ± 238; c	< 0.0001
Operational costs (€·ha^{-1}·yr^{-1})	348 ± 131; a	289 ± 125; a	339 ± 118; a	278 ± 127; a	308 ± 131; a	308 ± 63; a	337 ± 79; a	ns
Mechanical costs (€·ha^{-1}·yr^{-1})	234 ± 32; d	292 ± 64; c	320 ± 93; abc	276 ± 56; cd	351 ± 53; ab	307 ± 76; bc	361 ± 88; a	< 0.0001
Energy efficiency (%)	8.0 ± 3.8; a	7.3 ± 3.4; a	6.7 ± 3.0; a	7.9 ± 3.1; a	6.6 ± 2.3; a	7.5 ± 3.2; a	6.6 ± 3.1; a	ns

4 Discussion

4.1 Representativeness of the common 2-year durum wheat/sunflower cropping system

In order to evaluate the representativeness of our experimental practices, the performances of the common 2-year durum wheat/sunflower cropping system (COM) cropped in our experiment can be compared to local farmers' practices using public mandatory surveys performed by statistical services of the French Ministry of Agriculture for southwestern France (Agreste 2017). These surveys are a major tool for describing farmers' practices, calculating the profitability of actual farming systems, studying the impact of agricultural practices on the environment, and assessing their sustainability. Except for labor time (8 vs. 6 h·ha^{-1}), the COM had better performance indicators than the farmer's practices. The higher labor time in the COM is certainly due to more time dedicated to field observation at the basis of decision rules' practice but also to the fact that all working time is registered, even the time to prepare on-field operations, which is not necessarily the case when in farmers' answers to the public survey.

Thereby, the TFI of the COM was 37% lower than that of local farmers, due mainly to a smaller amount of fungicides (51% less), indicating a general more adjusted use of pesticides in the experiment. Finally, due to lower operational (348 vs. 431 € ha^{-1}·yr^{-1}) and mechanical costs (234 vs. 291 € ha^{-1}·yr^{-1}) and higher grain yield (4.7 vs. 4.1 t·ha^{-1}·yr^{-1}), the COM had finally a higher gross income (1256 vs. 1074 €·ha^{-1}·yr^{-1}) and then a semi-net margin 50% higher than the average value given by the farmers' survey.

This overperforming of the COM on the INRAE research station compared to farmer's practices is probably due to a better soil than that of many farmers who often grow sunflower on sloped clay soils with lower agronomic potential. Nevertheless, such a difference indicates that our COM was quite well-managed compared to the average performance obtained by local farmers. This is notably due to the time dedicated to observations and decisions and more opportunities to do the field operations in due time and at an optimal rate. In any case, this suggests that some improvements are still possible for farmers who currently grow these two crops in this region, despite the continuous technical progress in cropping practices and input-use efficiency that they benefited with the accompaniment of agricultural advisors.

4.2 Consequences for durum wheat and sunflower in the cropping system prototypes

Grain yield of sunflower and durum wheat in the prototypes did not differ significantly from that of the COM except in the VLI_SM(_CC) prototypes due to lower densities in the mixtures and interspecific competition with the associated crop. However, by diversifying the crop rotation in the prototypes from two to three species, sunflower and durum wheat covered only 33% of the surface area (compared to 50% for the COM). Therefore, the prototypes produced less sunflower and durum wheat per year than the COM. To avoid disrupting the organization of the current agrifood chain, cropping systems must be redesigned at the scales of regions, and the entire agrifood chain and a transition phase must be organized in order to accompany the ecological intensification of agriculture (Duru et al. 2015). Grain quality of sunflower and durum wheat in the prototypes did not differ significantly from that of the COM but again produced less sunflower oil and less durum wheat proteins per year than the COM. To support the economic benefits of crop diversification and unlock the current lock-ins, contracts between farmers, collectors, and industries could secure durum wheat and sunflower supplies, especially by returning added value to farmers involved in the agroecological transition. Indeed, the crop diversification required for a sustainable agrifood transition is a knowledge-intensive activity; thus, knowledge sharing between stakeholders in the agrifood chain could help a new supply chain to develop (Cholez et al. 2020).

4.3 The importance of multi-year assessment

For most indicators and for both 2-year durum wheat/sunflower rotation (COM) and prototypes, the 3-year period had a strong effect, as highlighted in several studies, with weather being a predominant factor (Lecomte et al. 2010). It is crucial to distinguish the potential effects of the cropping system from those of the weather conditions, which strongly influenced pest, disease, and weed pressure in our study. For example, conditions were more suitable for fungal diseases (rainier and warmer) during the second 3-year period comparatively to the first 3-year period, which clearly increased the needs of fungicide applications to meet the yield objective (mean of + 63% for $TFI_{Fungicide}$ for all prototypes and + 61% for the COM). These conditions also promoted weed growth, which was poorly controlled mechanically due to rainy periods. This resulted in an increase in herbicide catching up applications in order to avoid strong damages (mean of + 54% for $TFI_{Herbicide}$ for all prototypes but only + 3% for the COM).

This result highlights the importance of growing all species in crop rotations each year of a cropping system experiment as a "weather replication" when the experimental period is not long enough. Another relevant aspect is to test cropping systems over a sufficiently long period to avoid confounding effects and assessing performances in exceptional conditions. For instance, birds attacked sunflower plants during the emergence phase in several subplots of all cropping systems in the second year of the second 3-year period, which required a second sowing that significantly increased operational and mechanical costs leading to a lower semi-net margin for this particular year for all cropping systems.

4.4 Meeting the objective to reduce pesticide use in cropping systems

The objective of reducing pesticide use by 50% compared to the COM was met for the LI(_CC) prototypes (44% of the COM), almost for VLI_SM(_CC) (61% of the COM) but not for VLI_CM(_CC) (82% of the COM), with less toxic pesticides applied in most prototypes than in the COM. The reduction in both the quantities applied and the number of toxic pesticides on some prototypes should lead to a reduction in environmental, biodiversity, and health impacts (Lammoglia et al. 2017a, b).

Mechanical weed control was introduced in all prototypes to reduce herbicide use. Its performances differed greatly between winter and spring crops, as previously observed on other long-term experiments on low-input cropping systems (Chikowo et al. 2009). For winter crops, weather conditions were frequently unsuitable during the optimal period for mechanical weeding operations due to long rainy periods. This resulted in insufficient mechanical weeding that was ultimately supplemented with herbicide applications, since one decision rule was to avoid too large increase in the weed seed bank to prevent dramatic long-term effects. For spring crops, however, a longer period was available each year to use mechanical weeding equipment (relatively dry soil and 2–3 days without rain after weed control operations), which controlled weeds without requiring herbicides. For VLI_SM(_CC), $TFI_{Herbicide}$ decreased by 64% compared to the COM, while it was 50% lower for LI(_CC) and only 32% for VLI_CM(_CC). For VLI_SM(_CC), herbicide applications decreased greatly mainly due to the use of species mixtures: (i) indirectly because few herbicides are available on the market and sufficiently selective for both associated cash crops and (ii) directly since mixing species often results in a rapid soil cover, which limits weed growth (Amosse et al. 2013) and thus the use of herbicides.

The experiment also highlighted that introducing cover crops during the fallow period increased labor time due to sowing and mechanical destruction of the cover crops without allowing the decrease of herbicide use. However, according to the combination of multiple meta-analyses performed by Shackelford et al. (2019), we could have expected a weed control effect from the cover crops up to 27% fewer weeds. This setback may be due to regular tillage operations combined with occasional herbicide application, which may hide or even offset the potential effect of cover crops on weed control (Adeux et al. 2021). Moreover, the weed control effect from the cover crops was limited because the biomass was low, due to both dry winter conditions and early destruction before winter to avoid water and N pre-emptive competition. These results illustrate that avoiding herbicide use requires a combination of several agronomic practices to control weeds (Barzman et al. 2015; Adeux et al. 2019).

Similarly, several agronomic practices were applied to reduce fungicide use, but the crop species chosen for diversification are crucial (Barzman et al. 2015). In the LI(_CC) prototypes, introducing sorghum into the crop rotation and managing it without fungicides decreased $TFI_{Fungicide}$ (34% of the COM). Conversely, in the VLI_CM(_CC) prototypes, introducing faba bean into the crop rotation increased fungicide use, which caused them to fail to achieve the objective of decreasing pesticide use (109% of the COM). Indeed, faba bean was found to be highly sensitive to fungal diseases (brown rust and anthracnose, Mínguez and Rubiales 2021) and thus was actually poorly adapted to the low-input systems under the soil and weather conditions of the region, while it was chosen because it was a priori assumed to require few pesticides. Growing disease-tolerant cultivars may help reduce fungicide use, but it must be combined with replacing systematic fungicide applications with applications that follow decision rules according to damage thresholds. Applying these decision rules decreased $TFI_{Fungicide}$ in durum wheat for the LI(_CC) and VLI_CM(_CC) prototypes (52% and 59% of the durum wheat COM). Surprisingly, $TFI_{Fungicide}$ did not differ significantly between the wheat cultivar mixtures in the VLI_CM(_CC) and the single wheat cultivar in the LI(_CC) prototypes. This result may have been due to three factors: (i) the cultivar mixture was not relevantly designed to decrease disease damage (Kiaer et al. 2009), (ii) disease pressure was not high enough to give a real advantage to the cultivar mixture (Finckh et al. 2000), or (iii) cultivar mixture was not more effective than a single well-adapted and tolerant cultivar at decreasing disease damage significantly.

4.5 Meeting the objective of reducing N fertilizer use in cropping systems

The objectives were to reduce N fertilizer use by 25% for the LI(_CC) prototypes and by 50% for all VLI prototypes, compared to the COM. These objectives were met by the VLI_CM(_CC) and VLI_SM(_CC) prototypes (49% and 51% of the COM, respectively), while the LI(_CC) prototypes required the same amount of N fertilizer than the COM. Four strategies were applied to reduce N fertilizer use in the prototypes:

- The first strategy was to introduce low N demanding crops, such as sorghum for the LI(_CC) prototypes. Indeed, sorghum requires moderate N per unit of grain produced lying between those of durum wheat and sunflower and has a high yield potential in deep soils even in rainfed conditions. However, our initial objective was too ambitious when choosing sorghum and not compatible with the economic objectives of these prototypes (Section 4.4).
- The second strategy was to introduce grain legumes which do not require N fertilizers allowing to reduce N use by at least 33% in the VLI_CM prototypes because the legume represented one-third of the cash crops grown but also by decreasing N fertilizer use for the next wheat crop (71% of the durum wheat COM). The same strategy was used in the VLI_SM(_CC) with the presence of a grain legume in all mixtures allowing a greater decrease of N fertilizer notably on durum wheat–winter pea mixture (48% of the of the durum wheat COM) even if a further reduction does not seem conceivable since it would decrease cereal grain production and quality too much (Bedoussac and Justes 2010).
- The third strategy was to reduce N fertilizer use for wheat and, to a lesser extent, sunflower by (i) setting slightly lower grain yield objectives for the prototypes than for the COM and (ii) improving N fertilization management by adapting the amount of N fertilizer to crop needs (Ravier et al. 2018).
- The fourth strategy was to decrease N losses by (i) volatilization, mainly applying N fertilizer before precipitation (Cameron et al. 2013) and (ii) nitrate leaching during the drainage period by using cover crops (Plaza-Bonilla et al. 2015) that could lead 41% lower soil nitrogen content and 53% lower nitrate leaching with non-legume cover crops compared to controls according to the combination of multiple meta-analyses performed by Shackelford et al. (2019).

Although cover crops effectively capture nitrate, they did not always reduce N fertilizer use for the following crop in the prototypes. N fertilizer use even slightly increased in VLI_CM_CC for durum wheat (+21% more than VLI_CM) to counter the preemptive effect of buried cover crop residues on soil mineral N in a dry winter without nitrate leaching and to decrease its potential negative impacts on the following crop (Thorup-Kristensen and Dresboll 2010). This lack of decrease in N fertilizer use when using cover crops was explained mainly by the following:

- Dry winters, which resulted in a low level of nitrate leaching. No significant drainage and leaching occurred for 3 of the 6 years, as calculated with water and N balances. Even COM keeping bare soil during fallow periods leached little nitrate due to these dry conditions.
- Low cover crop biomass due to limited precipitation and early destruction to avoid preemptive competition for water (Meyer et al. 2020) and increase their decomposition before the following crop. Cover crops were destroyed early during the winter to synchronize N release with the N requirements of the following cash crop. Consequently, non-legume cover crops uptaken relatively little nitrate, while legume cover crops fixed little N_2.

4.6 Meeting the objectives for the semi-net margin of cropping system prototypes

The objectives for the semi-net margin for the LI(_CC), VLI_CM(_CC), and VLI_SM(_CC) prototypes (100%, 90%, and 85% of the COM, respectively) were not met, notably because of the very challenging target for the comparison of the prototypes. Indeed, the COM already appears to be optimized with respect to the regional on-farm durum wheat/sunflower rotation. Conversely, the comparison of the performance of the prototypes with that of the farmers' practices reveals the margins of progress in terms of management, profitability, and environment issues that farmers could obtain by adopting more diversified systems.

Since crop prices and subsidies of each cash crop were the same over the 6 years, the lower semi-net margin of the prototypes compared to the COM was mainly due to a decrease in gross income and an increase in mechanical costs. We certainly did not adequately configure the low-input cropping systems due to a lack of knowledge and technical know-how, especially about species mixtures. The technical practices applied and decision rules used to adapt the agricultural practices were not based on long technical experience. Although the practices and decision rules were well controlled and managed in the COM, those in the low-input prototypes clearly required a learning process. In any case, this suggests that a potential exists to redesign efficient and profitable innovative cropping systems that depend less on chemical pesticides and can be used to build a more biodiversified agriculture as a pathway in the agroecological transition (Duru et al. 2015).

4.7 Combining agronomic practices to design innovative cropping systems

Designing cropping systems that combine the agronomic practices tested in the prototypes may improve their performances. During the co-design workshops, the choice of certain practices was done to discriminate prototypes and create a gradient of diversification. Thus, some prototypes included mainly cultivar mixtures, others species mixtures, and half of them cover crops, which resulted in different performances. The results allowed us to assess the ability to combine practices to mitigate certain poor performances while maintaining the decrease of inputs. Among others, we identified ways to improve the economic performances of low-input cropping systems:

- Introduce high added-value crops into the cropping system. In both the LI(_CC) and VLI_CM(_CC) prototypes, sorghum and faba bean had a lower selling price than the durum wheat and sunflower in the COM. The high yield of sorghum did not compensate for its low price, whereas faba bean's low yield increased its poor economic performance. We then suggest diversifying with crops for human consumption (e.g., lentil, chickpea) or special crops under contract (e.g., waxy maize or "health food" crops such as chia, buckwheat, and quinoa) that provide high gross income.
- Switching to organic farming. Given the low levels of pesticides and N fertilizers used in some prototypes, it may be possible to go further and stop using pesticides to switch production to organic farming and get the higher prices of products.
- Develop and improve techniques for sowing and separating species mixtures. Species mixtures increased mechanical costs greatly, such as for the sunflower–soybean or soft wheat–faba bean mixtures that combined two harvest and two sowing operations, respectively. Moreover, grains from the soft wheat–faba bean and durum wheat–pea mixtures were sold mixed for animal feed and thus had a low selling price, while sorting the grains would result in higher prices. Recent improvements in agricultural machinery for sowing, separating, and cleaning grains at low cost could solve this point. However, there is no solution to prevent the two harvests for the sunflower–soybean mixture.
- Develop and improve multi-service cover crops. Further reduction in herbicide use would require more productive cover crops capable of providing a greater weed control in the succeeding cash crops (Couedel et al. 2019). One option is to increase the number of crops to more than three (Adeux et al. 2019) and diversifying them such as a mixture of leguminous and cruciferous plants (Couedel et al. 2019) able to reduce the use of both pesticides and N fertilizer.
- Include negative externalities in calculations of production costs due to disservice such as water, soil, and air pollution or impacts on human and wildlife health (Pretty et al. 2000). Most previous prototypes introduced agronomic practices to replace chemical inputs, which increased mechanical costs that were not compensated by a decrease in operational costs. When hidden costs of using chemical inputs (especially pesticide toxicity to applicators or the community, contamination of environmental resources, and its treatment) are not explicitly included in estimates of production costs, it becomes challenging to design innovative cropping systems that have high biodiversity, decrease input use significantly, and remain as profitable as current systems in the short term. Conventional agriculture has also benefited from low energy costs and few taxes, which has given it unequivocal economic efficiency without considering negative externalities or optimization of input use.

5 Conclusion and perspectives

Agronomists and farmers have long discussed the principles of diversifying species in time and space and their ability to improve agricultural sustainability. However, these principles are rarely applied in current cereal-based conventional systems in Europe due to many well-known agronomic, economic, and commercial considerations and technological lock-ins. To significantly reduce the use of chemical inputs and replace them with multiple ecosystem services, the challenge is to design profitable but sustainable arable cropping systems based on high diversification of species.

Our experimental study demonstrated that this was technically feasible but also highlighted that several factors and management practices still need to be optimized to achieve the same profitability as the current 2-year cropping system of sunflower and durum wheat. European Union and national policy frameworks do not support low-input agriculture sufficiently, especially by ignoring negative externalities, which strongly reinforces the higher apparent profitability of high-input conventional agriculture.

From technical and agronomic viewpoints, many practices can reduce the use of pesticides and N fertilizers. However, we found that innovative cropping systems that replaced certain chemical inputs with technical practices were less productive. In particular, combining mechanical weeding, disease-tolerant cultivars, and reduced N fertilization only partially reduced the damage caused by pathogens in our study's soil and weather conditions. Using a combination of techniques effectively is more difficult because the effects of each technique are partial and preventative, which often leads to incomplete control of pests and diseases than when curative treatments are used. This emphasizes that more scientific and technical efforts are needed to decrease yield losses when pesticides are not used. For a broader scope, such a system approach will have to be extended by modeling.

The diversification gradient tested here, both in time with longer rotations and inclusion of multi-service cover crops and in space with mixtures of cultivars and/or species, indicates that the first one is the simplest and most cost-effective way to diversify during a transitional phase. Diversification in space requires additional research to optimize the mixtures of cultivars and/or species to achieve the same profitability as that in conventional agriculture. Targeting niche markets of high-priced species to compensate for lower yields in low-input systems is a key option for designing innovative cropping systems with acceptable profitability. This is also true for species mixtures, which must be designed for human consumption and not for low-cost animal feed.

Finally, this agroecology paradigm, based on highly diversified agriculture, demonstrates the potential of certain sets of agronomic solutions and encourages researchers, advisors, and farmers to work together to design cropping systems that are adapted to local conditions. It also implies considering agricultural production and diversification at the regional scale, since they will influence the logistics and organization of the entire agrifood chain.

Reorienting subsidies and rethinking the agrifood system as a whole to return added value to farmers engaged in the agroecological transition is necessary to support the economic value of crop diversification and encourage the transition to low-input cropping systems.

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

Code availability Not applicable.

Declarations

Ethical approval The study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Consent to participate Not appropriate.

Consent for publication Not appropriate.

Conflict of interest The authors declare no competing interests.

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