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Performance of co-designed diversified Mediterranean cropping systems: Hybridizing stakeholders' knowledge and modelling data

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ABSTRACT

Mediterranean cropping systems, characterised by continuous cereal cropping, are largely dependent on synthetic inputs, such as N fertilisers. On the other hand, they face difficult pedoclimatic conditions, exacerbated by climate change. Diversification is seen as a way to increase cropping systems resilience. The aim of this study was to co-design diversified cropping systems based on the expertise of local stakeholders and co-assess their performance, using modelling data. Our case study is the Ebro valley in Spain, a Mediterranean area with great potential for diversification, particularly where irrigation is available. Two workshops were organized to i) define the reference system in the study area and its limitations ii) co-design diversified systems to overcome these limitations and iii) co-assess reference and diversified systems. Between the two workshops, the STICS soil-crop model was calibrated with local experimental data, enabling to simulate the inter-annual (2000–2021) agronomic and environmental performance of the reference and diversified systems. An economic analysis was conducted. Stakeholders evaluated all economic, agronomic and environmental aspects. The reference system was a continuous winter cereal crop based on synthetic N fertilisation and intensive tillage. The four diversified co-designed systems consisted in introducing pea and/or rapeseed every 2 or 4 years, reducing tillage and partially replacing synthetic N fertilisation with locally sourced livestock manure. Simulation results showed that wheat and barley grain yields remained stable with diversification. Pea and rapeseed yields were lower in rotations where both were introduced compared to when each was the only break crop over 4 years. At the system level, protein yield remained stable with diversification, however, energy yield decreased by 20 % when break crops were introduced twice and by 10 % when introduced once. Gross margins improved with diversification only when pea was introduced once (12 %), mainly due to reduced expenses (-31 %), while incomes remained stable compared to RCS. However, incomes decreased by 5 % when rapeseed was introduced once, and by 10 % when both break crops were introduced. Unexpectedly, environmental performance deteriorated with diversification, with increased N losses through ammonia volatilisation and nitrate leaching in the years following pea and rapeseed cropping, due to greater N availability in the soil. An increased use of pesticides was predicted by the stakeholders in diversified systems, where the environmental impacts were exacerbated with the higher presence of break crops. The reference system presented slightly lower N availability and increased soil organic carbon storage. Overall, the approach proved useful in identifying a diversification strategy that improved agronomic and economic performance, with the system including pea once every four years being the most efficient. However, the environmental trade-offs associated with the increased presence of pea and rapeseed in the crop rotation must be considered in order to mitigate the environmental risks.

Abbreviations: ACV, adjusted coefficient of variation; CS, cropping systems; DCS, diversified cropping systems; FTI, Frequency Treatment Index; HDCS, highly diversified cropping systems; RCS, reference cropping system; SOC, soil organic carbon.

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1. Introduction

Cereals account for the bulk of cultivated land in the Mediterranean. Their production relies on N supply, generally external from the farm, given that 50 % of the N fertilisers applied in the basin are synthetic (Romero et al., 2021). Synthetic N is associated with environmental damage due to the greenhouse gases emissions from its production, transport and use (Menegat et al., 2022). Population growth will increase the demand for calories and the food production's dependence on fertilisers, thus, increasing the likelihood of environmental harm. Diversifying crop rotations could be a way to increase N use efficiency and to reduce the supply of synthetic N without compromising yields. The Mediterranean climate, characterised by hot summer temperatures, scarce and highly variable precipitation (Seager et al., 2019), poses significant challenges to maintain stable productivity in cropping systems. Consequently, increasing the resilience of cropping systems (CS) is paramount to ensure their sustainability. Mediterranean soils tend to be shallow with low infiltration rates, high erosion rates and low organic matter content (Ferreira et al., 2022). Avoiding soil degradation is essential to maintain its ecosystem services, including food production, which is a key factor in ensuring food sovereignty. Fertilisation, tillage practices, and crop sequences can be leverage to improve soil fertility (Jarecki and Lal, 2003). However, their effectiveness depends on the pedoclimatic context. Most of the Ebro Valley in north-eastern Spain is characterised by a semiarid Mediterranean climate with continental trends. Intensive swine and poultry production in the area provides high nitrogen (N) availability from livestock manure, that could be recycled to reduce synthetic N fertilisation and simultaneously improve soil quality. However, this could also present environmental risks if surplus N is not properly managed. The efficient use of N sources must be considered in conjunction with the choice of crop species and other management practices.

Participatory CS design is a useful tool for building high-performance systems in the long term. It has been increasingly used in research during the last decades (Martin et al., 2013). This approach helps connect scientific research with stakeholders, enabling a better understanding of daily challenges and limitations stakeholders face, providing valuable insights for further investigations. Therefore, stakeholders must be actively included in the design process from the beginning in order to combine both local expertise with scientific knowledge. Different types of participation exist: contractual, consultative, collaborative and collegiate (Barreteau et al., 2010). Only collegiate participation allows decision to be made by agreement or consensus among all actors, including them all from the start and valuing their knowhow (Barreteau et al., 2010). However, among the 41 CS design studies reviewed by Martin et al. (2013), only a minority (11) actively included stakeholder participation through collegiate (6) or collaborative (5) approaches, while the majority involved them in a consultative role (15) or did not include their participation at all (15). Furthermore, many studies have focused primarily on a single aspect of CS, such as agronomics (e.g. Andrieu et al., 2007; Barioni et al., 1999). Consequently, these studies may overlook the overall sustainability of the CS, as socio-economic and environmental impacts are not considered. A multidimensional approach is essential to assess the performance of CS as a whole (Bonnet et al., 2021).

Process-based soil-crop models are valuable tools for assessing CS performance, as they can simulate a wide range of variables, incorporating numerous agronomic and environmental processes. They provide a comprehensive framework for understanding the interactions between crops, soils, and the environment. These models enable researchers and end-users to evaluate different management strategies and predict their outcomes (Lopez-Jimenez et al., 2022). Models are particularly effective for assessing the long-term performance of CS, given the limitations of short-term experimental approaches for fully understanding the impact of climate on crop yield variability. Short-term experiments may also miss long-term processes that occur in soils and affect the ecosystem services they provide, including fertility (Carof et al., 2022). Additionally, models play a crucial role in conducting *ex-ante* evaluations of various scenarios and assessing CS beyond simply comparing individual crop phases. Considering the entire crop sequence of the rotation is crucial as it has a significant impact on the overall economic performance of the CS (Preissel et al., 2015).

Combining a participatory approach and modelling is a way to bridge the gap between scientific expertise and local knowledge. It facilitates a collaborative space where stakeholders can refine their understanding of complex issues, and collaboratively develop strategies and solutions for sustainable decision-making (Etienne, 2014). Recent studies have demonstrated the successful application of participatory modelling in the development of CS tailored to specific conditions (e.g. Delmotte et al., 2017; Hossard et al., 2022). These studies have revealed that while simulations may show improved performance in one aspect, there may be trade-offs resulting in poorer performance in other areas. This underlines once again the importance of adopting a multi-dimensional approach to consider the different aspects of sustainability, and thus grasp the feasible trade-offs between them (Gutzler et al., 2015).

The aim of this study was to design and assess sustainable CS specifically tailored to the Mediterranean climate. Our hypothesis was that collaboratively designing CS would lead to more sustainable and high-performing CS, realistic and adoptable by farmers.

2. Materials and methods

An eight-step process was followed (Fig. 1) to fulfil the objective. These steps included two participatory workshops with stakeholders, and modelling of the CS with STICS soil-crop model.

2.1. Participatory approach: steps one to three

Key stakeholders involved in arable crop production in the Ebro valley were identified and invited to two workshops: 13 attended the first workshop, and 10 the second. The stakeholders' profile was diverse and representative of the case study with farmers (4 at the 1st workshop, 3 at the 2nd), private consultants (1 then 2), regional administration (1), farmer researcher consultant (1), agricultural engineering students (2 then 0), irrigation company (1 then 0) and researchers (3). The two workshops were held a year apart, to complete the modelling tasks required in the interim.

First, current winter cropping systems were collectively defined (Step 1, Fig. 1). Then, a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats identification) was collectively constructed, followed by a discussion about alternative management practices already experimented by stakeholders (i.e., fertilisation, tillage, crop sequences, irrigation, pest control). The 2nd step (Fig. 1) was to co-design innovative Diversified Cropping Systems (DCS). Stakeholders were asked to describe each practice defining their proposed DCS, i.e.: crop sequence, tillage practices (depth, frequency, date), crops sowing date and rate, N fertilisation (type, rate, date), irrigation (amount, frequency), pest control, and market destination. During the 3rd step (Fig. 1), stakeholders had to define specific criteria they deemed relevant for evaluating CS performance, for each of the environmental, socio-economic, and agronomic dimension.

2.2. Modelling approach: steps four, five and eight

2.2.1. Overview of STICS soil-crop model

The STICS soil-crop model (Brisson et al., 1998, 2008; Beaudoin et al., 2022) is a dynamic model that simulates with a daily time step plant growth, carbon (C), N and water cycles. It is a one-dimensional model that considers soil characteristics, climate, management practices as inputs to the simulation, considering crucial variables such as crop residues amount and C/N ratio. It was chosen for its ability to

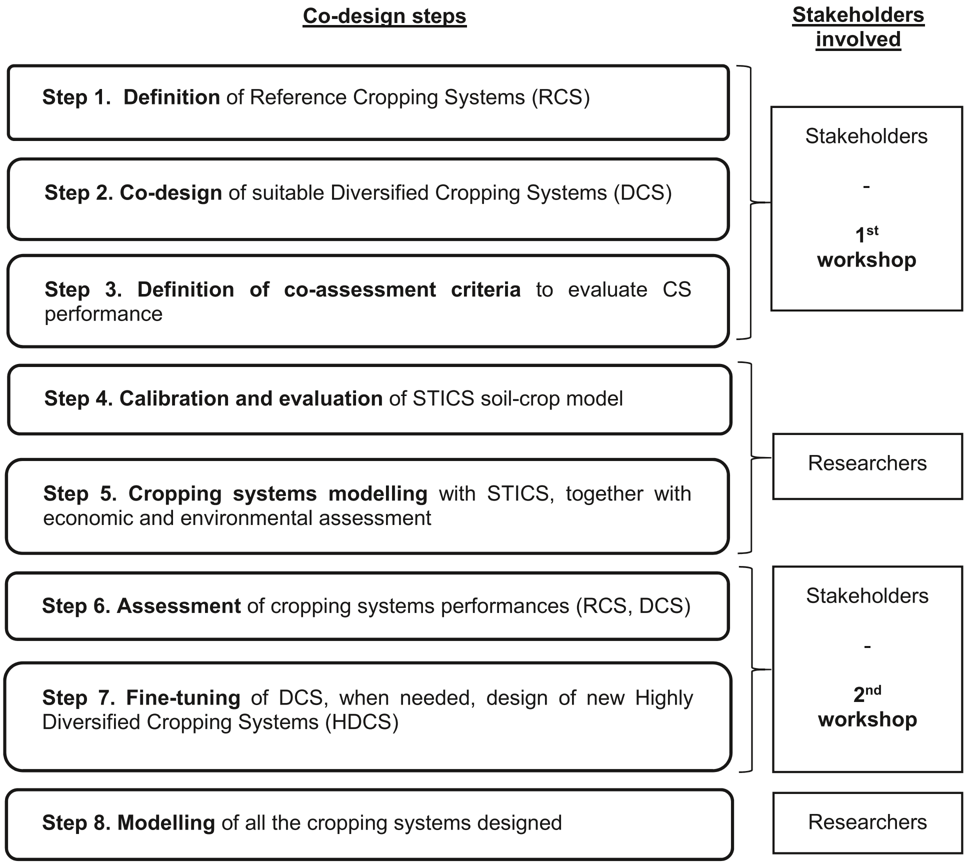


Fig. 1. Main steps of the co-design and modelling process.

model agro-environmental processes and crop rotations in the long term, and its robustness. The latest version available (9.2), was used. Indeed, several studies showed its ability to adequately simulate contrasting environmental conditions and management practices in both temperate (Constantin et al., 2012; Coucheney et al., 2015; Yin et al., 2020) and Mediterranean climate (Plaza-Bonilla et al., 2015), enabling to analyse the impact of different agricultural management practices on N losses. In additions, processes related to the losses of NO_3^-, NH_4^+ and N_2O which are costly and time-consuming to assess in the field, have been efficiently modelled with STICS under Mediterranean conditions (Kherif et al., 2022; Plaza-Bonilla et al., 2017, 2018).

2.2.2. *Model calibration and evaluation*

The data used to calibrate and evaluate the model (step 4) were collected in two on-farm experiments located in the Ebro valley. One farm was representative of irrigated areas and the other reflected a rainfed production zone. These experiments were selected because the crop species and the management practices were relevant to co-designed cropping systems. The irrigated experiment (Sucs, Lleida, 41°42’0.81"N, 0°26’52.60"E, 289 masl), tested different crops under two N fertilisation scenarios over two cropping seasons (80 and 155 kg N ha^{-1} yr^{-1} in 2020–2021, 0 and 75 kg N ha^{-1} yr^{-1} in 2021–2022). The rainfed experiment (Selvanera, Lleida, 41°49’52.27"N, 1°17’40.98"E, 465 masl), tested different crops under four rates of top-dressing synthetic N fertilisation (0, 40, 80, 120 kg N ha^{-1} yr^{-1}) over three cropping seasons (2019–2020, 2020–2021, 2021–2022). Pedoclimatic characteristics of both sites are detailed in Supplementary Material (Table S1). These experiments provided data on crop phenological stages, leaf area index (Sucs site only), crop aboveground biomass, N biomass concentration, N derived from biological fixation (at flowering and physiological maturity), grain yield, grain N concentration, and soil water and nitrate content down to 60 cm before sowing and after harvest. The database was split in two independent datasets, separated by cropping season and fertilisation treatments, creating one set for calibration of the crop parameters, and the other for evaluation. Each set contained all cropping seasons and half of the fertilisation scenarios, allowing to take into account the full range of productivity observed empirically. An independent calibration and evaluation of the model performance was carried out for each of the species included in the CS (step 4, Fig. 1). The model performance was assessed with the Root Mean Square Error (RMSE, Eq. (1)), its relative value (rRMSE, Eq. (2)) and the Model Efficiency (EF, Eq. (3)):

$$RMSE = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n}(O_i - S_i)^2} \tag{1}$$

$$rRMSE = \frac{RMSE}{\bar{O}} \times 100 \tag{2}$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{3}$$

where O_i and S_i are the observed and simulated values for the i^{th} measurement, respectively; n the number of observations, and $\bar{O}$ the mean of the observed values. The rRMSE determines if the simulation accuracy is either excellent when < 10 %, good < 20 %, fair <30 % and poor >30 % (Jamieson et al., 1991). The EF is a dimensionless measure, with a value closer to 1 indicating higher efficiency.

2.2.3. *Cropping systems modelling*

Stakeholders designed irrigated CS. Hence, to model them, pedoclimatic characteristics considered were the one of Sucs experimental site, representative of a large surface of irrigated areas within the Ebro valley. The nearest weather station (Raïmat, 7 km from the site) was used for climatic data. Cropping systems were modelled during step 5 (Fig. 1), using daily climate data from 2000 to 2021 (Supplementary Material, Fig. S1), in order to assess their long-term performance, their response to increasing climate variability and their carry-over effect. Continuous modelling was used for all CS. Each crop phase was modelled every year in the period under consideration, as it is done in rotation experiments where all the phases of the rotation are grown every year to compare all of them under the same climatic conditions. The management practices modelled were determined by the stakeholders during the participatory workshops for the RCS and diversified systems (Step 2 & 7, Fig. 1). Among them, tillage, fertilisation and irrigation operations were simulated each year at the same date.

2.3. Multi-dimension assessment

2.3.1. Agronomic assessment

To compare CS productivity, grain yields were standardised in terms of protein and energy. Grain N concentration was simulated by STICS and multiplied by the current conversion factor to protein content in Spain, defined by the regulation UNE-EN ISO 20483 (UNE, 2014) and 16634–1 (UNE, 2009). In line with previous studies, grain energy was the gross energy content of each crop, as obtained from www.feedipedia.com, which was multiplied by grain dry matter (e.g. Simon-Miquel et al., 2023). The annual protein and energy yield of each CS was calculated by averaging all the simulated phases of each rotation for each year. To assess yield stability in the long-term, the adjusted coefficient of variation (aCV), developed by Döring and Reckling (2018) to accounts for the dependence of variance on the mean, was used:

$$\text{Adjusted CV}(\%) \quad = \frac{1}{\mu_i}\left[10^{(2-b)m_i+(b-2)\overline{m}+v_i}\right]^{0.5}\cdot 100\% \tag{4}$$

where i is the crop phase considered, μ the mean, $m_i = \log10(\mu_i)$, $v_i = \log10(\text{variance}_i)$, b is the slope of the linear regression $= a + bm$ and $\overline{m}$ is the mean of all years.

2.3.2. Economic assessment

Mean expenses (Eq. (5)) and incomes (Eq. (7)) were calculated for each crop phase i of the cropping system, dividing the total amount by the number of modelled years n:

$$\text{Expenses(crop phasei)} = \left(\sum_{i=1}^{n=21}(\mathit{tillage} + \mathit{sowing} + \mathit{fertilisation} + \mathit{pest\ control} + \mathit{water} + \mathit{harvest} + \mathit{workforce} + \mathit{insurance})\right) \Big/ n \tag{5}$$

$$\text{Income}(\text{crop phase}_i) \quad = \quad \frac{\sum_{i=1}^{n=21}(\mathit{Grain\ yield} * \mathit{grain\ selling\ price} + \mathit{CAP\ subsidies})}{n} \tag{6}$$

The annual gross margin for each CS was calculated as the difference between the Income and the Expenses. Data was taken from local references when available, when not, national or global data was used. Regional data was used for the seed costs, crop protection products, irrigation water, workforce and insurance for each crop and years modelled (XCAC, 2020). The cost of agricultural machinery use (e.g., tillage, sowing, fertilisation) was calculated using the formula defined by the Spanish Ministry of Agriculture (MAPA, 2014). This price included the depreciation due to wear, tear and obsolescence, the interest, insurance, guards, and maintenance, as well as the fuel consumption and labour. The price of synthetic N fertiliser was set at 0.98€ kg N^{-1}, i.e. the average annual price paid by Spanish farmers between 2000 and 2021 (MAPA, 2021a). Income from grain sales was calculated for each year by applying the price at which grain was sold for the respective year in Spain (MAPA, 2021a) (Eq. (7)). CAP (Common Agricultural Policy) subsidies were estimated for each year during the simulated period, considering a farm of 31.5 ha (average farm acreage in Ebro valley) (MAPA, 2021b). Wheat and barley were judged suitable for baking and malting sale with protein concentration above 11 % and between 10 % and 12.5 %, respectively (Serra et al., 2016; Luo et al., 2019).

2.3.3. Environmental assessment

Three indicators were considered in the environmental assessment: nitrogen, carbon and pesticides. Nitrate leaching, ammonia volatilization, nitrous oxide emissions, and soil N mineralisation values were obtained from the model at the end of each simulated cropping season, for each crop phase, representing cumulative values. Two sources of N mineralisation were identified: crop residues and soil organic matter. The annual variation in soil organic carbon (SOC) content for each CS was calculated as the difference between the content at the end and the beginning of the modelled period, divided by the number of years. Pest control strategies (i.e., pesticide use and dose of active ingredient) were defined by the stakeholders during the co-design stage (step 2 and 7, Fig. 1). Stakeholders suggested a different strategy for each decade modelled (2000–2010 and 2011–2021), to consider any changes in the dose of products used as a result of diversification over the long term. The Treatment Frequency index (TFI) was calculated (Lechenet et al., 2014) by dividing the applied dose by the recommended dose (Eq. (7)), over all pesticide applications. The TFI for a crop phase corresponds to its average within the CS it is included. The average TFI for each CS was calculated by weighting the values of each crop phase within it. The standard dose for each active ingredient was taken from the Spanish register of phytosanitary products (MAPA, 2023).

$$\mathit{TFI}(\mathit{crop\ phase}_i) = \sum\nolimits_P \mathit{Applied\ Dose}_P \Big/ \mathit{Recomanded\ Dose}_P \tag{7}$$

where P is the index of pesticide product.

2.3.4. Co-assessment of cropping systems performance

During the 2nd workshop, the stakeholders rated the importance of each criterion from one (minimum importance) to five (maximum importance) and gave relative importance (%) to the agronomic, socio-economic, and environmental dimension (Step 6, Fig. 1). The functioning of STICS soil-crop model was explained to stakeholders, mentioning the processes modelled, the variables of inputs, of outputs and the ones which cannot be modelled. Then, researchers presented the performance of the CS previously designed in the 1st workshop (i.e., RCS and DCS). A collective discussion summarized the strengths and weaknesses of the CS considered. This led to step 7 (Fig. 1), during which the design of previous DCS could be improved and new CS could be designed. All systems were then modelled by the researchers (Step 8, Fig. 1).

2.3.5. *Statistical analysis*

All statistical analysis was conducted using JMP Pro 17 (SAS Institute Inc, 2019). One analysis compared the average energy and protein production of each cropping systems (CS), with *CS* as the main factor. Another analysis compared the grain yield and grain N content of each crop species within the different CS: CS was the main factor, when a crop was included several times within a single CS, thus having different preceding crops, an additional factor, *Pre-crop*, was introduced and nested within the CS factor. The number of years (i.e., 21 years) acted as the pseudo-replication and was considered as the block. Tukey's HSD test was used for the mean separation when an effect was statistically significant (p-value <0.05).

3. Results

3.1. *Participatory approach*

3.1.1. *Co-designed systems*

The RCS in Ebro valley defined during the 1st workshop was a 2-year rotation of winter wheat (*Triticum aestivum* L.), and barley (*Hordeum vulgare* L.) (Fig. 2). It included a pre-sowing application of 85 kg N ha^{-1} of pig slurry in early October, a top-dressing N fertilisation with urea-ammonium nitrate (UAN) of 85 kg N ha^{-1} in early February, and another with UAN of 40 kg N ha^{-1} early April (Fig. 2). The RCS involved intensive tillage consisting of one subsoiler pass at 45 cm depth and one chisel pass right after pre-sowing fertilisation at 15 cm depth for slurry incorporation (Fig. 2). Surface irrigation was considered with three irrigation events of 100 mm each applied per cropping season, at the end of March, April, and May. The stakeholders designed DCS during the 1st workshops (Step 2, Fig. 1), based on the introduction of winter pea (*Pisum sativum* L.) or rapeseed (*Brassica napus* L.), in 4-year rotations: wheat-pea-wheat-barley (DCS1) and wheat-rapeseed-wheat-barley (DCS2) (Fig. 2). During the 2nd workshop (Step 7, Fig. 1) stakeholders designed HDCS introducing both species in 4-year rotations: wheat-pea-barley-rapeseed (HDCS1) and wheat-rapeseed-barley-pea (HDCS2) (Fig. 2). Another objective was to maximize the use of pig slurry in order to decrease the reliance on synthetic N and, if feasible, to lower the overall N input (-21 % in CS including pea) without compromising yields. All diversified CS maintained the pre-sowing fertilisation (in early September in the case of rapeseed, and early October for the rest of the crops) with pig slurry at 85 kg N ha^{-1} (Fig. 2). The 1st top dress fertilisation (February) at 85 kg N ha^{-1} in DCS and HDCS was done with pig slurry for cereals and was removed for pea. For rapeseed, this 1st top dress fertilisation was done with UAN in DCS2 and with pig slurry in HDCS1 and HDCS2 (Fig. 2). The 2nd top dress fertilisation was avoided for pea and for cereals preceded by pea, while for the rest of the crops it consisted of 40 kg N ha^{-1} of UAN (Fig. 2). The composition of the pig slurry considered was derived from a previous study in the same area (Plaza-Bonilla et al., 2014). The last objective was to reduce tillage intensity (number of passes and working depth) by considering only one cultivator pass at 10 cm depth for both DCS and HDCS (Fig. 2), always done the day of pre-sowing fertilisation with slurry. Irrigation practices remained unchanged in the DCS and HDCS. For all CS, crop residues were left on the plots after harvesting and were then incorporated into the soil at 10 cm depth when tillage was performed (Fig. 2).

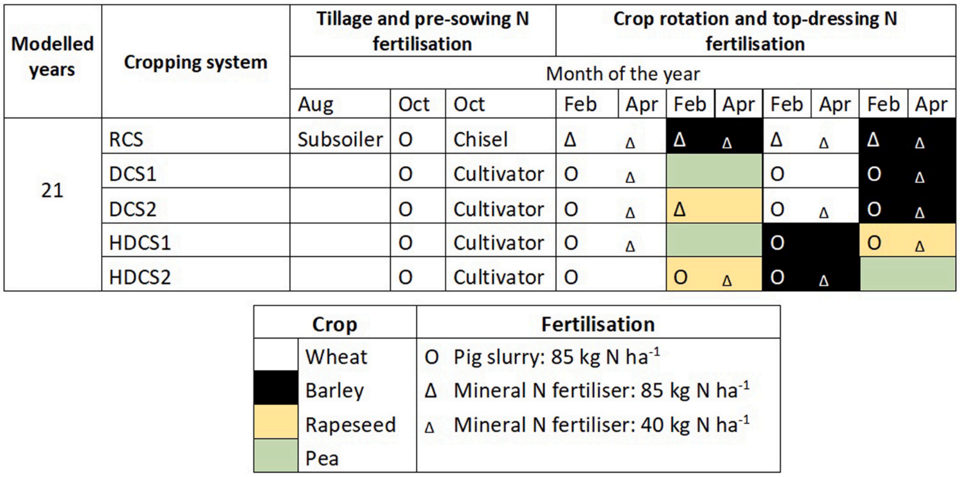
Stakeholders considered that the cereals were always sold to feed industry in RCS, whilst in DCS and HDCS the shift in fertilisation and crop species would increase the grain protein content of cereals. This increase would made the cereals more suitable for sale to the brewing or baking industry, each of which should bring a higher selling price than the feed industry.

3.1.2. *Assessment criteria*

For stakeholders, the most important dimension of farming systems was the socio-economic one with a relative importance of 44 %, followed by the agronomic dimension (37 %) and lastly the environmental dimension (19 %) (Fig. 3). The criteria defined by the stakeholders at the first workshop to assess CS performance (Step 3, Fig. 1) are shown in Fig. 3, along with the importance they attached to them. Farming profit was the first criterion of interest (rated 4.9 out of 5), followed by grain yield (4.3), yield stability (4.1), pest control (4.1), and soil organic matter (4.0) (Fig. 3).

3.2. *STICS calibration and evaluation*

A particular attention was paid to the adequacy of simulations for the variables linked to the criteria most important to stakeholders such as grain yield, grain protein content and aboveground biomass (Fig. 3). The EF for these variables was 0.81, 0.66 and 0.47, respectively, within the evaluation data set (Fig. 4). These values fall within the range of EF considered acceptable in other studies (e.g. Coucheney et al., 2015). Simulation of grain yield, led to a rRMSE ranging between excellent (7 %) to fair (23 %) in the evaluation dataset (Table 1). The parameters calibrated for the 4 species included in the co-design are presented in Table S2. The values assigned to each parameter after calibration with the software package OptimiSTICS are presented in Table S3.



Modelled years	Cropping system	Tillage and pre-sowing N fertilisation			Crop rotation and top-dressing N fertilisation							
		Month of the year										
		Aug	Oct	Oct	Feb	Apr	Feb	Apr	Feb	Apr	Feb	Apr
21	RCS	Subsoiler	O	Chisel	⬜ Δ	⬜ ▵	⬛ Δ	⬛ ▵	⬜ Δ	⬜ ▵	⬛ Δ	⬛ ▵
	DCS1		O	Cultivator	⬜ O	⬜ ▵	🟩	🟩	⬜ O	⬜	⬛ O	⬛ ▵
	DCS2		O	Cultivator	⬜ O	⬜ ▵	🟨 Δ	🟨	⬜ O	⬜ ▵	⬛ O	⬛ ▵
	HDCS1		O	Cultivator	⬜ O	⬜ ▵	🟩	🟩	⬛ O	⬛	🟨 O	🟨 ▵
	HDCS2		O	Cultivator	⬜ O	⬜	🟨 O	🟨 ▵	⬛ O	⬛ ▵	🟩	🟩

Crop		Fertilisation
⬜	Wheat	O Pig slurry: 85 kg N ha^{-1}
⬛	Barley	Δ Mineral N fertiliser: 85 kg N ha^{-1}
🟨	Rapeseed	▵ Mineral N fertiliser: 40 kg N ha^{-1}
🟩	Pea	

Fig. 2. Description of co-designed cropping systems during the participatory workshops. RCS: Reference cropping system; DCS1: Diversified cropping system 1; DCS2: Diversified cropping system 2; HDCS1: Highly diversified cropping system 1; HDCS2: Highly diversified cropping system 2.

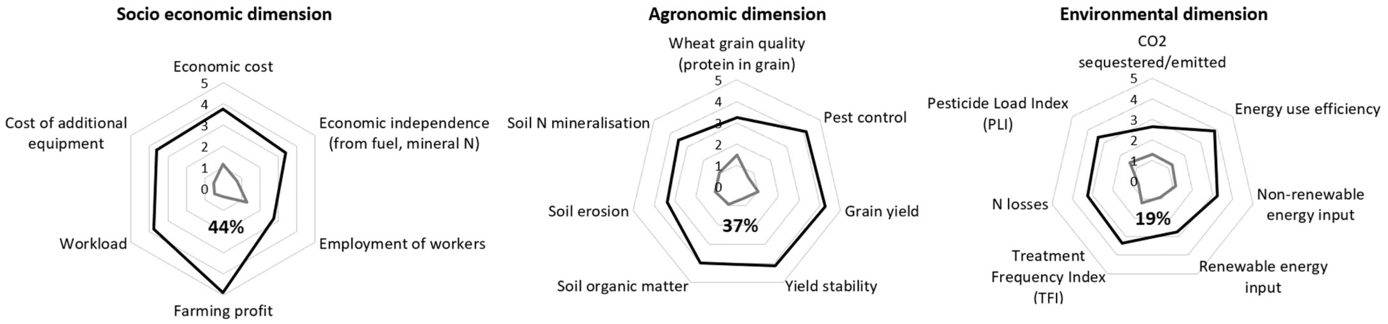


Fig. 3. Relative importance given to each dimension of farming production (in percentage), as well as on each criterion included in these dimensions for the assessment of cropping system performance, ranked by stakeholders during the second participatory workshop. Each stakeholder voted individually. The bold black line and percentage values represent the average of votes (n=10). The grey bold line in the center represents the standard deviation.

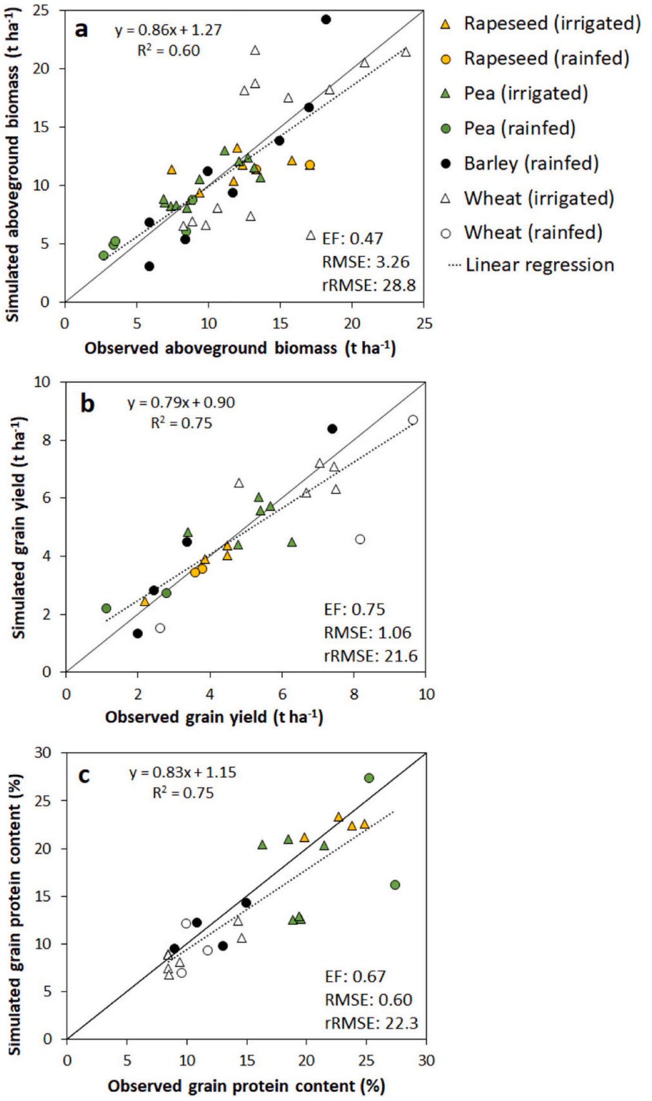


Fig. 4. Observed vs. simulated (evaluation data set) aboveground biomass a), grain yield b), and grain protein content c) for the 4 crops modelled. The black line is the 1:1 line. The dotted line represents the linear regression between observed and simulated values. EF: Model efficiency; RMSE: Root Mean Square Error; rRMSE: Relative Root Mean Square Error.

3.3. Agronomic performance of cropping systems

3.3.1. Simulated grain yield and its stability

According to the simulations, wheat grain yield was 7.3 t ha^{-1} yr^{-1} in the RCS and it was not significantly different in DCS, and HDCS. However, when wheat was preceded by rapeseed in HDCS1, its yield was significantly lower (6.90 t ha^{-1} yr^{-1}) than when it was preceded by pea and rapeseed in DCS1 and DCS2 (7.3 t ha^{-1} yr^{-1}) (Fig. 5). Mean barley simulated yield was of 6.8 t ha^{-1} yr^{-1} in RCS and wasn't significantly different in the other scenarios. However, yield was significantly higher in HDCS1 (i.e. where preceded by pea) than in DCS1 and DCS2 (preceded by wheat), and HDCS2 (preceded by rapeseed) with 7.5, 6.1, 6.2 and 6.3 t ha^{-1} yr^{-1}, respectively ($p<0.0001$, Fig. 5). Pea simulated yield was significantly higher in DCS1 (4.9 t ha^{-1} yr^{-1}) compared to HDCS1–2 (4.6 t ha^{-1} yr^{-1}) ($p=0.001$, Fig. 5). Rapeseed yielded significantly more in DCS2 than in HDCS, and in HDC2 significantly more than in HDCS1 with 3.1, 2.8 and 2.6 t ha^{-1} yr^{-1}, respectively ($p<0.0001$, Fig. 5).

A trend of higher barley grain yield stability was observed when cropped after pea and rapeseed in both HDCS (aCV=15 %) compared to preceded by wheat (RCS, DCS1 and DCS2) (aCV of 27 %, 25 % and 25 %, respectively). Wheat grain yield stability was only marginally affected by CS or preceding crop with aCV ranging from 10 % (when cropped after barley in both DCS) to 15 % (when cropped after pea in DCS1). Pea presented the most unstable yield with aCV of 26 %, 25 % and 24 % in DCS1, HDCS1 and HDCS2, respectively. Pea also experienced the highest water stress during the crop cycle, and within the highest nitrogen stress during the leaf senescence period. Conversely, rapeseed tended to have the most stable yields, with aCV of 12 % in HDCS1 and 13 % in both DCS2 and HDCS2. Rapeseed experienced the lowest water stress in the CS where it was included.

3.3.2. Simulated protein and energy yields

Introducing pea or rapeseed once in a 4-yr rotation (DCS) significantly decreased energy productivity per unit of surface by 10 % and 9 % for DCS1 and DCS2, respectively, compared to RCS. Introducing both crops in the rotation decreased even more energy productivity: by 18 % in HDCS1 and 21 % in HDCS2 (Fig. 6a). Diversification maintained similar protein yield compared to RCS. However, DCS1 protein yield was the highest (763 kg ha^{-1} year^{-1}) and significantly higher than HDCS1 which had the lowest value (717 kg ha^{-1} year^{-1}) (Fig. 6b).

3.3.3. Simulated cereals grain protein content

The simulation results showed a significant increase in wheat grain protein content with diversification. The average wheat grain protein content in RCS for the period simulated was 9.3 %, which was lower than the wheat cropped after pea in DCS1 and HDCS2, and also lower than the wheat cropped after rapeseed in DCS2, with 11.3 %, 10.2 %, and 10.1 % respectively ($p<0.0001$). At the CS scale, this would warrant

Table 1
Characteristics of calibration and evaluation data sets for each of the modelled crops, (n: number of pairs of observed and simulated data). EF: Model efficiency; rRMSE: Relative Root Mean Square Error. Rating refers to rRMSE values.

Crop	Water availability conditions	Dataset considered	Site-year	n	Grain yield		
					EF	rRMSE	Rating
Wheat	Irrigated & rainfed	Calibration	9	156	0.39	18	Good
		Evaluation	9	160	0.38	23	Fair
Barley	Rainfed	Calibration	4	50	0.96	13	Good
		Evaluation	4	50	0.85	22	Fair
Rapeseed	Irrigated & rainfed	Calibration	6	77	0.40	21	Fair
		Evaluation	6	114	0.90	7	Excellent
Pea	Irrigated & rainfed	Calibration	9	164	0.77	19	Good
		Evaluation	9	189	0.67	22	Fair

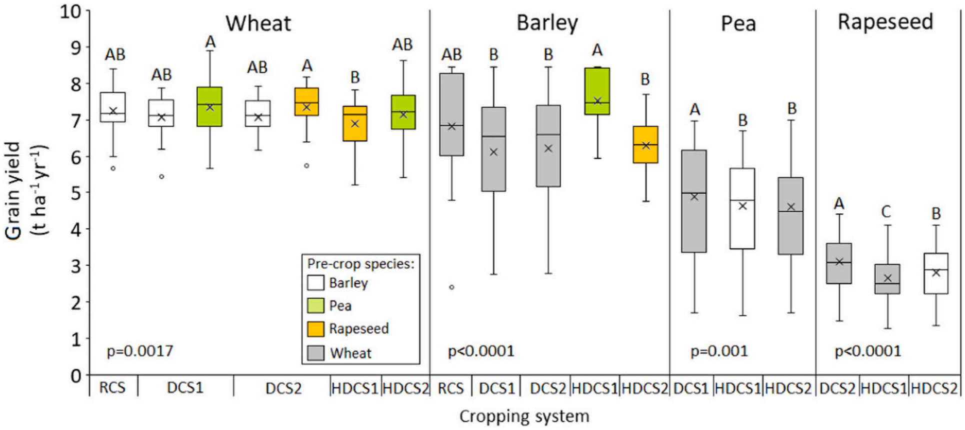


Fig. 5. Simulated grain yield (0 % moisture), within each cropping system assessed (RCS: Reference cropping system; DCS1: Diversified cropping system 1; DCS2: Diversified cropping system 2; HDCS1: Highly diversified cropping system 1; HDCS2: Highly diversified cropping system 2) depending on the preceding crop. Boxes indicate the lower and upper quartiles. Whiskers indicate the most extreme data point which is no more than 1.5 times the interquartile range from the box, and the outlier dots are the observations that are beyond that range. The crosses indicate the mean. Levels not connected by the same letter are significantly different at the p value* indicated.

selling wheat to the bread industry in 9, 6, 1 and 9 cropping seasons out of 21 in DCS1, DCS2, HDCS1 and HDCS2, respectively, whilst it would have been possible in 5 in RCS. Simulated barley grain protein content was maintained at the RCS level with diversification (p=0.46), with an average value of 11.2 % for all systems.

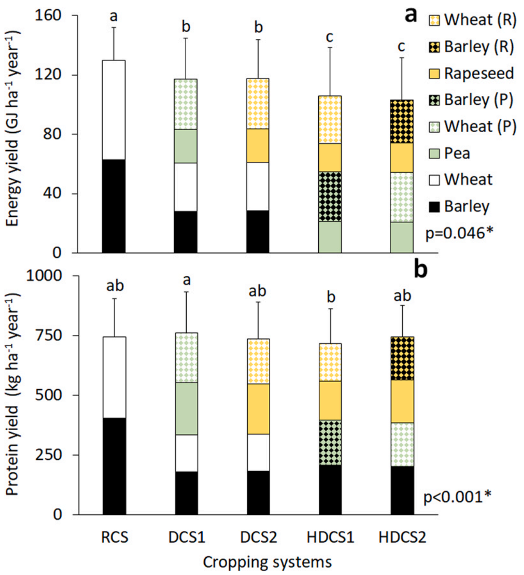


Fig. 6. Annual energy a) and protein b) yield modelled for each cropping system assessed (RCS: Reference cropping system; DCS1: Diversified cropping system 1; DCS2: Diversified cropping system 2; HDCS1: Highly diversified cropping system 1; HDCS2: Highly diversified cropping system 2). Upper case letters between brackets refer to the precedent crop: (R) rapeseed, (P) pea. Levels not connected by the same letter are significantly different at the p value* indicated. The value for each cropping system is the average of the crop phases it comprises.

3.4. *Environmental results*

3.4.1. *Pesticides used: Treatment Frequency Index*

Among the 20 criteria rated, pest control was the 3rd most important for stakeholders (on par with yield stability), with a score of 4.1 (Fig. 3). Stakeholders designed crop protection strategies tailored to each crop species within their specific CS, choosing chemical control (Fig. 7a). On average, cereals were the crops with the lowest TFI, compared to pea and rapeseed (Fig. 7a). Stakeholders considered that, in the long run, RCS could result in weed resistance. Therefore, they suggested an increased herbicide dose: TFI of 3.0 for the first decade, of 3.5 for the second decade (average TFI=3.25 for the period, Fig. 7a). Conversely, cereals preceded by pea in DCS and HDCS, could face a lower weed presence, which would avoid the application of pre-emergent herbicide (TFI=2). This would lead to a stable long-term pesticide use for DCS1, DCS2, HDCS1 and HDCS2, with average TFI of 2.9, 3.8, 3.7 and 3.7 respectively, whereas RCS would rely on an increased pesticide use with an average TFI of 3.25 (Fig. 7b).

3.4.2. *Simulated soil organic carbon, N mineralisation and N losses*

According to model simulation, annual SOC content variation was higher in RCS, compared to DCS2, DCS1, HDCS1 and HDCS2 with on average +216, +67, +50, +3 and −28 kg C ha^{-1} yr^{-1}, respectively. The

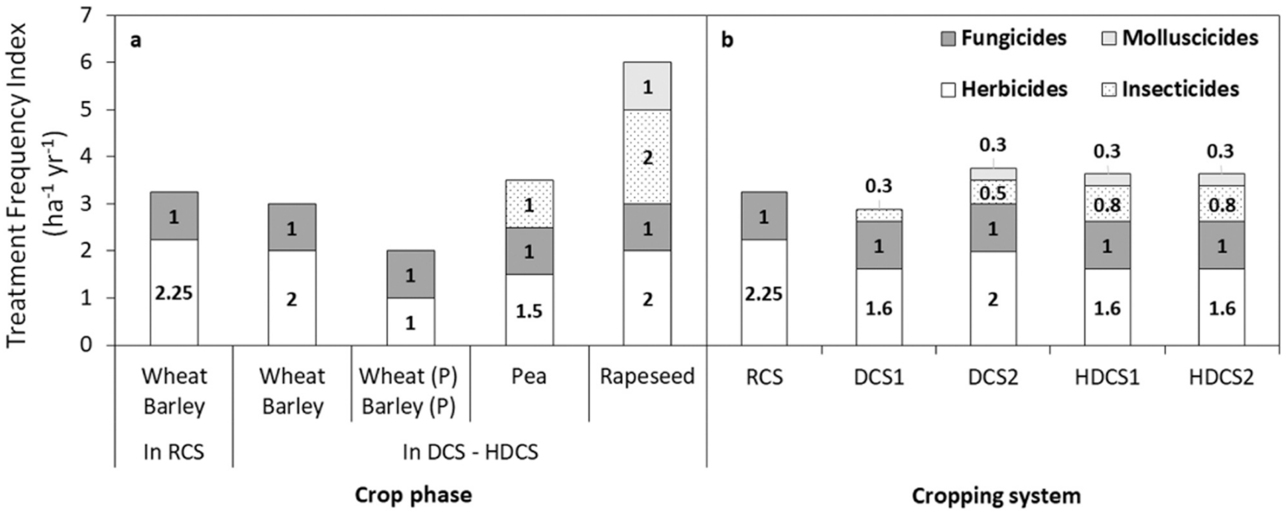


Fig. 7. Treatment Frequency Index (TFI) for each crop phase a), and for each cropping system assessed b) (RCS: Reference cropping system; DCS1: Diversified cropping system 1; DCS2: Diversified cropping system 2; HDCS1: Highly diversified cropping system 1; HDCS2: Highly diversified cropping system 2). The value for each crop phase is the average over the period 2000–2021. The value for each cropping system is the average of the crop phases it includes. Values show the partial TFI for each pesticide group. Upper case letters between parenthesis refer to the precedent crop: (P) pea.

change in SOC was correlated with N immobilisation from crop residues, which tended to be higher in RCS and DCS2, followed by DCS1, HDCS1, and HDCS2 with respectively −80, −75, −56, −55, and −53 kg N ha^{-1} yr^{-1} (Table S4). Cereals following pea presented much lower N immobilisation from crop residues in DCS1, HDCS1 and HDCS2 (−1, −12 and −9 kg N ha^{-1} yr^{-1}, respectively), compared to RCS (−80 kg N ha^{-1} yr^{-1}). The N mineralised from organic matter was of 135, 122, 137 and 138 kg N ha^{-1} yr^{-1} in RCS, DCS1–2, HDCS1 and HDCS1, respectively (Table S4). A trend for higher released of N during and after pea and sometimes after rapeseed compared to after cereals was observed. As a result, net N mineralisation tended to be lower in DCS2, RCS and DCS1 than in HDCS1 and HDCS2, with values of 47, 55, 66, 83 and 84 kg N ha^{-1} yr^{-1}, respectively (Fig. 8a), with a greater variability in DCS and HDCS crop sequences.

Soil N losses were higher in DCS and HDCS, compared to RCS, in particular ammonia volatilisation and nitrate N leaching. Ammonia volatilisation was highest in HDCS2 and HDCS1, followed by DCS2, DCS1, and RCS with on average 77, 69, 58, 52 and 32 kg NH_3-N ha^{-1} yr^{-1} volatilised, respectively. This increase was linked with the higher proportion of slurry fertilisation in DCS and HDCS compared to RCS. In RCS, 210 kg N ha^{-1} yr^{-1} of fertiliser were applied, including 125 from UAN and 85 kg N ha^{-1} yr^{-1} from pig slurry, from which 24 and 8 kg N ha^{-1} yr^{-1} were volatilised, respectively. In HDCS2, 169 kg N ha^{-1} yr^{-1} of fertiliser were applied, including 20 from UAN and 149 kg N ha^{-1} yr^{-1} from pig slurry, from which 4 and 74 kg N ha^{-1} yr^{-1} were volatilised, respectively. Nitrate leaching for each cropping system ranged from 37 to 48 kg NO_3^--N ha^{-1} yr^{-1} in HDCS2 and DCS1, respectively. However, discrepancies were found between the crop phases of DCS and HDCS, with the highest amount of N leached for cereals preceded by pea, followed by those preceded by rapeseed and finally those preceded by cereals: on average 84, 50, and 38 kg NO_3^--N ha^{-1} yr^{-1} were leached, respectively (Fig. 8b). The lowest N leaching modelled took place during the rapeseed crop phase, averaging 15±2.4 kg NO_3^--N ha^{-1} yr^{-1}. On the other hand, the average N leached for RCS was of 39 kg N ha^{-1} yr^{-1} (i.e., cereal cropped after cereal).

Simulated N_2O emissions showed a trend towards higher emissions in RCS, followed by DCS2, DCS1, HDCS1 and HDCS2, with averages of 0.90, 0.83, 0.81, 0.77 and 0.74 kg N_2O-N ha^{-1} yr^{-1}, respectively (Fig. 8c). Nitrification was responsible for 70 % of these emissions. These emissions corresponded to 0.42–0.46 % of the total N fertiliser applied (Hergoualc'h et al., 2019). Components of the N balance inputs, outputs and mineralisation of N for each cropping system are presented in Table S4.

3.5. Calculated economic performance: expenses, income, and gross margin

The highest expenses were quantified in RCS, followed by DCS2, HDCS1, HDCS2 and DCS1 with respectively: 445, 356, 313, 312, 304 € ha^{-1} yr^{-1} (Fig. 9). The decrease in expenses in diversified systems was mainly linked to a reduced reliance on synthetic N fertiliser and a decrease in tillage frequency and depth, which were responsible of 68 % and 19 % of the decrease in DCS1, respectively, compared with RCS (Fig. 9). Soil tillage represented 48€ ha^{-1} yr^{-1} in RCS and 10€ ha^{-1} yr^{-1} in all DCS and HDCS. Among all crop phases, barley preceded by pea in HDCS1 had the lowest expenses (247€ ha^{-1} yr^{-1}), whilst wheat preceded by barley in RCS had the highest (463€ ha^{-1} yr^{-1}). Among DCS and HDCS, rapeseed in DCS2 showed the highest expenses (408€ ha^{-1} yr^{-1}) mainly linked to pest control, which accounted for 101€ ha^{-1} yr^{-1}. In the RCS, pest control costs for wheat and barley were 84 and 72€ ha^{-1} yr^{-1}, respectively, whilst it dropped to 51 and 44€ ha^{-1} yr^{-1} when preceded by pea in DCS and HDCS, due to reduced herbicide use. As results, expenses decreased by 31 % in DCS1 and both HDCS and by 21 % in DCS2 compared to RCS.

The highest incomes were earned for RCS, followed by DCS1, DCS2, HDCS1 and HDCS2 with respectively 1468, 1448, 1396, 1336 and 1300€ ha^{-1} yr^{-1} (Fig. 9). Among the different species studied, wheat led to higher income in all CS except in HDCS1, where barley preceded by pea presented the highest income. The difference in the selling price for wheat and barley sold for feed or human consumption was negligible (184.6 vs. 185.4 € t^{-1} and 165.3 vs. 174.7 € t^{-1}, respectively), and resulted in income increases for barley only (+4 %). Pea and rapeseed showed higher income in DCS (+5 % and 9 %, respectively) compared to the crop sequence in HDCS. Diversification allowed for higher subsidies beginning from 2015, with the introduction of CAP's greening measures. At the CS level, higher income due to CAP subsidies were observed in HDCS, followed by DCS1, DCS2 and RCS with 254, 251, 232 and 229€ ha^{-1} yr^{-1}, respectively (Fig. 9). As a result, the gross margin increased with diversification in DCS1 and DCS2, with 1145 and 1041 € ha^{-1} yr^{-1}, corresponding to an increase of 12 % and 2 %, respectively, compared to RCS (1023 € ha^{-1} yr^{-1}) (Fig. 9). Whereas in HDCS1, gross margin was similar to RCS, and in HDCS2 gross margin decreased by 3 % (988 € ha^{-1} yr^{-1}). Detailed economic data are presented in Supplementary material (Table S5).

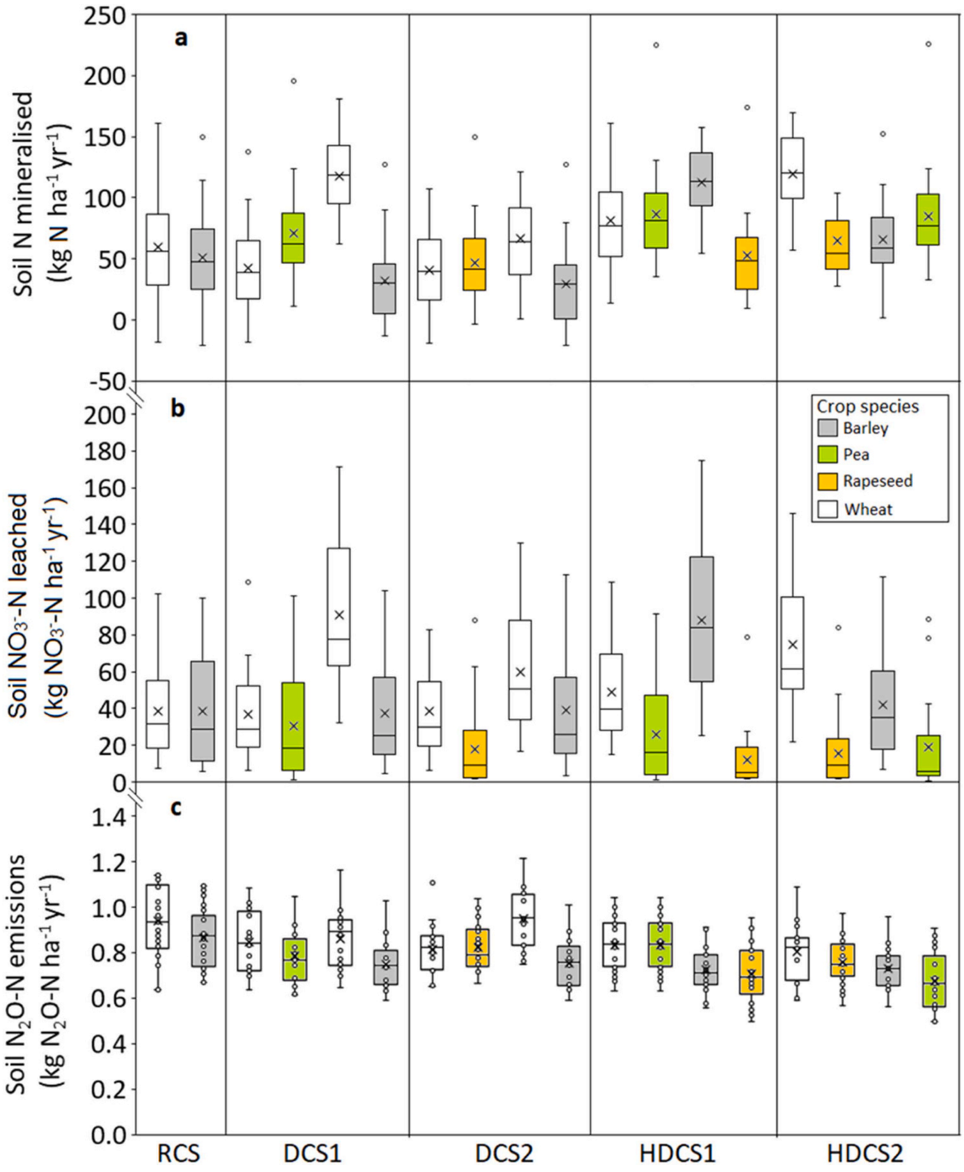


Fig. 8. Simulated soil net N mineralised a), nitrate N leached b) and N_2O-N emissions c) for each crop sequence in each cropping system assessed (RCS: Reference cropping system; DCS1: Diversified cropping system 1; DCS2: Diversified cropping system 2; HDCS1: Highly diversified cropping system 1; HDCS2: Highly diversified cropping system 2). For each cropping system, the average values for each of its crop phases are show. Boxes indicate the lower and upper quartiles. Whiskers indicate the most extreme data point which is no more than 1.5 times the interquartile range from the box, and the outlier dots are the observations that are beyond that range. The crosses indicate the mean.

4. Discussion

4.1. Model calibration and evaluation

Modelling is an efficient tool for assessing numerous parameters that would be costly and time-consuming to measure in the field. However, perfect calibration for all modelled variables is unfeasible due to the extensive amount of data required, the exhaustive measurement of which would render the modelling pointless. In this study, having access to a dataset on crop aboveground biomass under different pedoclimatic conditions over several years and various crop management conditions (i.e., several N fertilisation rates, in rainfed and irrigated systems) allowed for a reliable calibration and validation of the crop-related parameters, as evidenced by the statistical criteria presented. The model was used as an ex-ante tool to evaluate diversification. Consequently, limited data were available for evaluating soil processes, and no direct measurement data were available for gas emissions in these specific scenarios. However, STICS soil-crop model has been shown to be effective in modelling soil processes and gas emissions in Mediterranean climate. Here, we found values for soil gas emissions and nitrogen losses in line with previous results (Kherif et al., 2022; Plaza-Bonilla et al., 2017, 2018). This further confirms the reliability of STICS for evaluating the different cropping systems co-designed in the present study.

4.2. Agronomic performance

Simulated wheat and barley grain yields remained stable with diversification compared to RCS. This contrasts with the average 8.5 % yield increases reported globally when wheat is cropped after a break crop (e.g. Angus et al., 2015). The underestimation could be explained by the fact that STICS, as many soil-crop models, does not simulate all the processes that contribute to yield increases in crop rotations, such as: 1) increased soil porosity and water retention, 2) increased soil P availability following legume crops, 3) reduced weed seedbank through

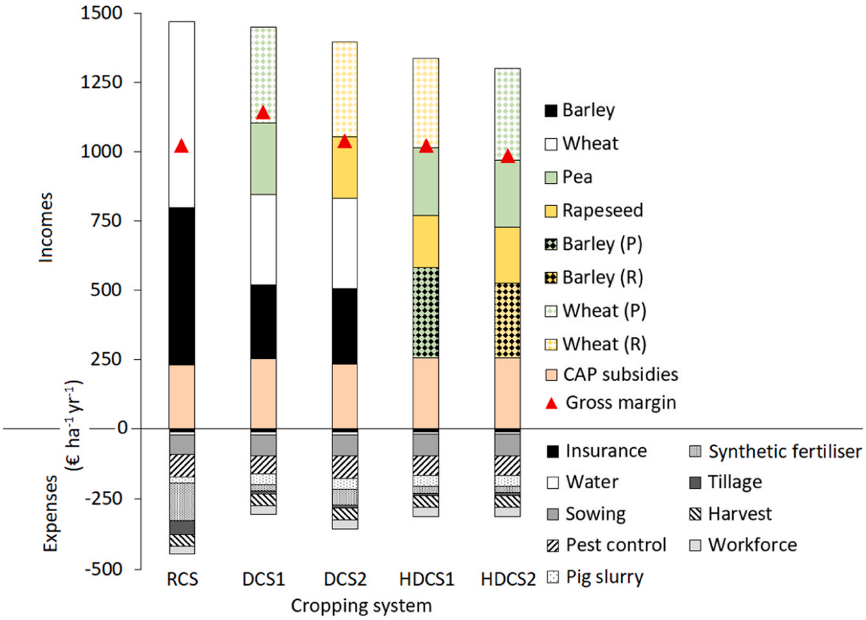


Fig. 9. Incomes, expenses, and gross margin for each of the cropping systems assessed (RCS: Reference cropping system; DCS1: Diversified cropping system 1; DCS2: Diversified cropping system 2; HDCS1: Highly diversified cropping system 1; HDCS2: Highly diversified cropping system 2). The value for each cropping system is the average of the crop phases. Letters between brackets show precedent crop: (P) pea, and (R) rapeseed.

diverse weed control strategies, 4) enhanced biological processes, including bacterial populations and soil micro-organisms stimulated by legume H_2 release, and 5) secretion of allelopathic compounds. These processes are complex and site-specific, making them difficult to model accurately (Bennett et al., 2012). Despite the potential underestimation of the break crop effect, yields remained similar across scenarios, even with reduced N fertilisation by 20 % in HDCS and DCS1, and by 5 % in DCS2 compared to RCS. This suggests higher N use efficiency in diversified scenarios, achieving comparable cereal yields with lower N inputs. The absence of an increase in cereal grain yield after one year of a break crop aligns with observation in the study area (Nascimento et al., 2023). This could be explained by the high soil fertility in the studied area, where soil organic matter exceeds 2 % in both studies, which is higher than the average values in the Mediterranean region, generally below 2 % (Ferreira et al., 2022). Additionally, the application of N fertilisation in all CS contributes to maintain sufficient levels of soil N, preventing N deficiency from impacting yields. Indeed, yield increase observed with rotation are greater in low-fertility context compared to high-yield potential environments, a trend observed globally (Zhao et al., 2022), and in the studied area (Simon-Miquel et al., 2024).

Yield stability increased only for barley when diversifying. It was observed when cropped after pea and rapeseed (HDCS) compared to wheat, and was linked to higher soil N and water content at sowing. The mean aCV of 25 % for pea and 12 % for wheat were in agreement with empirical studies (Reckling et al., 2018; Chloupek et al., 2004). Rapeseed presented a high stability (aCV 12 %), pointing out the potential for this crop under irrigated conditions in the Mediterranean, probably related to its long flowering period (1–2 months). The fact that the break crop effects may have been underestimated by modelling in our study, could explain the small increase observed in yield stability when diversifying crop rotations. Indeed, it has been demonstrated that a greater crop diversity stabilises yields at the rotation scale, particularly in semi-arid conditions (St. Luce et al., 2020).

Energy yields decreased when pea and rapeseed were introduced in the 4-year rotations as they presented lower energy yields compared to cereals. The decrease was even higher when both crops were introduced in the 4-year rotation (-19 %, HDCS), compared to when only one crop was introduced (-10 % in DCS). This result aligns with empirical results in semiarid Mediterranean irrigated conditions (Simon-Miquel et al., 2023) and with the modelling of diverse rotations across Europe (Costa et al., 2021). Indeed, a lower presence of these crops in the rotation is recommended to maintain an energy yield similar to that of the RCS, while reducing N fertilisation, as previously observed in Spain (Nemecek et al., 2008).

An increase in the protein content of wheat grains was observed with diversification strategies, specifically when cropped after pea and rapeseed, which increased N availability at the whole rotation scale and particularly for subsequent crops (Fig. 8a). This was observed in previous studies, where the pulses' pre-crop on subsequent cereal were linked to higher N supply from crop residues (e.g. Wright, 1990). For rapeseed, this may be attributed to the lower N losses modelled, which are likely due to its root system's ability to explore deeper or wider soil areas compared to cereals (Wong et al., 2023). This could explain the higher N availability for the succeeding cereal, as observed by Harris et al., (2002). At the CS level, this resulted in maintaining stable protein yield in the diversified systems, despite lower N inputs compared to RCS. This finding contrasts with Costa et al. (2021), who reported increased protein production in legume rotations at a lower environmental cost. In our study, protein production was maintained stable with reduced synthetic N and total N inputs, demonstrating higher efficiency when diversifying rotations with pea and rapeseed. These aspects are essential for reducing the environmental damage associated with the use of synthetic N (Menegat et al., 2022), as well as for reducing Europe's dependence on imported protein sources (Simon-Miquel et al., 2023).

4.3. Environmental performance

Continuous cereal cropping (RCS) demonstrated the highest increases in SOC storage due to the higher quantities of crop residues incorporated, thereby enhancing long-term soil fertility by 5 % over 21 years. This was followed by DCS2 and DCS1, which showed a quarter of the SOC increase of RCS. HDCS1–2 did not show any SOC storage, which pose a risk for soil fertility improvement in the Mediterranean. These findings align with Bonciarelli et al. (2016), who observed higher SOC content in continuous cereals CS compared to rotations including legumes in Mediterranean conditions. Conversely, DCS2 and the RCS exhibited lower N mineralisation ($\leq$50 kg N ha^{-1} yr^{-1}) compared to DCS1 and HDCS1–2 ($>$ 60 kg N ha^{-1} yr^{-1}). This is attributed to the easier mineralisation of pea crop residues, which have a lower C/N ratio and are not included in RCS and DCS2. These findings are consistent with the idea that CS can either increase SOC storage or enhance N availability, but achieving both simultaneously is challenging (Janzen, 2006). This echoes the fact that farming systems are all about compromise, and that win-win scenarios are hard to achieve.

The higher N availability in DCS1 and HDCS resulted in higher N losses. The increase in NH_3 volatilisation simulated in the DCS and HDCS (30 % and 43 % of the total applied N, respectively) compared to RCS (15 %) was firstly related to the shift from using synthetic N sources (UAN) to slurry for N fertilisation, given its much higher ammonium concentration, which is easily transformed to ammonia. Secondly, the slurry applied as top dressing in early February in DCS and HDCS would not be incorporated with tillage, as crops would already be developed, whereas in RCS, the only slurry application made at pre-sowing was incorporated with tillage. It is well known that incorporating slurry considerably reduces N volatilization through ammonia (Sommer and Ersbøll, 1994), explaining the lower emissions simulated in RCS. However, it is also known that incorporating slurry increases denitrification (Webb et al., 2010), and therefore potential N_2O and N_2 emissions. In this study, the increase in N_2O emissions in RCS was small, ranging from 0.07 to 0.17 kg N ha^{-1} yr^{-1}, compared to DCS2 and HDCS2, respectively (Table S4). The average emission for all systems of 0.44 % ±0.02 % of the total N fertiliser applied, is on the range of the default emission factor recommended by the IPCC for dry climate of 0.50 % (Hergoualc'h et al., 2019). Therefore, the slight increase in N_2O emissions in RCS does not negate the benefits of reducing NH_3 emissions compared to DCS and HDCS. The increase in ammonia volatilisation was also linked to the earlier application of pre-sowing slurry fertilisation in rapeseed compared to other species, creating more favourable conditions for volatilisation (higher air temperature and solar radiation). An effective solution, which can be suggested to reduce ammonia volatilisation whilst remaining faithful to the stakeholders' design (rates and type of fertilisers), may be to apply slurry progressively, via fertigation (Gómez-Garrido et al., 2018), provided that pressurised systems are available.

Nitrate leaching decreased in both DCS and HDCS during the pea and rapeseed crop phases compared to RCS but increased during cereals following them. In HDCS, 45±27 and 81±39 kg NO_3^--N ha^{-1} yr^{-1} were leached on cereals following rapeseed and pea, respectively, while 14 ±19 and 22±26 kg NO_3^--N ha^{-1} yr^{-1} were leached during rapeseed and pea phase (Fig. 8b). In RCS, the average nitrate leaching was 39±28 kg NO_3^--N ha^{-1} yr^{-1}. The shift of N fertilisation from synthetic to slurry did not impact N leaching according to our modelling results. Rapeseed, by being able to explore more soil surface area than cereals (Wong et al., 2023), could retain nutrient, reducing N leaching and leaving more N available for the following crop, as suggested by Harris et al., (2002). The low N leaching modelled for pea is linked to its N fertilisation, which is half or less than half of the other crops. However, its low C/N ratio increases N leaching after its cultivation, aligning with previous research showing asynchrony between N release from grain legume crop residues decomposition and subsequent crops' N uptake (Plaza-Bonilla et al., 2015). In wetter climates cover crops are seen as a lever to significantly reduce nitrate leaching compared to the use of bare fallow between cash crops (Constantin et al., 2010). However, in semiarid areas, low water availability makes the introduction of summer cover crops unfeasible, as this strategy results in a reduction of the grain yield of the following crop (Nielsen and Vigil, 2005), unless irrigation is available.

Stakeholders suggested that DCS and HDCS could enhance pest control, compared to RCS, and subsequently designed strategies considering the crop sequence effect on pesticide use, idea supported by scientific findings (Andert et al., 2016). This resulted in a decrease TFI for herbicides in all diversified systems compared to the reference, in line with empirical observations showing a lesser need for herbicides in diversified rotations (Adeux et al., 2019). However, the total TFI increased in most of the diversified systems compared to the reference: +12 % in both HDCS, +15 % in DCS2 compared to RCS (TFI of 3.25), explained by the higher need of insecticides and molluscicides, for pea and especially rapeseed. Indeed, these crops are more sensitive to pest such as aphids, beetles and slugs than cereals. This corresponds to the actual trend in Europe: in France where TFI was registered yearly from 2001 to 2014, the average values for pea and rapeseed were of 4.5 and 5.8 respectively, compared with a TFI of 3 for cereals (Hossard et al., 2017). The stakeholders co-design resulted in the RCS having the lowest average TFI. However, they predicted that this value would increase over the considered period for RCS, while it would remain stable for the diversified systems. Hence, in the long term, an inversion of this trend could happen, which would be in line with the long-run on-farm observations, showing lower total pesticides use in diversified systems (Andert et al., 2016). While diversification practices are often beneficial for both ecosystem services and crop yields (Rasmussen et al., 2024), our results concur with those of Tamburini et al. (2020), demonstrating that results are highly context-dependent and that diversification can also give rise to trade-offs.

4.4. *Socio-economic performance*

The long-term viability and profitability of CS are crucial for farmers' continued engagement in agriculture and global food production, as the decline in farm numbers observed in Europe during the last decades is mainly linked to economic issues (Terres et al., 2015). In this study, stakeholders also stressed the vital importance of the economic pillar, and in particular farming profits, the criterion they rated with the highest importance. The increase in gross margins compared to RCS obtained in only 1 out of 4 CS (i.e. +12 % in DCS1) shows that the diversification strategies may not always be a viable way of improving the economic situation of farms. In the other CS, the gross margins variations were negligible (+2 %, 0 % and −3 % for DCS1, HDCS1 and HDCS2, respectively). This aligns with Zabala et al. (2023), who found that most crop diversification strategies across Europe did not significantly change economic results, with few instances of positive changes. Expenses were reduced in all DCS and HDCS, mainly associated with the lower use of synthetic N fertiliser, which was exacerbated, as the cost of synthetic liquid N fertiliser more than doubled between 2000 and 2020 in the studied area, from 0.52 to 1.25 € kg N^{-1} (MAPA, 2021a). Income decreased in DCS2 (-5 %) and even more in HDCS1 and HDCS2 (-9 % and −11 %) compared with RCS. This decrease is attributed to 1) the lower presence of cereals, which are the most profitable crops studied and which also showed, on average, lower yields in these CS compared to RCS, and 2) the lower incomes from rapeseed compared to pea. Wheat, pea and rapeseed yielded less in HDCS compared to DCS, which highlights the economic risk of introducing break crops too frequently into rotations, as they provide lower and less stable yields than cereals, particularly legumes. This is consistent with empirical observations, showing higher yield variability of legumes species compared to winter cereals (Reckling et al., 2018). Several reasons can be given, including their high sensitivity to biotic and abiotic stresses for biological N fixation, the lack of investment in genetic selection in Europe, and a general lack of specific agronomic references to manage them correctly (Cernay et al., 2015). Stakeholders' expectations of income growth through market changes due to increased cereals protein content was negligible (0 % for wheat, 5 % for barley), as well as the impact of CAP subsidies (+11 % maximum, observed for HDCS1–2).

As a result, gross margins increased only in DCS1, compared to the RCS, mainly linked to the decrease in expenses (-31 %), while incomes remained stable (Fig. 9). The increase in gross margins observed only when pea was introduced 1 year out of 4, compared with 2 years of break crops, is in line with a previous study comparing several co-designed CS across Europe. Reckling et al. (2016) reported decreases in gross margins when legumes (grain or forage uses) were included in rotations every two to three years. Shift from synthetic to locally sourced N fertiliser was a key aspect for maintaining a stable profitability despite lower yields in DCS2 and HDCS compared to RCS, as well as the reduction in tillage depth and frequency.

4.5. Participatory approach

The participatory approach was well-received by stakeholders, providing them a platform to share experiences, knowledge, and discuss challenges and potential solutions. The fact that majority of participants returned to the 2nd workshop (10 out of 13) shows their confidence in the process. While stakeholders provided constructive criticism on the modelling outputs, identifying areas for calibration improvement and missing variables, they remained willing to design new HDCS after seeing the performance of RCS and DCS, demonstrating their trust in the model performance. However, stakeholders expressed concerns about the limited applicability of the process, as it may not impact current regulations or market conditions, leaving them feeling powerless. From a research perspective, questions remain about stakeholders' willingness to adopt the co-designed systems, whether the process changed any of their ideas or intentions to change practices, and whether they would engage in a similar process in the future to explore other cropping system designs. These questions should be asked to stakeholders if the process is repeated, to gain more comprehensive feedback, and to continue improving the process.

5. Conclusions

The participatory modelling approach used in this study allowed to find alternatives that enhanced agronomic and in a lesser extent economic performances of CS over the long-term, fulfilling stakeholders' concerns in Mediterranean pedoclimatic conditions. The reference system, a succession of winter cereals ran under intensive tillage and synthetic N fertilisation was compared with stakeholders' co-designed diversified systems including pea and rapeseed once (DCS) or twice (HDCS) in 4-year rotations together with reduced tillage and N fertilisation from slurry.

According to simulations, DCS and HDCS present enhanced agronomic performance, maintaining cereal grain yields and protein yields at a similar level at the whole cropping system scale, despite less N inputs and reduced synthetic N fertilisation. Energy yield decreases with diversification, to a greater extent in HDCS (-20 %) than in DCS (-10 %). Increased gross margins were observed only in the system including once pea in the rotation compared to the reference, phenomenon that was also driven by lower expenses enabled by the reduction of synthetic N fertiliser use and tillage intensity. Surprisingly, diversified systems show contrasted environmental performance metrics: decreased N losses through leaching during pea and rapeseed crop phase but increased in the crop sequence after them compared to the reference. Moreover, higher N volatilisation was simulated and increased pesticides use was predicted in diversified systems compared to continuous cereal. These effects are exacerbated when break crops are introduced twice in the 4-year rotations. The reference system exhibits the highest increase in soil organic carbon with a +5 % change over 21 years. In contrast, DCS shows a smaller increase in SOC (+1.3 %), while HDCS exhibits a slight decrease (-0.3 %). A low intensity of crop diversification should be favoured to mitigate the environmental impacts associated.

CRediT authorship contribution statement

Daniel Plaza-Bonilla: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Laure Hossard:** Conceptualization, Methodology, Resources, Writing – review & editing. **Ferdaous Rezgui:** Data curation, Writing – review & editing. **Genís Simon-Miquel:** Data curation, Investigation, Writing – review & editing. **Jorge Lampurlanés:** Funding acquisition, Project administration, Writing – review & editing. **Louise Blanc:** Conceptualization, Methodology, Software, Visualization, Writing – original draft.

Declaration of Competing Interest

The authors 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 will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127282.

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