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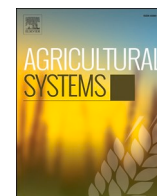
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Assessing cropping system multifunctionality: An analysis of trade-offs and synergies in French cereal fields

Audrey Alignier^{a,b,*}, Matthieu Carof^c, Stéphanie Aviron^{a,b}

^a UMR 0980 BAGAP, L'Institut Agro Rennes-Angers-ESA-INRAE, 65 rue de Saint Briec, 35042 Rennes Cedex, France

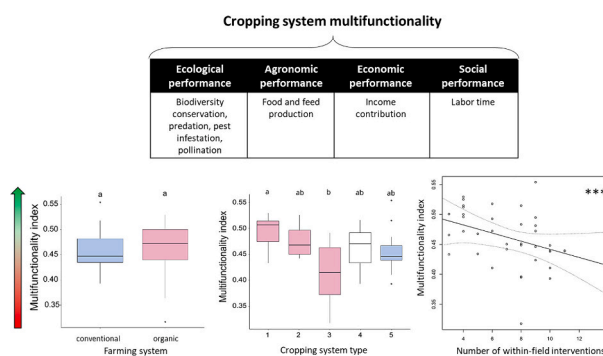
^b LTSER « Zone Atelier Armorique », 35042 Rennes Cedex, France

^c Institut Agro, INRAE, SAS, 35042 Rennes, France

HIGHLIGHTS

- Assessing agroecosystem multifunctionality is a way to promote sustainable cropping systems.
- Five annual cropping systems were compared using fourteen primary variables underlying seven functions and four performances of agroecosystems.
- Despite similar multifunctionality index, cropping systems had contrasted performances.
- No cropping system enhanced both crop production and biodiversity conservation.
- Agroecosystem multifunctionality decreased with the number of field interventions and nitrogen inputs.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Identifying the strengths and weaknesses of existing cropping systems in a given context is a key first step before designing new, more sustainable cropping systems. The concept of multifunctionality can be a useful tool for cropping system assessment. Whether and how cropping systems and specific management practices might modulate agroecosystem multifunctionality remains unknown, as do the potential trade-offs and synergies among functions.

OBJECTIVE: This study aimed to (i) assess the multifunctionality of annual cropping systems by estimating their agronomic, ecological and socio-economic performances; (ii) identify trade-offs and synergies among functions; (iii) highlight management practices that can be mobilized to foster synergies between agricultural production and other functions.

METHODS: We measured 14 primary variables, used as proxies for seven functions, in 20 conventional and 20 organic winter cereal fields, in northwestern France. We considered three management practice description levels: (i) farming system (*i.e.* organic vs. conventional), (ii) combination of management practices that defines a cropping system, and (iii) individual management practices.

RESULTS AND CONCLUSIONS: We found a strong trade-off between functions related to ecological performance and agronomic, socio-economic performances, especially between biodiversity conservation and food and feed production. Organic systems tended to minimize this trade-off. Our study also revealed contrasts in levels of

* Corresponding author at: UMR 0980 BAGAP, L'Institut Agro Rennes-Angers-ESA-INRAE, 65 rue de Saint Briec, 35042 Rennes Cedex, France.

E-mail address: audrey.alignier@inrae.fr (A. Alignier).

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functions despite similar multifunctionality value across cropping systems. The number of field interventions and nitrogen inputs were the main drivers of cropping system multifunctionality and its underlying functions. The results indicate that specific management practices, such as reducing within-field interventions and nitrogen fertilization amount, could be integrated even in conventional cropping systems to improve multifunctionality. More generally, our work opens the door to further studies on how agricultural management fosters the simultaneous provision of multiple functions including socio-economic ones.

SIGNIFICANCE: Besides multifunctionality assessment of cropping systems, our study emphasizes the need to further explore how management practices shape the provision of multiple functions and their potential trade-offs. This knowledge is crucial to develop effective strategies for the design of sustainable cropping systems.

1. Introduction

Given the backdrop of global climate change and the biodiversity crisis, transition towards sustainability requires a profound change in agriculture and the development of innovative cropping systems with high environmental, economic and social performances. This has led to renewed research in cropping system design (Doré et al., 2011; Malézieux, 2012; Gaba et al., 2015).

When applied to cropping systems, sustainability implies the production of sufficient amounts of agricultural products to feed the population whilst maintaining the environment, preserving natural resources and biodiversity and ensuring the financial viability and quality of life of farmers (Deytieux et al., 2016). Besides, cropping system management results from logic and decision processes. Farmers conceive and choose their own succession of actions and combination of management practices, depending on socio-economic factors, agronomic objectives and constraints, spatial heterogeneity, resulting in diverse state and performance of cropping systems (Aouadi et al., 2015; Wang et al., 2018). Identifying the strengths (and weaknesses) of existing cropping systems, *i.e.* management practices that enhance multiple functions, is thus a key first step before designing new, more sustainable cropping systems. Single-site studies collecting better contextual information are required for the identification of promising cropping systems in a given context (Deytieux et al., 2016). In this respect, the concept of multifunctional agriculture (MFA) can be a useful tool for cropping system assessment.

Multifunctional agriculture (MFA) emerged as a concept in the 1980's and was disseminated following the World Commission on Environment and Development as a way to reconnect the economic function of agriculture to its ecological and social roots (Caron et al., 2008). Applying this concept to agriculture is to recognize that, beyond its role of producing food, agriculture may also have other functions and contributes to resources management, biodiversity conservation, welfare of farmers and citizens, rural development and employment, cultural identity and landscape, *etc.* (Renting et al., 2009; Carmona-Torres et al., 2014; Stürck and Verburg, 2017). Thus, assessing MFA requires to deal with complexity, to mix concepts from various disciplines *i.e.* agronomy and ecology, to understand the links between the multiple functions of agriculture with the characteristics of cropping systems before to forecast results for scenarios and inform policy and planning (Carmona-Torres et al., 2014).

Various methods and tools are available for MFA assessment, from farm to regional or national level, based on mathematical programming or optimization models (*e.g.* Landscape IMAGES model, Groot et al., 2007), or analytical models mixing qualitative (mostly based on expert knowledge) to quantitative data (*e.g.* the Analytic Network Process; Saaty, 2001). Despite this considerable background, knowledge is still limited regarding how set up cropping systems influence MFA, as well trade-offs and synergies among their multiple functions (Power, 2010; Wittwer et al., 2021; Notaro et al., 2022). In particular, little research has focused on MFA assessment at the cropping system level, integrating not only quantitative information on agronomic and ecological performances, but also on social and economic performances. MFA assessment, based on real data (*i.e.* field measurement) and by identifying (i)

trade-off and synergy situations between agricultural production and other functions and, (ii) technical levers that can be mobilized to foster a high level of diverse functions, should increase chances of promising cropping systems being used by farmers in situations of a similar nature (Meylan et al., 2013).

Recent studies assessing MFA typically compared organic vs. conventional farming. Ecological functions supported by biodiversity, such as pollination and natural pest control, are expected to be enhanced under organic farming since it prohibits the use of synthetic inputs (Tuck et al., 2014; Muneret et al., 2018; Couthouis et al., 2023). Nevertheless, organic systems are often criticized due to lower yields compared with conventional systems, even if it may not compromise farmer income due to higher product valuation and subsidies (Shennan et al., 2017; Ostandie et al., 2022). Beyond the dichotomy organic vs. conventional, farmers adopt a wide range of management practices. These gradients in management practices can sometimes made organic and conventional farms more similar than between some farms within the same farming system (Puech et al., 2014). Besides synthetic pesticides use, fertilizer use is another key point in sustainable agriculture. One issue is decreasing the use of nitrogen fertilizers to decrease greenhouse gas emissions, to reduce the dependence of agriculture on fossil fuels and to prevent environmental health, without decreasing productivity (Spiertz, 2009). While the use of nitrogen fertilizers contributes to maintaining high productivity levels, it also represents a substantial share of management costs (Iddris et al., 2023). Another important management practice is weed control. A more sustainable alternative to herbicide application could be mechanical weeding which allows for fast regeneration of some perennial plants due to preservation of underground organs capable of forming new shoots (Chicouene, 2007). This consequently may lead to increased plant cover and diversity, supporting higher trophic levels *i.e.* animal abundance and diversity (Marshall et al., 2003). Nevertheless, these ecologically desirable effects may have adverse economic effects as mechanical weeding requires higher labor input compared with herbicide application, which may reduce profits (Iddris et al., 2023). In-depth analyses of synergy and trade-off analyses between multiple functions are thus necessary for cropping system assessment.

This study investigated how cropping systems affect MFA and trade-offs and synergies among agronomic, ecological, social and economic functions. It aimed to highlight management practices, whether combined or on their own, that can be mobilized to foster synergies between agricultural production and other functions. To do so, we quantified the provision of a wide range of functions within fields including socio-economic ones. We investigated their relationships and characterized their determinants. We revisited the data analyzed by Couthouis et al. (2023) considering three management practice description levels: (i) farming system (organic vs. conventional), (ii) combination of management practices that defines a cropping system, and (iii) individual management practices. We used data from 20 conventional and 20 organic winter cereal fields in Brittany, northwestern France.

2. Materials and methods

2.1. Study site

Our study site is located in the Zone Atelier Armorique (Long Term Socio-Ecological Research site, 48° 36' N, 1° 32' W) in the southern part of the Ille-et-Vilaine department in Brittany, northwestern France. The climate is temperate oceanic with ca. 700 mm of annual precipitation and an average annual temperature of 12 °C (18 °C in summer and 5 °C in winter). This site is characterized by a dense hedgerow network and small fields. Agriculture in the study site is oriented towards mixed dairy farming and the main cultivated crops are grassland (40%), maize silage (30%), and winter cereals (20%). Dominant soil types are brunisols and luvisols. The experimental design consisted of the selection of 40 winter cereal fields (20 organic and 20 conventional) distributed along two independent landscape gradients. Landscape gradients were based on the area of organic farming and the length of hedgerows (Spearman correlation, $\rho = 0.19$, 500 m radius circles centered on studied fields). The average distance between selected fields was 1361 ± 253 m and the minimum distance between two fields was 222 m.

Winter cereal fields were (i) sole crops, sown with wheat (*Triticum spp.*), triticale (*Triticosecale spp.*), or oat (*Avena sativa* L.), hereafter referred to as 'cereal crops' (10 organic and 20 conventional fields); and (ii) intercropped with legumes, namely faba bean (*Vicia faba* L.) or pea (*Pisum sativum* L.), hereafter referred to as 'mixed crops' (10 organic fields; Table S1). This design reflects the practices of farmers in the study area; cultivation of mixed crops is more frequent on organic farms while single crops predominate in conventional farms (Carof et al., 2019). Field size was comparable between organic and conventional fields.

2.2. Data collection

We measured 14 primary variables that are used as proxies for seven functions (Table 1): biodiversity conservation, predation, pest infestation, pollination capacity, food and feed production, income contribution and labor time. These functions corresponded to four performance types and three ecosystem services (Table 1). We evaluated biodiversity

Table 1

Correspondence between selected proxies measured in the selected fields, functions, performance types, and ecosystem services according to Millennium Ecosystem Assessment classification.

Proxy (primary variables)	Function	Performance	Ecosystem service
Species richness of weeds	Biodiversity conservation	Ecological	Support
Species richness of carabids	Biodiversity conservation	Ecological	Support
Species richness of flower-visiting insect morpho-groups	Biodiversity conservation	Ecological	Support
Abundance of carabids	Predation	Ecological	Regulation
Abundance of staphylinids	Predation	Ecological	Regulation
Abundance of spiders	Predation	Ecological	Regulation
Abundance of aphidophagous hoverflies	Predation	Ecological	Regulation
Abundance of ladybird larvae	Predation	Ecological	Regulation
Abundance of aphids	Pest infestation*	Ecological	Regulation
Abundance of troublesome weeds	Pest infestation*	Ecological	Regulation
Abundance of flower-visiting insects	Pollination capacity	Ecological	Regulation
Yield	Food and feed production	Agronomic	Provision
Semi-net margin	Income contribution	Economic	/
Working hours	Labor time*	Social	/

* Values for these functions were inverted in the calculation of the multi-functionality index.

conservation by considering species richness of carabids (*Coleoptera: Carabidae*), of flower-visiting insect morpho-groups, and of weeds. Predation was quantified by measuring the abundance of pest natural enemies including carabids (*Coleoptera: Carabidae*), spiders (*Araneae*), staphylinids (*Coleoptera: Staphylinidae*), ladybird larvae (*Coleoptera: Coccinellidae*), and aphidophagous hoverflies (*Hemiptera: Syrphidea*). Pest infestation consisted of the abundance of two main pests of winter cereal fields: aphids (*Hemiptera: Aphidoidea*) and troublesome weeds. We considered as troublesome a wild plant species which induces yield loss, harvest pollution (i.e. increased levels of impurities), or harvesting problems due to biomass blocking the combine. Classification of weeds as troublesome was based on expert knowledge, with the assistance of a representative of the Chamber of Agriculture of Brittany. Pollination capacity supply was evaluated through the abundance of insects visiting weed flowers. Food and feed production was quantified using yield (quantity of products per hectare). Labor time was based on the number of working hours in the field. Lastly, income contribution was assessed using costs (materials used and inputs) and sales of crop production. Details about data collection for each function are provided below. Correlations between the 14 primary variables (proxies of functions) were shown in Fig. S1.

2.2.1. Biodiversity conservation, predation, infestation and pollination capacity

Carabids, spiders, staphylinids, ladybird larvae, and aphids were collected twice, in May and June 2020, corresponding to the peak activity for these insects in our study site. We used a vacuum method (D-vac), with a series of five aspirations performed at 10 min intervals along a 50 m transect located in the field center (Couthouis et al., 2023). D-vac aspirations were carried out through the vegetation and on the ground in order to capture all the arthropods present on these two strata. Data from the series of aspirations ($N = 5$) and the sampling periods ($N = 2$) were pooled to obtain estimates of the total abundance of i) carabids, spiders, ladybird larvae, and ii) aphids used respectively as proxies of predation and pest infestation. Only carabid beetles were identified at the species level following Roger et al. (2010). Flower-visiting insects were sampled three times, in May, June, and July 2020 (before crop harvest), by walking along 50 m transects (one per habitat) at a slow pace for 5 min (Couthouis et al., 2023). Flower-visiting insects were assigned to one of the following morpho-groups: honeybees, *Bombus terrestris* agg., *Bombus lapidarius*, *Bombus pascuorum*, solitary bees <1 cm, solitary bees >1 cm, aphidophagous hoverflies, non-aphidophagous hoverflies, butterflies, other Diptera, other Coleoptera, and other Hymenoptera. Data were pooled over the three sampling periods to determine the abundance and richness of morpho-groups of flower-visiting insects. Species richness of carabids and species richness of morpho-groups of flower-visiting insects were used as proxies of biodiversity conservation whereas the abundance of flower-visiting insects was used as proxy of pollination supply capacity. Single surveys of weeds were conducted in 10 quadrats (1 × 1 m) placed at 5 m intervals along each 50 m transect. Weed were identified at species level and corresponding percentage cover was estimated visually. Data from the 10 quadrats were pooled to obtain total species richness (used as biodiversity conservation proxy) and mean cover of troublesome weeds per field (used as pest infestation proxy).

2.2.2. Food and feed production, and descriptions of cropping systems

For each field, detailed information on management practices from harvesting the preceding crop to sowing the next crop, including ploughing, pest management (mechanical or chemical weeding, insecticide and fungicide use, and seed treatment), amount, frequency, and type of fertilization (mineral or organic), and yield were collected by interviewing farmers during winter 2020. For each management practice, the type of tractor and equipment, as well as the inputs associated with applied doses were recorded. All variables were registered using Agrosyst software (Jolys et al., 2016). Yield was used as proxy of food

and feed production. We used Agrosyst to calculate treatment frequency index (TFI) for herbicides, insecticides, and fungicides, as well as for all treatments (TFI tot) in conventional fields. Note that organic fields were characterized by the absence of pesticide treatment. TFI was calculated as the cumulative ratio of the dose applied vs. the recommended dose multiplied by the proportion of the field treated, for all treatments applied during the growing season (Halberg, 1999). TFI for insecticides was not taken into account in analyses because it varied little (only used by one farmer). TFI for fungicides was very similar to TFI tot (Spearman correlation, $\rho = 0.90$) and was thus excluded from analyses. Similarly, mineral and organic fertilizer frequencies were very similar to mineral and organic fertilizer quantities (Spearman correlations, $\rho > 0.80$) and also excluded from analyses. In total, 10 variables were extracted from farmer interviews and retained for analyses (Table 2). Differences in qualitative and quantitative variables between conventional and organic fields are shown in Fig. S2 and Fig. S3 respectively. The 10 variables extracted from farmer interviews were then used to determine groups of winter cereal fields with similar management practices. A mixed principal component analysis (PCA) (Hill and Smith, 1976) followed by an ascendant hierarchical cluster analysis (AHC) (Ward Jr, 1963) on the two first principal components enabled the identification of five clusters of fields (Fig. S4).

2.2.3. Income contribution and labor time

We used Agrosyst software to calculate income contribution (semi-net margin) and labor time (working hours). Semi-net margin (€) was calculated by subtracting operational costs (seeds and inputs) and equipment (depreciation, maintenance, and gasoline) from the market price of crops multiplied by crop products. Price of crops came from INSEE (<https://www.insee.fr/fr/statistiques/series/109144301>). Price of equipment came from the BCMA referential (Walter, 2022). The semi-net margin closely approximates the actual income of farmers. Working hours (h.ha^{-1}) corresponded to the cumulative duration of interventions (including manual ones when they exist) in sampled fields. It was calculated as the cropped area concerned by intervention $i \times$ temporal frequency of intervention $i \times$ site throughput (h.ha^{-1}) based upon the BCMA referential (Walter, 2022). We assumed that the longer the working hours, the lower the level of social performance and well-being (time spent for social interactions, leisure, training, etc.).

Table 2

List of management practices extracted from farmer interviews and considered for cropping system description.

Short name	Description	Type	Class or unit
Sowing	Sowing period	Qualitative	Usual; Late ^a
Crop	Crop type	Qualitative	Cereal; Mix
Icrop	Presence of intermediary crop	Qualitative	Yes; No
Pcrop	Previous crop	Qualitative	Maize; Meadow; Other
TFI tot	TFI total ^b	Quantitative	Score
UN org	Organic nitrogen fertilization quantity	Quantitative	kg of N per ha
UN min	Mineral nitrogen fertilization quantity	Quantitative	kg of N per ha
Plough.	Ploughing	Quantitative	Number of ploughing steps
Mec_post_sowing	Soil operations post-sowing	Quantitative	Number of mechanical soil interventions after sowing
Nint	Total number of field interventions	Quantitative	Number of interventions

^a We considered as 'usual' and 'late' winter cereal sowing until and after October 25th, respectively.

^b TFI, Treatment Frequency Index.

2.3. Calculation of multifunctionality indices

We used the 'averaging approach' by averaging the normalized values of proxies to yield a single index. The averaging approach is widely used in multifunctionality studies since it provides a straightforward measure to evaluate the ability of ecosystems to simultaneously provide multiple functions. The two main methods for normalization are standardization by the maximum value (Mouillot et al., 2011) or using z-score (Maestre et al., 2012). Although there are certain reservations regarding the use of maximum values for standardization (e.g. sensitivity to outliers), standardizing the scale of a multifunctional index by a maximum value creates a metric that is intuitively understandable in comparison with the z-score method (Manning et al., 2018).

We first standardized (0–1 scale) each of the 14 proxies (primary variables) using the maximum and minimum values observed across all fields to remove the effects of differences in the scales of measurement among functions (Mouillot et al., 2011). Standardized proxies were averaged to obtain a measure of each function ($N = 7$). Functions values were then averaged to obtain the multifunctionality index. To maintain directional change when proxies represented an undesirable ecological (i.e. pest infestation) or social (i.e. labor time) perspective, the values of the proxies were inverted such as $1 - \text{infestation}$ and $1 - \text{working hours}$. In the absence of clearly defined objectives to be achieved by farmers, we have applied the same weight to all functions.

To test whether our averaging approach could affect the results (by overweighting ecological aspects), we then calculated a performance-multifunctionality index. We averaged normalized proxies by performance (Table 1) leading to one value for ecological, agronomic, economic and social performances. The multifunctionality index resulted from averaged values of the four performances, giving equal weight to each.

To evaluate the sensitivity of our results in relation to the normalization, we also applied standardization using the z-score method i.e. by subtracting the mean of the values and dividing by the standard deviation (Maestre et al., 2012). In the case of functions for which negative values indicate higher levels of function (i.e. pest infestation and labor time), we transformed functions to a negative scale by multiplying by -1 .

Pairwise correlations between the four resulting multifunctionality indices were shown in Fig. S5.

2.4. Statistical analysis

Generalized Linear Mixed effect Models (GLMMs) were built to assess the effects of management practices on multifunctionality index and each function, with a Gaussian error distribution. In a previous work, we showed that landscape gradients had no influence on multifunctionality index and functions (Couthouis et al., 2023). Nevertheless, to take into account potential differences in pedo-climatic conditions, we added landscape identity as a random effect in models. The three levels of description of management practices, namely farming systems (organic vs. conventional), cropping systems, and individual management practices, were tested using multifunctionality index and functions with three separate linear models.

Owing to the large number of individual management practices compared with the number of fields, we performed a variable selection procedure among all variables reported in Table 2 using a conditional random forest model. Random forests have grown in popularity in many scientific fields due to their robustness in 'small n large p' situations, complex interactions, and highly correlated predictor variables (Strobl et al., 2008). Random forests are recursive partitioning methods used in ecology for variable selection (see Puech et al., 2014 for example). By providing a measure of 'variable importance' for each explanatory variable (Strobl et al., 2008), random forests allow selection of the most relevant variables to be considered in linear models. Herein, random forests were grown based on 500 bootstrap samples (robustness of

results was checked with 1000 trees) using the party R package (Hothorn et al., 2006). We fixed the number of input variables randomly sampled as candidates at each node as the square root of the total number of variables. Model stability was verified by checking that the same ranking was achieved with different random seeds (Puech et al., 2014). Variables were considered as informative and relevant when their conditional score was above the absolute value of the lowest negative-scoring variable (Strobl et al., 2008). In the case of two highly correlated 'important' variables (Spearman ρ coefficient > |0.70|, Table S2), only the most important one (in terms of the conditional importance measure from random forests) was retained in models.

The residuals of all GLMMs were visually checked for normality and homoscedasticity. Collinearity between explanatory variables was assessed using the Variance Inflation Factor (all VIFs were < 2.5). When spatial autocorrelation was detected, models were re-run adding geographical coordinates as fixed effects. In order to identify trade-offs and synergies between functions, we performed pairwise correlation tests among functions within each farming system and within each cropping system. Due to the low number of fields per cropping system, Spearman rank correlation tests among functions were performed.

Analyses were performed for the two standardization methods (maximum value and z-score) using R (R Core Team, 2020).

3. Results

3.1. Typology of cropping systems

The two first principal components from the mixed PCA performed on the 10 variables describing management practices explained 46% of the total variance. On one side, the low amount of mineral nitrogen input was associated with late sowing, limited use of pesticides, numerous mechanical soil operations, and meadow as the preceding crop. On the other side, a large amount of mineral nitrogen input was associated with usual sowing dates, high levels of field interventions, high pesticide use, and maize as the preceding crop (Fig. S4a).

Clustering analysis performed on the PCA data enabled differentiation of the five groups of cropping systems (Fig. S4b). Group 1 was characterized by organic mixed crops without intermediary crops, usual sowing dates, and low organic nitrogen inputs (mean \pm SD = 8.72 \pm 21.36), as well as few field interventions (3.50 \pm 0.55). Group 2 was characterized by organic cereal crops with late sowing dates and meadow as the preceding crop, relatively low organic nitrogen inputs (37.20 \pm 44.26), and few field interventions (5.40 \pm 1.52). Group 3 was characterized by organic fields, either with cereal or mixed crops, quasi

systematic soil tillage (1.00 \pm 0.63), high organic nitrogen inputs (58.17 \pm 68.76), and numerous field mechanical interventions after sowing (1.33 \pm 0.82). Group 4 was characterized by mixed organic and conventional fields with late sowing, maize as the main preceding crop, systematic soil tillage (1.00 \pm 0.00), and moderate levels of TFI (2.65 \pm 1.89, two third less than group 5) and mineral nitrogen inputs (104.55 \pm 78.06, one third less than group 5). Group 5 was characterized by intensive conventional fields, with maize as the main preceding crop, normal sowing dates, high mineral nitrogen inputs (160.39 \pm 27.06), and numerous field interventions (9.18 \pm 1.08; Table 3).

3.2. Multifunctionality and functions analysis

The multifunctionality index, based on the seven functions, showed no difference between organic and conventional systems regardless of the standardization method (Fig. S6; Fig. S7). Conversely, the multifunctionality index based on the four performances was significantly higher in conventional than in organic system (Fig. S8). When analyzing function by function, we found that fields under organic management had higher biodiversity conservation (+ 36%), predation (+ 13%), pest infestation (+ 24%), and pollination capacity (+ 26%) values than fields under conventional management. They also had lower (− 42%) food and feed production values. No difference between organic and conventional management was found for income contribution and labor time (Fig. 1). These results hold true regardless of the standardization method (Fig. S6; Fig. S7).

At the cropping system level, we observed marked differences in multifunctionality and functions between groups (Fig. 2; Fig. S9; Fig. S10). Group 3 significantly differed from the other groups: it had the lowest multifunctionality index value but the highest values for predation, infestation and labor time. Group 3 was also characterized by strong variability in predation, infestation, and pollination capacity (Fig. 2; Fig. S9). Group 1 had similar values for functions to group 3 but lower labor time (− 36%), resulting in the highest multifunctionality index. Groups 2, 4 and 5 had similar and intermediate values of multifunctionality. Groups 2, 4 and 5 have similar values for pollination capacity, infestation, labor time and income contribution (Fig. 2; Fig. S9). Groups 4 and 5, based on all conventional fields, had very similar levels of functions. Groups 4 and 5 had the lowest values for biodiversity conservation, predation, pest infestation, and pollination, but higher food and feed production values than groups 1, 2, and 3 (> + 35%). Group 2 had relatively high values for biodiversity conservation but low values for predation and infestation. No significant difference in income contribution was observed between groups. These results hold true

Table 3

Description of the five cropping system groups. (a) Number of fields according to cropping system and categorical management practices, (b) Mean \pm standard deviation values for quantitative management practices. For abbreviations, see Table 2.

(a)												
Cropping system group	No. of fields	Farming system		Crop type		Sowing		Intermediary crop		Preceding crop		
		Organic	Conventional	Cereal	Mixed	Classic	Late	No	Yes	Maize	Meadow	Other
1	6	6			6	5	1	6		3		3
2	5	5		5			5	5			5	
3	6	6		4	2	4	2	2	4	1	1	4
4	12	3	9	11	1		12	12		10		2
5	11		11	11		11		10	1	8		3

(b)						
Cropping system group	TFI tot	UN org	UN min	Plough.	Mec_post_sowing	Nint
1	0.00 \pm 0.00	8.72 \pm 21.36	0.00 \pm 0.00	0.67 \pm 0.52	0.00 \pm 0.00	3.50 \pm 0.55
2	0.00 \pm 0.00	37.20 \pm 44.26	0.00 \pm 0.00	0.80 \pm 0.45	0.40 \pm 0.55	5.40 \pm 1.52
3	0.00 \pm 0.00	58.17 \pm 68.76	0.00 \pm 0.00	1.00 \pm 0.63	1.33 \pm 0.82	9.17 \pm 3.92
4	2.65 \pm 1.89	32.30 \pm 49.08	104.55 \pm 78.06	1.00 \pm 0.00	0.00 \pm 0.00	7.58 \pm 2.31
5	4.60 \pm 2.01	0.00 \pm 0.00	160.39 \pm 27.06	0.64 \pm 0.50	0.00 \pm 0.00	9.18 \pm 1.08

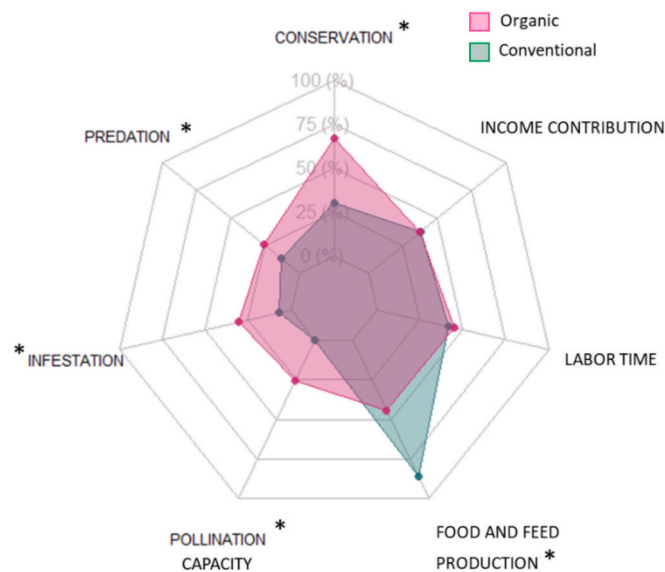


Fig. 1. Radar plot showing the average standardized values (by the maximum) of the seven functions. * indicates significant differences between organic and conventional management as obtained from Generalized Linear Mixed effects Models (GLMMs) for each function.

regardless of the standardization method used.

At the individual practices level, we found that the number of field interventions was negatively correlated with the multifunctionality index based upon functions (Fig. 3), regardless of the standardization method used (Table 4; Table S3). The multifunctionality index based upon performances and standardized by the maximum was also negatively correlated with the number of field interventions but positively correlated with mineral and organic nitrogen fertilization (Table S4). The multifunctionality index based upon performances and standardized by the z-score was positively correlated with mineral nitrogen fertilization and negatively correlated with meadow sown as previous crops (Table S4).

The number of field interventions was negatively correlated with biodiversity conservation, but positively correlated with labor time. The quantity of mineral nitrogen fertilization had a negative effect on biodiversity conservation, predation, pest infestation, pollination capacity, and labor time but a positive effect on food and feed production. We also found a positive effect of organic nitrogen fertilization on food and feed production. Lastly, the type of crop sown significantly influenced predation, with higher predation in mixed than in cereal crop fields (Table 4). These results hold true regardless of the standardization method used (Table S3).

3.3. Trade-offs and synergies

Overall fields, we found a strong trade-off between functions related to ecological and agronomic performance types (Fig. S11). Biodiversity conservation, predation, pest infestation, and pollination capacity were strongly and negatively correlated with food and feed production (yield). Alternatively, synergies occurred between all ecological functions, namely biodiversity conservation, predation, pest infestation, and pollination capacity.

The trade-offs between functions related to ecological performance and those related to agronomic and socio-economic performance types also held for both farming systems, but with overall higher intensity for conventional than organic systems (Fig. S12; Fig. S13). Synergies between ecological functions were higher for conventional than organic fields, except between predation and infestation. A trade-off between pollination capacity and infestation was only found in organic fields. Most ecological functions were negatively correlated with income

contribution in organic fields (Fig. S12; Fig. S13).

At the cropping system level, trade-off and synergy patterns were similar for groups 1 and 3 on one side and groups 2, 4 and 5 on the other side (Fig. 4). Group 1 and group 3 with respectively the highest and the lowest multifunctionality value, were the only groups showing a trade-off among ecological functions, *i.e.* pollination capacity with infestation or predation. Group 1 was characterized by synergies between functions related to agronomic and socio-economic performances. Group 1 showed a trade-off between functions related to ecological and economic performances: all ecological functions were negatively correlated to income contribution. Patterns in group 3 were more nuanced with positive correlations between predation, pest infestation and income contribution (Fig. 4). Groups 2, 4 and 5, with intermediate values of multifunctionality, were characterized by synergies among all ecological functions. While a trade-off occurred between income contribution with food and feed production and labor time, synergies were observed between income contribution and most ecological functions in group 2. On the contrary, trade-offs occurred between income contribution with ecological functions and labor time but not with yield in group 4 (Fig. 4). With a few exceptions, group 5 had a similar pattern to group 4. For all groups, we observed a recurrent trade-off between functions related to ecological performance and those related to agronomic performance (Fig. 4). This trade-off was particularly exacerbated for group 4. These results hold true for the two standardization methods (Fig. S13).

4. Discussion

We showed that the multifunctionality index based upon functions did not differ according to farming system (organic vs. conventional). We observed strong trade-offs between functions related to ecological performance and other performances, in particular between biodiversity conservation and food and feed production. Organic management of agroecosystems tended to minimize these trade-offs. More interestingly, our study showed similar multifunctionality values can be achieved with contrasting cropping system types. Trade-offs and synergies among functions reveal different strategies and concerns of farmers. Lastly, our analysis highlighted the number of field interventions and nitrogen inputs as major technical drivers of agroecosystem multifunctionality and its underlying functions.

4.1. Improved biodiversity-based functions in organic systems

Contrary to our first hypothesis, multifunctionality index did not differ between organic and conventional systems. These results contradict recent observations (Wittwer et al., 2021) but are in line with other studies in annual (*e.g.* Herzog et al., 2019) and perennial (*e.g.* Ostandie et al., 2022) crops. Interestingly, downweighing ecological aspects led to significant higher multifunctionality in conventional than in organic systems. This result provides supplementary evidence that organic farming is particularly benefitting biodiversity-based functions (Tuck et al., 2014; Gong et al., 2022).

Our analysis further showed that the increase in biodiversity-based functions under organic management was coupled with a decrease in food and feed production (Reganold and Wachter, 2016; Wittwer et al., 2021; Gong et al., 2022). This trade-off can partly be explained by the accumulation of pathogens and troublesome weeds in the absence of pesticide application (Shennan et al., 2017), as observed here with the infestation function. Interestingly, the trade-off between biodiversity conservation or pollination and food and feed production was slightly reduced in organic systems compared with conventional ones. Despite lower and more variable yields, organic systems showed similar socio-economic performance to conventional ones. Although the social proxy we chose (*i.e.* decreasing working hours) can transcribe a limitation in favor to mechanization, we did not observe significant difference between conventional and organic systems. Previous review report that there is little consistent evidence in high-income countries on

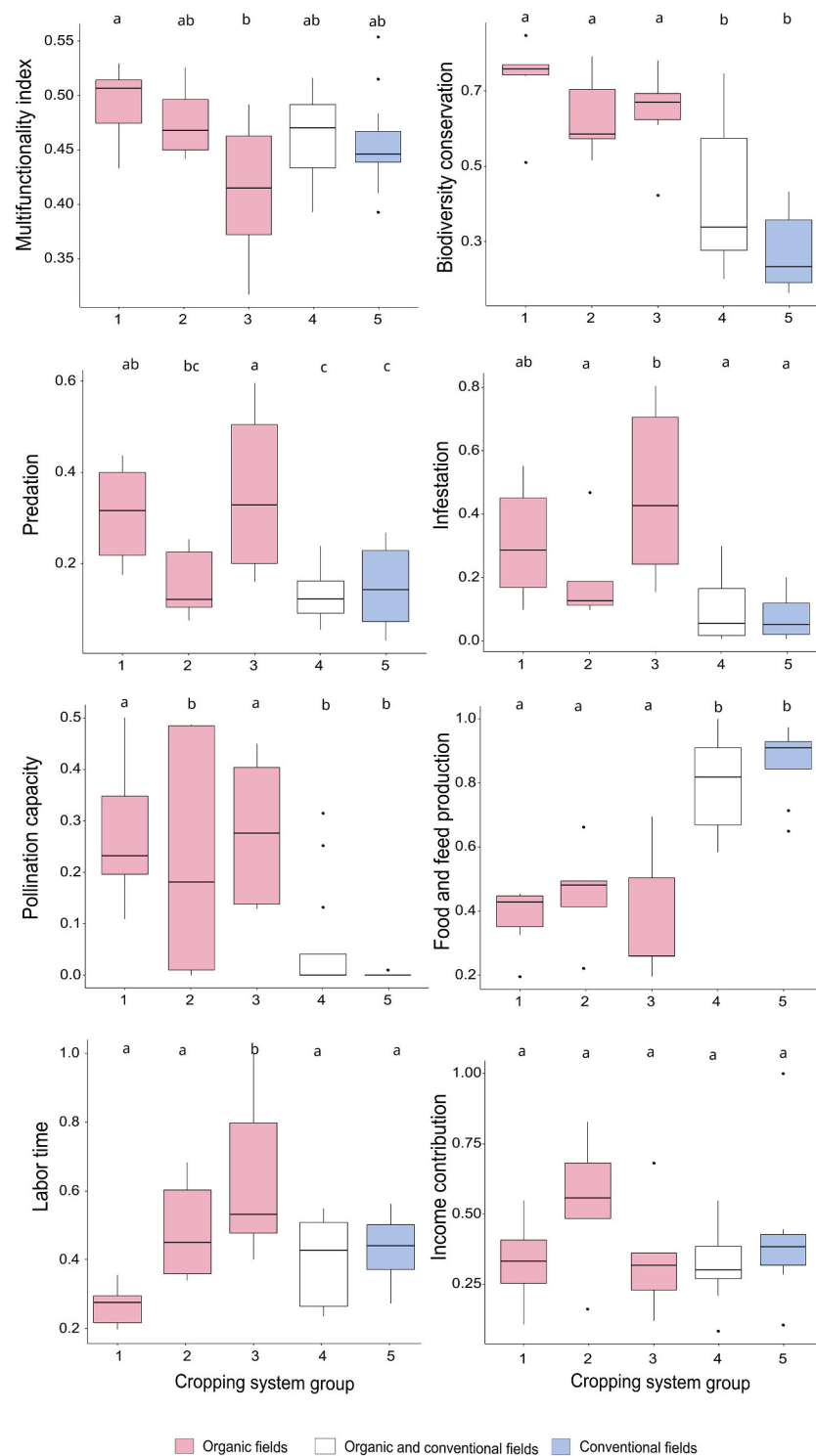


Fig. 2. Boxplots representing the average multifunctionality index (based upon functions) and the seven functions, standardized by the maximum value, according to cropping system groups. Different letters indicate significant differences based on Generalized Linear Mixed effects Models (GLMMs). See Table 3 for description of cropping system groups.

differences in labor conditions between organic and conventional farms (Seufert and Ramankutty, 2017). Similar semi-net margins can be explained by higher market prices and lower inputs costs (non-use of agrochemical products) in organic systems (Sutherland et al., 2015).

Altogether, these results suggest that the multifunctionality approach, in which functions are assumed to be substitutable, is indissociable from a ‘function by function’ analysis. While some performances have received considerable attention (*i.e.* agronomic and

ecological), others (*i.e.* social and economic) have received far less attention partly because they are difficult to quantify *e.g.* livelihood, labor conditions, quality of life, farmer autonomy, health risk, *etc.* (Jansen, 2000). Here, we limited our analysis to a very few quantitative proxies for socio-economic performances. This could have led to underestimation of organic system benefits. We also limited our analysis of the ‘environmental’ dimension of sustainability to aboveground biodiversity-based functions and did not consider other important

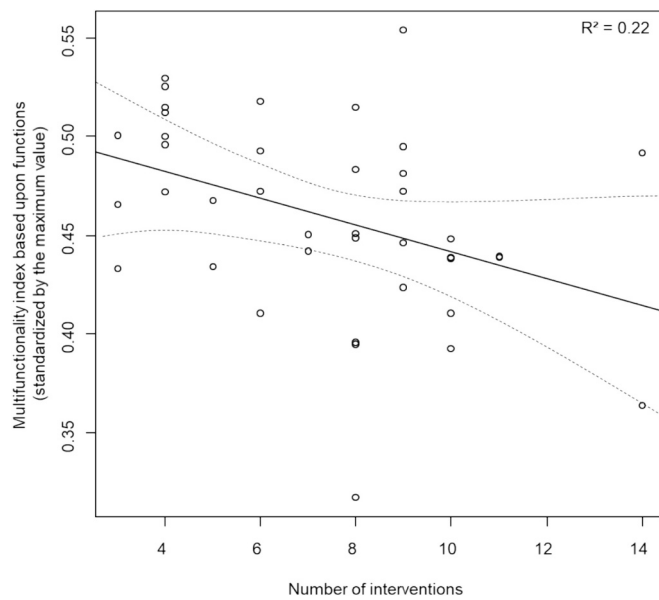


Fig. 3. Relationship between multifunctionality index based upon functions (standardized by the maximum value) and the number of field interventions (all 40 winter cereal fields included).

functions like climate mitigation, water regulation or carbon sequestration. We recognize that in a further development of this framework the list of proxies and functions should be extended. Despite these limitations, our results challenge the widespread view that organic farming is the key farming approach to reconcile agricultural production with biodiversity conservation, and emphasize the need to go beyond the organic vs. conventional dichotomy to achieve sustainable agriculture.

4.2. Trade-offs and synergies in functions among cropping systems reveal distinct strategies

Of most interest to stakeholders is the demonstration that both yield and biodiversity conservation could be simultaneously increased in a given cropping system. We showed that no cropping system maximized both food and feed production and biodiversity-based functions. This result would suggest that current incentives, such as ‘green payment’ in Common Agricultural Policy in Europe, are still insufficient to counterbalance this trade-off. However, we showed that income contribution did not differ significantly among cropping systems. This calls for maintaining and even strengthening current policies and incentives to simultaneously support biodiversity protection and compensate farmers for yield reduction.

Interestingly, we found that contrasting cropping systems namely group 2 (exclusively organic) and group 4 (mixing organic and conventional fields) had similar multifunctionality and function levels. This result suggests that multifunctionality may be achievable via different management paths, potentially allowing farmers to choose the strategies most adapted to the particular objectives and constraints of their farm (e. g. pedoclimatic conditions, farm machinery, workload), as highlighted by Mézière et al. (2015).

In-depth analysis of functions and their interactions revealed great variability among cropping systems suggesting they tended to optimize particular subsets of objectives. For instance, group 1 maximized the multifunctionality index by a ‘biodiversity-friendly’ and ‘low interventionist’ strategy which strongly preserved biodiversity-based functions and reduced labor time. In contrast, group 5, with a slightly lower level of multifunctionality, adopted a ‘productivist’ strategy based upon high inputs (mineral nitrogen fertilizers and pesticides) use: food and feed production was maximized at the expense of biodiversity-based functions, particularly biodiversity conservation and pollination capacity.

Table 4

Results from Generalized Linear Mixed effects Models (GLMMs) testing the effects of ‘important’ variables selected by random forests on the multifunctionality index (based upon functions) and the seven functions, standardized by the maximum value. Values in bold indicate significant effects (** $p < 0.01$, *** $p < 0.001$; ns, not significant). For abbreviations, see Table 2.

Response variables	Predictors	Intercept ± SE	p-value	R ²
Multifunctionality index	<i>Intercept</i>	0.516 ± 0.020	***	0.22
	Nint	-0.009 ± 0.0001 ± 0.0001	***	
	UNmin	0.0001	ns	
Biodiversity conservation	<i>Intercept</i>	0.809 ± 0.033	***	0.93
	Nint	-0.002 ± -0.023 ± 0.005	***	
	UNmin	0.005	***	
	UNnorga	0.0002	ns	
Predation	<i>Intercept</i>	0.185 ± 0.053	***	0.86
	Crop type [Mix]	-0.0005 ± -0.052 ± 0.0301	***	
	UNmin	0.0002	**	
	Sowing date [Late]	0.0301	ns	
	Nint	0.006 ± 0.005	ns	
		-0.532 ± -0.1631 ± 0.325	ns	
		0.013 ± 0.438	ns	
Infestation	<i>Intercept</i>	0.590	ns	0.76
	UNmin	-0.011 ± -0.1631 ± 0.325	**	
	Sowing date [Late]	0.325	ns	
	Crop type [Mix]	0.013 ± 0.438	ns	
Pollination capacity	<i>Intercept</i>	0.192	***	0.77
	UNmin	-0.017 ± 0.002	***	
	UNnorga	0.0005	**	
Food and feed production	<i>Intercept</i>	0.399 ± 0.038	***	0.73
	UNmin	0.003 ± 0.0003	***	
	UNnorga	0.001 ± 0.0005	**	
	UNnorga	0.0005	**	
Labor time	<i>Intercept</i>	0.167 ± 0.052	***	0.54
	Nint	0.046 ± 0.008	***	
	Preceding crop [Meadow]	0.081 ± 0.060	ns	
	Preceding crop [Other]	-0.008 ± 0.045	ns	
		-0.001 ± 0.0003	***	
Income contribution	<i>Intercept</i>	0.370 ± 0.042	***	0.19
	UNmin	0.00008 ± 0.0003	ns	

Besides, group 3 adopted a ‘labor intensive’ strategy characterized by higher levels of organic fertilizers use and numerous field interventions likely to secure income, but resulting in the lowest multifunctionality level and the highest variability in biodiversity-based functions and yield. Nevertheless, no significant difference in income contribution between cropping systems was observed. This illustrates the diversity of cropping system management and points to the need to clarify farmers’ strategic reasoning behind such choices, which go far beyond cost–benefit considerations. Interviews with farmers can bring complementary data that can inform on farmers’ priorities and concerns, their personal, social and external factors such as natural and technical constraints, position face to government regulations and market, or risk perception (Hanger-Kopp and Palka, 2022). Capturing the complexity of farmers’ concerns, in a given context, would help identify the weights to be applied to the three sustainability dimensions in multifunctionality

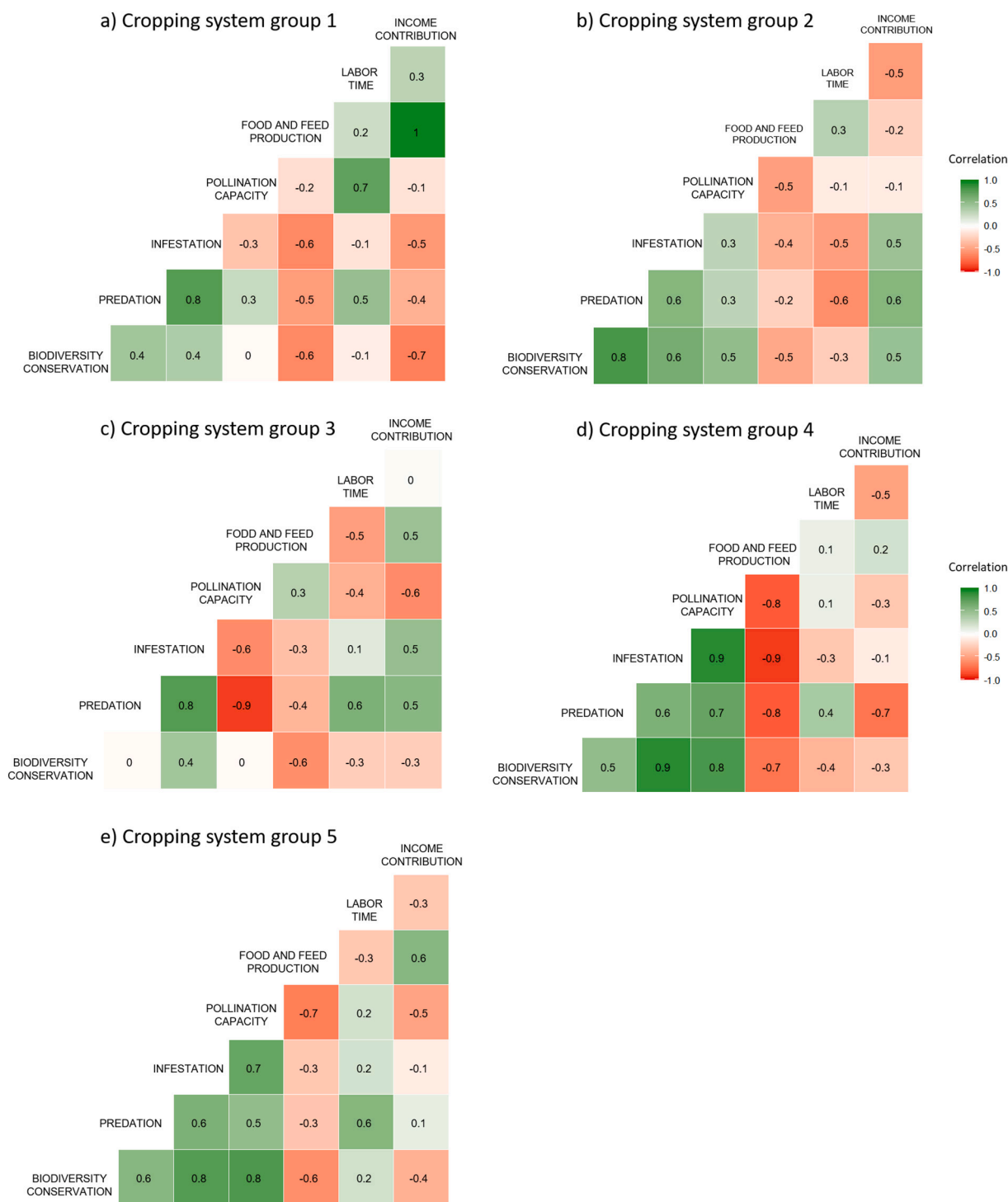


Fig. 4. Pairwise correlations between the seven functions (standardized by the maximum value) according to cropping system groups. Numbers correspond to Spearman correlation coefficients.

assessment. Such an approach would certainly make it possible to design effective policy instruments and recommendations that better guide and restore the balance between agronomic, ecological and socio-economic performances.

Overall, these results must be treated with care. The high degree of variability within each cropping system group demonstrates the importance of emphasizing the number of fields studied, as well as the importance of considering the determinants used to construct the typology, and the broad range of technical options available in each cropping system type (e.g. choice of material, intervention dates, crop

varieties) (Craheix et al., 2016). It should also be noted that we based our cropping systems assessment on a yearly description of the systems; it did not take into account the diversity of crops included in the rotation. Few scientific studies have considered the interannual variability of environmental, social, and economic performance of agroecosystems (Colomb et al., 2013; Craheix et al., 2016). In this respect, a more precise analysis of the robustness of performances over many years is warranted, and this should be addressed by researchers to determine the effects of climatic effects and market price variability on set-up cropping systems.

4.3. The number of field interventions as key determinant of multiple functions

Exploring the roles of individual management practices, we found that the number of field interventions and the nitrogen fertilization amount are the main determinants of cropping system performance. Increasing field interventions led to lower multifunctionality value and poorer ecological performance (*i.e.* lower biodiversity conservation and lower predation). Logically, fields that require numerous interventions to limit the proliferation of weeds, through mechanical weeding or more frequent application of herbicides, are also those placing greater labor costs on farmers. Similar to other forms of ecosystem disturbance, field interventions are known to be deleterious for biodiversity conservation (Villnäs et al., 2013). In agreement with previous observations, we found that arthropod predator abundance was positively influenced by decreased soil disturbance (*i.e.* limited mechanical soil operations) (Thorbek and Bilde, 2004; Tamburini et al., 2016).

We also showed that the amount of mineral nitrogen fertilization decreased biodiversity conservation, pest predation, and infestation, but increased food and feed production. Indeed, fertilizer application is among the most common practices used to maximize crop production in the short term (Tamburini et al., 2016). The negative effect of mineral nitrogen fertilization on pest predation was consistent with previous studies showing how nitrogen fertilization can increase weed growth, herbivore performance, and plant susceptibility to diseases (Matson et al., 1997). However, we must keep in mind that, in our study, the amount of mineral fertilization was highly correlated with pesticide use, which can explain the deleterious effects on biodiversity conservation, predation, and infestation.

Overall, these results indicate that specific management practices, such as reducing field interventions and nitrogen fertilization amount, could be integrated even in conventional cropping systems to improve their multifunctionality (Tamburini et al., 2020; Wittwer et al., 2021; Carof et al., 2022). This calls for substantial increases in knowledge and experience sharing among scientists and farmers about technical drivers and their efficient use to enhance performances underlying sustainable agriculture (Tilman et al., 2002).

5. Conclusion

Sustainability assessments based on single-site experimental studies are crucial for the identification of promising cropping systems in a given pedo-climatic and socio-economic context (Deytieu et al., 2016). Our study proposed an original approach by quantifying multifunctionality of annual cropping systems, integrating socio-economic performance assessment. The value of our approach lies in the possibility that it offers to compare different cropping systems and to identify technical levers that can be mobilized to foster multiple functions.

We showed that the investigated cropping systems were unable to reconcile crop production and biodiversity-based functions. The numerous trade-offs among functions as well as the large variability observed within cropping system makes the task of developing policies to promote multifunctional agriculture particularly challenging. It requires clearly defining the goals targeted, as these goals can be diverse and sometimes conflict with each other (Carof et al., 2022). Interestingly, we demonstrated that similar multifunctionality levels can be achieved through different management paths. Installing a balanced proportion between 'productive' cropping systems, providing a few functions at high levels, and 'biodiversity-friendly' cropping systems providing diverse functions at lower levels could be a way to simultaneously promote crop production and biodiversity-based functions.

Deepening management practices that may influence multifunctionality, we found the number of field interventions to be a major driver of a wide range of functions. Although we are aware that individual practices cannot be changed without considering the whole farm strategy, resources, and constraints, we showed that there is some

flexibility even in conventional systems to enhance multifunctionality. This opens the door to further studies on how agricultural management fosters the simultaneous provision of multiple functions and the potential trade-offs between them. It paves the way for identification of sound strategies for the design and management of sustainable cropping systems.

CRedit authorship contribution statement

Audrey Alignier: Writing – original draft, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Matthieu Carof:** Writing – review & editing, Validation. **Stéphanie Aviron:** Writing – review & editing, Methodology, Data curation, Conceptualization, Funding acquisition.

Declaration of competing interest

S. Aviron reports financial support was provided by Foundation of France. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available via the Dryad Digital Repository at <https://doi.org/10.5061/dryad.k98sf7m8z> (Couthouis et al., 2023).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agsy.2024.104100>.

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