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## Resilience of agricultural systems: biodiversity-based systems are stable, while intensified ones are resistant and high-yielding

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### HIGHLIGHTS

- Farming systems are based on a spectrum emphasising biodiversity and ecosystem services to anthropogenic inputs
- Little is known about the resilience levels across this spectrum or the factors that drive them
- We assessed the resilience of 30 highly contrasting cropping agroecosystems in north-eastern France
- Biodiversity-based systems demonstrated stability in yield, gross margin and workload
- Input-based systems had higher performance and resistance to shocks

### GRAPHICAL ABSTRACT

Comparative advantages of agricultural systems in the quest for resilient dynamics												
Agricultural systems ↓	Crop yield ↓			Gross margin €					Workload ↓			
	high level	stability	shock resistance	high level	stability	shock resistance	trend	general resistance	low level	stability	general resistance	
Ecosystem services, biodiversity, organic and natural-capital-based systems	-	+	-	-	+	-	+	+/-	+	+	+/-	
Anthropic-input-based systems	+	-	+	+	-	+	-		-	-	+	

Example: Biodiversity-based agricultural systems have low crop yields but stability in yields.

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### ABSTRACT

**CONTEXT:** New types of farming systems have emerged in response to societal demands to reduce environmental impacts and dependence on non-renewable resources. These agriculture models can be classified according to their relative use of anthropic inputs or biodiversity and associated ecosystem services as agricultural production factors. All these models are exposed to climate change, price volatility and other disturbances. However, little is known about their resilience levels and the factors that drive them.

**OBJECTIVE:** We assessed the resilience of 30 highly contrasted cropping agroecosystems in north-eastern France which covered a broad gradient from simplified and intensified to complex and biodiversity-based agroecosystems.

**METHODS:** We applied a quantitative analysis of the dynamics of three key performances over eight years: yield, gross margin and workload. An original combined set of adapted criteria – level, variability, trend and resistance – was used to assess their dynamics, i.e. their resilience. We use partial least squares regression, multiple regression trees and Pareto ranking to identify relationships among the characteristics and resilience performance of these systems.

**RESULTS AND CONCLUSIONS:** The results showed that biodiversity-based agroecosystems, which provide a high level of ecosystem services to farmers or an increase in natural capital, tended to have stable performances. These systems also had a lower workload than intensified systems. Conversely, input-based systems, especially irrigated

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and tillage-intensive systems, had higher yields and gross margins, were resistant to major disturbances but were less stable.

**SIGNIFICANCE:** While our results show benefits of relying on biodiversity to stabilise system performances, we highlight a potential trade-off between performance level and stability, as well as possible solutions to overcome it. We also discuss the short-term strategy of anthropic input-based systems, which perform well, but consume large amounts of human and natural resources. We show potential advantages of systems that balance both ecosystem services and anthropic inputs to provide a strategy to fill the yield gap and attain resilience.

## 1. Introduction

Many new types of farming systems have emerged in response to societal demands to increase food quality and reduce environmental impacts and dependence on non-renewable resources (Therond et al., 2017). These different “agriculture models” invest in two ways: they optimise the use of anthropic inputs (i.e. fertilisers, pesticides, energy for irrigation and labour) or replace them with ecosystem services provided by the biodiversity (Duru et al., 2015). For example, precision agriculture seeks to optimise the use of anthropic inputs to reduce their harmful effects (Pierce and Nowak, 1999), while biodiversity-based agriculture seeks to base agricultural production on ecosystem services provided to farmers (ESF). In the latter, ESF are considered production factors (Duru et al., 2015) as they counteract limiting factors (e.g. water, nutrients) and reducing factors (e.g. weeds, pests, diseases) (van Ittersum and Rabbinge, 1997). For example, increasing the service of nitrogen provision to crops by the soil can meet crop needs and replace mineral fertilisation. Existing agriculture models can be classified along a gradient representing the relative use of anthropic inputs and ESF for agricultural production: from anthropic input-based to biodiversity-based systems (Therond et al., 2017).

Most agricultural systems are exposed to climate changes, price volatility, pest outbreaks and/or other disturbances. Anthropic input-based systems can address biophysical risks by managing input levels when a disturbance occurs. For example, irrigation is considered a suitable strategy to avoid hydric stress (Zou et al., 2012) exacerbated by climate change (Grillakis, 2019; Konapala et al., 2020). Similarly, chemical insecticides are effective at limiting losses caused by pest outbreaks (Deutsch et al., 2018). However, these systems depend greatly on non-renewable resources (e.g. natural gas, petroleum, phosphorus and potassium) whose reserves are dwindling and becoming more energy-intensive to extract (Pelletier et al., 2011; Wachtmeister et al., 2018). Biodiversity-based systems tend to be freed from scarcity in non-renewable resources through developing and using ESF. They must address the inadequate state of natural capital in most agricultural areas that has resulted from decades of ecosystem simplification and intensive management (Nyström et al., 2019), which drastically reduces ecosystem functioning and the ability to provide ESF (Bommarco et al., 2013; Saha et al., 2017). However, increasing the ecosystem service of the retention and return of soil water to crop species can avoid or delay hydric stress when drought occurs. Similarly, improving conservation biological control could limit crop failure due to pest outbreaks. Consequently, increasing the level and use of ESF and developing the natural capital that supports their supply in the middle term could be a suitable strategy to prevent vulnerability. This could reduce their dependence on non-renewable resources while protecting against the harmful effects of climate change (Munang et al., 2013) and other biophysical risks. Both anthropic input-based and biodiversity-based systems are exposed to volatility in crop prices (Gaetano et al., 2018).

Biophysical and economic disturbances challenge a system’s “ability to ensure provision of system functions” (Meuwissen et al., 2019) (i.e. their resilience). A review of the influence of input intensification on the resilience of crop yield (Dardonville et al., 2020) highlighted that the level and type of fertilisation (Macholdt et al., 2020; Reidsma et al., 2009), irrigation (Reidsma et al., 2009), type of tillage (Gaudin et al., 2015) and the overall intensity of management (Urruty et al., 2017) can

be related to the resilience or vulnerability of yield, depending on the production situation. To date and to our knowledge, no study has addressed relationships between the level of ESF and resilience (Dardonville et al., 2021a; Dardonville et al., 2020). Studies have focused instead on the influence of diversification, a major determinant of ESF levels (Kleijn et al., 2019). A review of the influence of crop diversity on the resilience of yield showed generally positive relationships (Dardonville et al., 2020), in agreement with the “ecological insurance” hypothesis, i.e. diversity provides a greater probability that certain types of individuals (species, genotypes, production types, etc.) will maintain their functioning or level of production in a changing context (Yachi and Loreau, 1999). Farm diversity has a positive influence on yield and dynamics (i.e. resilience), except for specific crops such as rice or soya bean, as observed in several studies (Chavas and Di Falco, 2017; Gaudin et al., 2015; Li et al., 2019a, 2019b; Matsushita et al., 2016; Urruty et al., 2017). Recently, Zampieri et al. (2020) highlighted a potential nonlinear influence of crop diversity, with a threshold of six crops grown on the same farm. Dardonville et al. (2020) highlighted that available information on the influence of crop diversity or intensification is limited to an analysis of yield, which ignores the multifunctionality of agriculture (Hodobod et al., 2016). While biodiversity-based systems are promising from agronomic and environmental viewpoints (Weyers and Gramig, 2017), their absolute resilience to disruption, and relative resilience compared to that of input-based systems, has yet to be evaluated (Therond et al., 2017).

To address this knowledge gap, we assessed the resilience of 30 contrasting cropping agroecosystems in the Grand Est region (north-eastern France) and the determinants of resilience. This region has experienced climate change for decades in the form of increasing temperatures, short-term drought (as in 2003), flooding and intense rainfall (as in 2016) (Chambre régionale d’Agriculture du Grand Est, 2019) which decreased crop yields. For example, weather in 2016 decreased winter-wheat yield in this region by 20–30% (Ben-Ari et al., 2018). The 30 agroecosystems represented a wide range of production situations (i.e. crop rotations, management practices and field configurations). Dardonville et al. (2021b) showed that they cover a large gradient of anthropic inputs, ESF use and diversification (from highly simplified to highly diversified). They classified the 30 agroecosystems into 5 agriculture models as a function of their level of ESF. In this study, we analysed the production level and economic and social performances based on dynamics of gross margin and workload, as performed by Catarino et al. (2021), over eight years, which provided relevant analysis of the dynamics of several key performances. The performance dynamics were described by two or more criteria of dynamics (e.g. variability, trend) that represented an interesting set of dynamics from a resilience point of view (e.g. see Gaudin et al., 2015; Li et al., 2019b). We analysed a large set of explanatory factors (determinants) of the performance of resilience, such as (i) the type of agriculture model, as defined by Dardonville et al. (2021b); (ii) the anthropic intensity of cropping practices (total and by practice) and (iii) the biodiversity level of the agroecosystem (i.e. crop rotation, species mixture, surrounding semi-natural habitats (SNH)).

## 2. Methods

### 2.1. Agroecosystems and farm characteristics

The 30 cropping agroecosystems investigated belonged to 26 farms in the Grand Est region (Supplementary material 1). This region is one of the main crop-oriented regions in France and contains mainly input-intensive systems (Chambre Régionale d'Agriculture Grand Est, 2018). Like all regions, it is exposed to climate change (Caubel et al., 2018; Poumadere et al., 2005; Velde et al., 2012). While this region currently

produces more grain than any other region in France, its ability to sustain this production in the long term in the face of climatic and economic crises is less certain.

These agroecosystems, described in detail by Dardonville et al. (2021b), were chosen by advisors from the Regional Chamber of Agriculture and represented a wide range of rotations (from 1 to 9 crops in the rotation, with intermediate crops) and input intensities (from irrigated and fertilised to organic with soil-conservation practices). Based on a review of the relationships between system properties and ESF and associated indicators, these authors assessed, for each agroecosystem: (i)

**Table 1**

Performance attributes (response variables) and proxies of disturbances (exogenous) and explanatory variables tested as determinants of resilience.

Type of variable	Indicator	Unit	Calculation	Reference	Name	Mean $\pm$ SD
Performances	Gross margin	€/ha	Revenue – costs	–	gm	965 $\pm$ 521
	Workload	h/ha	Cumulative hours spent on arable field activities	–	wrkldha	2.5 $\pm$ 2
	Energy yield	kcal/ha	Energy equivalent of crops in kcal $\times$ production (t)	–	eyld	3.10 <sup>7</sup> $\pm$ 1.10 <sup>7</sup> (max)
Exogenous disturbances	Cumulative daily temperature	°C	Cumulative daily minimum and maximum temperatures respectively for quarters 1 and 4 and quarters 2 and 3	www.agrometinfo.fr	cum_temp_min/ max_quarter	5444 $\pm$ 348
	Number of hot days	–	–	www.agrometinfo.fr	hot_days	26 $\pm$ 9
	Maximum drought sequence	Days	Largest number of consecutive days of drought (rainfall – evapotranspiration < –5 mm)	www.agrometinfo.fr	seq_PETP5	5 $\pm$ 2.5
	Wheat price	€/t	–	Ancelet et al., 2014	wheat_price	20 $\pm$ 2
	Fuel price	€/L	–	Ancelet et al., 2014	fuel_price	0.7 $\pm$ 0.1
	Real capacity of ESF	–	Aggregated score of the quality with which the spatial and temporal compositions of the agroecosystems provide ESF, as influenced by crop practices	Dardonville et al., 2021b	ESF_r	0.4 $\pm$ 0.2
	Actual use of ESF	–	Precision of the action performed by farmers to use ESF, given the ability of the agroecosystem to provide ESF instead of using anthropic inputs to replace them	Dardonville et al., 2021b	ESF_u	0.5 $\pm$ 0.2
	Natural capital dynamics	–	Aggregated score of erosion sensitivity, soil carbon and phosphorus dynamics, and biodiversity dynamics	Dardonville et al., 2021b	nat_cap	0 $\pm$ 0.4
	Input intensity	–	Aggregated scores of (i) intensity of mineral fertilisation relative to the regional mean, (ii) pesticide treatment frequency index relative to the regional mean treatment frequency index and (iii) the frequency of ploughing and irrigation	Dardonville et al., 2021b	intensity	0.5 $\pm$ 0.2
	Rotational complexity index	–	Square root of the number of cash and cover-crop species (richness) in a rotation $\times$ the rotation duration	Bowles et al., 2020	RCI	4.5 $\pm$ 1.7
Endogenous explanatory variables	Proportion of species mixtures in the rotation	–	Proportion of crops and intercrops with a species mixture	Dardonville et al., 2021b	mix	0.4 $\pm$ 0.2
	SNH	–	Mean scores for the proportion of nearby field areas and herbaceous habitat and the quality and distance of semi-natural habitats to the field barycentre	Dardonville et al., 2021b, Rega et al., 2018	SNH	0.5 $\pm$ 0.2
	Organic matter	%	–	–	SOM	2.8 $\pm$ 0.5
	Tillage type	–	Mean score for ploughing frequency (1 = always, 0.5 = occasionally, 0 = never) of crops	–	tillage	0.6 $\pm$ 0.3
	Pesticide intensity	–	Treatment frequency index ([0;1]) (1 = intensive) relative to the regional mean (0.5)	Dardonville et al., 2021b	pesticide	0.5 $\pm$ 0.2
	Fertilisation intensity	–	Amount of mineral nitrogen and phosphorus supplied ([0;1]) (1 = intensive) relative to the regional mean (0.5)	Dardonville et al., 2021b	fertilisation	0.6 $\pm$ 0.3
	Irrigation intensity	–	([0;1]) (1 = intensive), with two levels: 0 = no irrigation, 1 = irrigated	Dardonville et al., 2021b	irrigation	0.3 $\pm$ 0.5
	Soil conservation agriculture	0/1	Synergistic effect of conservation agriculture: crop diversity, permanent soil coverage and no-till (Supplementary material 6)	Dardonville et al., 2021b	SCA	–
	organic	0/1	Two levels: 0 = no organic label, 1 = organic label	–	organic	–
	Agriculture model I_M	–	Inefficient use of Medium ESF capacity	Dardonville et al., 2021b	I_M	–
Agriculture model I_LM_D	–	Inefficient use of Low-to-Medium ESF capacity, with Depletion of natural capital	Dardonville et al., 2021b	I_LM_D	–	
Agriculture model M_LM_C	–	Medium use of Low-to-Medium ESF capacity, with Capitalization of natural capital	Dardonville et al., 2021b	M_LM_C	–	
Agriculture model MH_H	–	Medium-high use of High ESF capacity	Dardonville et al., 2021b	MH_H	–	
Agriculture model E_LM_D	–	Efficient use of Low-to-Medium ESF capacity, with Depletion of natural capital	Dardonville et al., 2021b	E_LM_D	–	

Ecosystem services provided to farmers (ESF) are analysed through their real capacity, their actual use and the dynamics of natural capital which underlie ESF supply. Means and standard deviations (SD) are calculated over all agroecosystems and years.

real capacity of ESF (i.e. potential ESF influenced by crop management practices during the cropping season), (ii) actual use of ESF by the farmer and (iii) dynamics of natural capital that underpins ESF (Table 1). Based on their results, the agroecosystems were classified into five types of agriculture models using a clustering approach (Table 1, Box 1).

Historical data on performances from 2012 to 2020 were obtained from the farmers' computer-based management tool "Mes Parcelles®", which included data for at least four years of observations. This tool records daily crop management data for each field, including the amounts of inputs applied and products harvested. Fields receiving special interventions were excluded (e.g. floodable). The prices of mineral fertilisers, crops sold, pesticides, fuel and irrigation were obtained from the INRAE Agrosyst database (Ancelet et al., 2014). Prices of organic fertiliser and pesticides were assumed to have remained constant over the 8-year period. Fuel consumption of the equipment and the duration they were used per ha were extracted from the French national reference source (CUMA, 2019).

The semi-continental climate of the Grand Est region has a large amount and high frequency of rainfall each year (except for central Alsace). From 1959 to 2013, the region experienced an increase in mean annual temperature of +1.3 °C, an increase in the number of days when

the temperature exceeds 25 °C, a decrease in the number of frost days and an increase in total annual evapotranspiration (CRAGE, 2018). This has caused wheat yield to stagnate since 1990, advanced phenological stages, stunted development, induced water stress and fostered the expansion and colonisation of certain pests (e.g. bivoltine corn borer on maize).

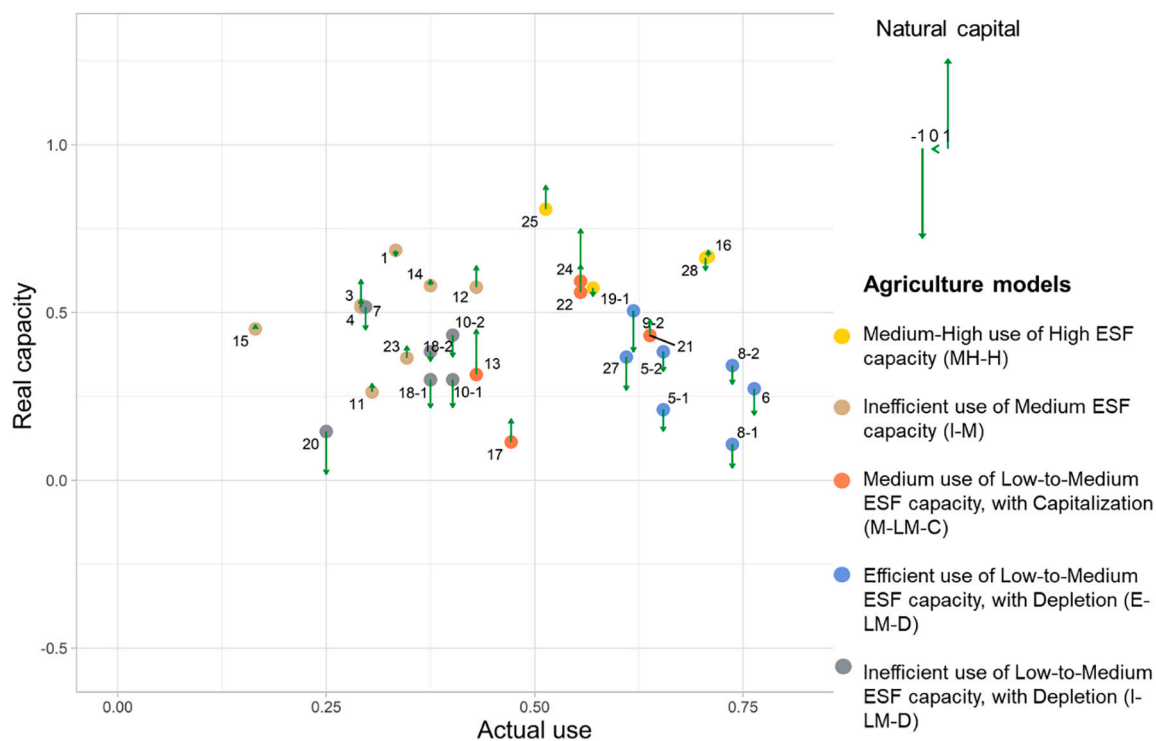
## 2.2. Performances and explanatory variables

### 2.2.1. Attributes of performances

To address the question "resilience for what purpose?" (Meuwissen et al., 2019), we considered the following agronomic, social and economic performances as important to maintain in the face of disturbances: crop energy yield (kcal per ha), workload (hours of work per ha) and agroecosystem gross margin (input – output in € per ha). Thus, we believe it is important to guarantee a certain level of food production, maintain sustainable work hours for each farmer and maintain economic viability. Energy yield was calculated by converting each harvested product into an energy equivalent, as reported by Sauvant et al. (2004) and recommended by Zampieri et al. (2020). In addition, wheat yield was analysed to ensure that the coefficients used to convert the yields to energy equivalents did not induce distortions. Workload equalled the

#### Box 1

Five clusters of 30 agroecosystems (26 farms) in the Grand-Est region (north-eastern France) identified by (Dardonville et al., 2021b) according to (i) the ecosystem's real capacity to provide ecosystem services to farmers (ESF), (ii) actual use of ESF by farmers and (iii) dynamics of natural capital. Figure adapted from (Dardonville et al., 2021b).



The MH-H model has high ESF capacity and medium-high ESF use but no specific natural capital dynamics. It includes relatively long rotations of legumes and uncommon crops and reduced or no tillage. The I-M model uses its medium ESF capacity inefficiently and has neutral or positive natural capital dynamics. It includes longer and complex rotations and varied types of tillage. The M-LM-C model has medium use of its low-to-medium ESF capacity with capitalisation of natural capital. It includes long rotations of uncommon crops, is ploughed and uses pesticides and mineral fertilisers. The E-LM-D model uses its low-to-medium ESF capacity efficiently but depletes natural capital. It includes short maize-based rotations that are usually irrigated and ploughed. The I-LM-D model uses its low-to-medium ESF capacity inefficiently and all depletes natural capital. It includes only maize-based rotations and varied agricultural practices.

total person hours per year spent on arable field activities for all crops in the agroecosystem per ha. Gross margin equalled crop revenue (from harvested crops) minus costs (i.e. fertilisation, irrigation, pesticides and fuel consumption) per ha (Supplementary material 2).

### 2.2.2. Exogenous disturbances

Meteorological data (i.e. daily rainfall; minimum, maximum and mean temperatures; and evapotranspiration), interpolated to grid of  $8 \times 8$  km, came from Météo France. We selected variables (proxies) to characterise exposure and sensitivity of agroecosystems to climatic and economic disturbances. To characterise climate, the main agro-climatic indicators developed by [Caubel et al. \(2015\)](#) (see also [www.agrometinfo.fr](http://www.agrometinfo.fr)) were calculated for each year from 2012 to 2019 (Table 1, Supplementary material 3) for the location of each agroecosystem. After analysing the correlation between these indicators, we selected the least correlated indicators (Table 1): cumulative daily minimum and maximum temperature ( $^{\circ}\text{C}$ ) respectively for quarters 1 and 4 and quarters 2 and 3, the number of hot days ( $> 27^{\circ}\text{C}$ ) and the largest number of consecutive days of drought in a year (rainfall – evapotranspiration  $< -5$  mm). The hottest years in France since 1900 were 2015, 2018 and 2019, which also had the longest droughts, highest heat stress (i.e. hot days), and longest drought (Supplementary material 3). In addition, as the agroecosystems were spread over 50,000  $\text{km}^2$  and could have had different local climates (Supplementary material 1), we analysed differences in climatic situations. Differences in the three agro-climatic indicators among agroecosystems were generally not significant, except for one agroecosystem (#14) near the northern border ( $p < 0.05$ , pairwise Tukey HSD test, see Supplementary material 4). Price volatility, described by wheat price ( $\text{€}/\text{t}$ ) and fuel price ( $\text{€}/\text{L}$ ) ([Ancelet et al., 2014](#)), decreased significantly until 2016, when it increased (Supplementary material 5).

### 2.2.3. Endogenous explanatory variables

Endogenous explanatory variables correspond to variables that characterise the agroecosystems (Table 1). In addition to the five agriculture models and their determinants (i.e. levels of real capacity and

actual use of ESF, and natural capital dynamics), we tested characteristics that are often considered as resilience factors: (i) input (i.e. pesticides, irrigation and fertilisers) intensity, (ii) crop diversity (i.e. rotation duration and number of crops), proportion of species mixtures in the rotation and an indicator that aggregated the quantity and quality of SNH; and (iii) soil organic matter content. We also tested agroecosystems' membership in common classifications of agricultural systems, such as organic and soil-conservation practices.

### 2.3. Criteria of dynamics

The following criteria were used to describe the dynamics of agricultural performances ([Dardonville et al., 2021a](#)):

- level of performance (e.g. mean level);
- stability or, conversely, variability;
- trend (i.e. maintenance, increase or decrease in the level over time);
- resistance (i.e. the ability to resist a specific or unspecified event).

Not all criteria were relevant for all performance attributes. Thus, for each performance attribute, we selected criteria of dynamics based on their suitability (Table 2). For energy yield, high level, resistance and stability are usually desirable targets, as guaranteeing a certain level of production to ensure the food supply, avoiding frequent crop failures and decreasing variability in production over time are crucial to ensure resilience. This is also true for gross margin, but an increasing trend is often expected to keep up with inflation. For these two attributes, we also considered resistance to the historic decrease in wheat yield in France in 2016 due to excess rainfall in spring and abnormally high temperatures in autumn that caused lodging ([Ben-Ari et al., 2018](#)). For workload, we assumed that a lower level, higher stability and high resistance to peak work are desirable objectives for resilience, as labour-intensive systems are sensitive to the lack of available workers (as [Mitaritonna et al. \(2020\)](#) observed during the COVID-19 health crisis), and if the workload is likely to peak or is highly variable, a lack of labour may not be bearable or even feasible for the farmer due to the

**Table 2**

List of criteria of dynamics and associated metrics related to each performance attribute.

Performance attribute	Criterion of dynamics	Metric	Name	Description	Reference	Direction for resilience
Energy yield	Level	Mean level	Level	Mean level	<a href="#">Perrin et al., 2020</a>	Higher
	Stability	Stability around a moving average	MSV	Inverse of the absolute difference between the yield of each year and the mean of the preceding year and following year, averaged over the time series	<a href="#">Redhead et al., 2020</a>	Higher
	Resistance to an event	Resistance to 2016	RESe	2016 level – averaged 2015, 2014, 2013 level	<a href="#">Redhead et al., 2020</a>	Higher
	Level	Mean relative distance to regional margin	RD	Mean relative distance to the regional gross margin (Supplementary material 8)	<a href="#">Redhead et al., 2020</a> ; <a href="#">Sneessens et al., 2019</a>	Positive and high
Gross margin	Stability	Stability around a moving average	MSV	Inverse of the absolute difference between the gross margin of each year and the mean of the preceding year and following year, averaged across the time series	<a href="#">Redhead et al., 2020</a>	Higher
	Resistance to unspecified events	Probability of failure	probalow	Probability of gross margin $>75\%$ of the mean level over the time series using the normal distribution	Adapted from <a href="#">Li et al., 2019a, 2019b</a>	Higher
	Resistance to an event	Resistance to 2016	RESe	2016 level – averaged 2015, 2014 and 2013 level	<a href="#">Redhead et al., 2020</a>	Higher
	Trend	Trend of mixed regression	TRENDr	Random slope coefficient of mixed linear regression	<a href="#">Martin et al., 2017</a>	Increasing
Workload	Level	Inverse of averaged level	level	Inverse of mean level	Adapted from <a href="#">Martin et al., 2017</a>	Higher
	Stability	Stability around a moving average	MSV	Inverse of the absolute difference between the workload of each year and the mean of the preceding year and following year, averaged over the time series	<a href="#">Redhead et al., 2020</a>	Higher
	Resistance to unspecified events	Probability of peak work intensity	probahigh	Probability of workload $>125\%$ of the mean level over the time series using the normal distribution	Adapted from <a href="#">Li et al., 2019a, 2019b</a> )	Higher

“Direction for resilience” indicates the dynamics of the metric that would improve resilience.

adjustment in labour required.

For each criterion of dynamics, several metrics were explored due to the wide variety of ways in which these criteria can be measured. For example, to estimate ecosystem stability, Wang et al. (2019) used the standard deviation and coefficient of variation. We summarised the main metrics (Supplementary material 7) and selected a metric for the criterion of each performance attribute (Table 2). The selection was based on (i) minimising the correlation between the metrics of the criteria, (ii) the predictability (percentage of variance explained by random forest) of each metric for each attribute, considering all explanatory variables, and (iii) the interpretability (i.e. easily understandable and makes sense to experts) of each metric. Level was the mean level, as developed by Perrin et al. (2020). For workload, we used the inverse of level, as low workload is considered better for farmers. For gross margin, as recommended by Sneessens et al. (2019), we used the mean relative distance (RD) to the regional gross margin (Supplementary material 8) to consider the social acceptance of the income level. A strongly negative RD indicated that the gross margin was significantly below the regional mean, while a strongly positive RD indicated the ability to generate above-average profit. Stability (Mean Stability Variable, MSV) was calculated as the difference between each year and the mean of the preceding year and following year, averaged over the time series (Redhead et al., 2020). Low or high resistance to unspecified events was the probability of respectively falling under 75% (probalow) or exceeding 125% (probahigh) of the mean over the eight years (adapted from Gaudin et al. (2015) and Li et al. (2019a, 2019b)). Resistance to 2016's decrease in wheat yield (RESe) was calculated as the proportional decrease in 2016 from the 2013–2015 mean (Redhead et al., 2020). Trend (TRENDR) was calculated as the random slope coefficient of mixed linear regression of individuals, which excluded the group trend due to technological and genetic improvements (see Martin et al. (2017)).

#### 2.4. Explanatory factor test

Three additional approaches were used to analyse relationships deeply between the metrics of dynamics for each performance and the explanatory factor: partial least squares regression (PLS, statistical method), multivariate regression trees (MRT, a machine-learning method) and Pareto ranking. They are complementary as they can perform several levels of analysis. Using PLS to evaluate resilience was recommended by Martin et al. (2017) and applied by Bouttes et al. (2018) and Perrin et al. (2020). To our knowledge, however, MRT have never been used in agricultural research to identify predictors of dynamics. To verify this, we queried the Web of Science Core Collection from 2000 to November 2020 using the query of Dardonville et al. (2020), which was divided into three sections: (i) the concepts of vulnerability, resilience, robustness and adaptive capacity; (ii) agricultural systems and (iii) quantitative assessment plus “*regression tree\**” (Supplementary material 9). Of the 39 references identified, 3 mentioned the topic. Hou et al. (2020) used regression tree analysis to evaluate explanatory factors of fruit yields. Lokonon (2019) used regression tree analysis to identify the utility of combining exposure, sensitivity and adaptive capacity into a vulnerability index. Diack et al. (2017) used the CART model to quantify the level of vulnerability of a zone, but not to identify explanatory factors. In short, they did not use regression to analyse dynamics or multiple response variables.

##### 2.4.1. Exploratory univariate approach using PLS

We applied the method developed by Martin et al. (2017) and applied by Bouttes et al. (2018) and Perrin et al. (2020) which uses PLS to identify explanatory factors of performance dynamics (i.e. to explain determinants of resilience). At the crossroads of principal component analysis and linear regression, it performs multiple linear regression by maximising the square covariance between response and explanatory variables (through a linear combination of each) for each component,

and handles correlated and incomplete data well (Wold et al., 2001). We performed PLS using the *mixOmics* package of R software (Lê Cao et al., 2018; R Core Team, 2013, Supplementary material). To define the explicative and predictive ability of the model,  $R^2$ , the mean squared error of prediction and  $Q^2$  values were analysed (maximised, minimised and maximised, respectively). The NIPALS algorithm was used to fill in missing climate data (since 2018). The common ad hoc threshold of total  $Q^2 > 0.0975$  was used.

##### 2.4.2. Predictive multivariate approach using MRT

In addition to the PLS, we used MRT (De'Ath, 2002), which is an extension of univariate regression trees (Breiman et al., 1984). The approach considers multiple response variable patterns and then identifies trade-offs between (normalized) metrics of dynamics of each performance attribute and predictors among explanatory variables by considering potential thresholds due to non-linear effects (Borcard et al., 2018). We performed MRT using the archived *mypart* 1.6–2 package of R software (Therneau et al., 2014). A 10-fold cross-validation procedure was conducted to calculate the cross-validated error. As suggested by Breiman et al. (1984), we selected the optimal size of the tree (i.e. number of leaves) following the “1-SE” rule, which consists of using as the smallest tree within 1 standard error of the minimum cross-validated error (Supplementary material 10). Like Obiang-Ndong et al. (2020) and Smith et al. (2019), we replaced bar plot leaves with boxplot leaves to show the distribution of each metric. We included explanatory variables of disturbance that described the climate to test whether the agroecosystems experienced different meteorological situations which resulted in different dynamic patterns.

##### 2.4.3. Identifying positive deviants with Pareto ranking

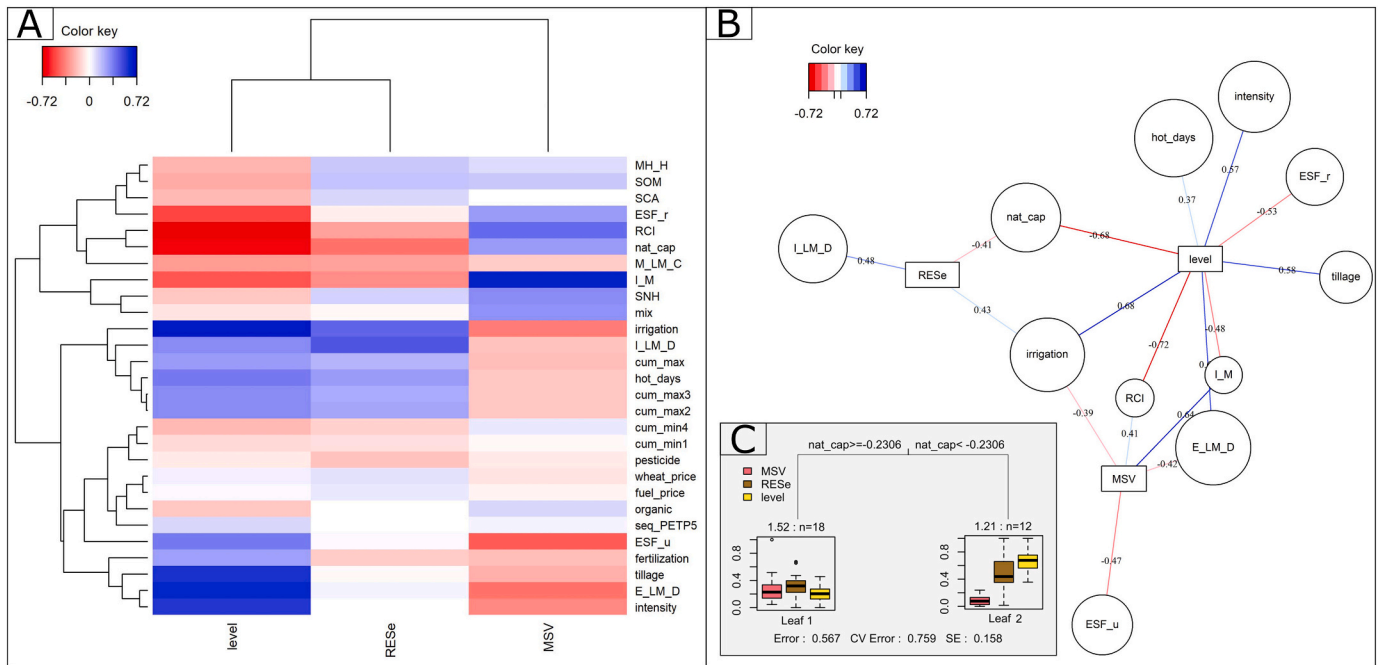
Pareto ranking was used to identify positive deviant agroecosystems with the best combination of multiple performances without subjective weights (i.e. agroecosystems that were exemplary in achieving all dynamic objectives) (Modernel et al., 2018; Steinke et al., 2019; Toorop et al., 2020). We analysed the combination of all criteria for agronomic, social and economic attributes. We used the *emoa* package of R software following the procedure of Steinke et al. (2019) (Supplementary material 10).

### 3. Results

#### 3.1. Energy yield

Level, stability (MSV) and resistance to 2016's decrease in wheat production (RESe) were used to describe energy yield (kcal/ha) dynamics. Three PLS components were acceptable: the first component represents mainly the level (mainly), the second the resistance and the third stability (Supplementary materials 11 and 12). Level was positively related to the intensity of cropping practices, particularly irrigated and tillage-intensive systems (Fig. 1A and B). Level was also positively related to the “Efficient use of Low-to-Medium ESF capacity, with Depletion of natural capital” (E\_LM\_D) model, which referred mainly to intensive and irrigated maize monocropping systems. Farms with more hot days had slightly higher levels. In comparison, level was negatively related to natural capital dynamics, crop diversification, real ESF capacity and the “Inefficient use of Medium ESF capacity” (I\_M) model, whose agroecosystems had significantly lower yields than the others (pairwise Tukey HSD test, Supplementary material 13). Natural capital dynamics was negatively related to resistance, which was positively related to the “Inefficient use of Low-to-Medium ESF capacity, with Depletion of natural capital” (I\_LM\_D) model and irrigation. Conversely, stability was negatively related to irrigation, E\_LM\_D (and to a lesser extent, intensification) and the level of ESF used. Stability was positively related to crop diversification, the I\_M model and, to a lesser extent, natural capital dynamics, SNH and use of species mixtures.

The MRT was organised into two levels and two leaves with

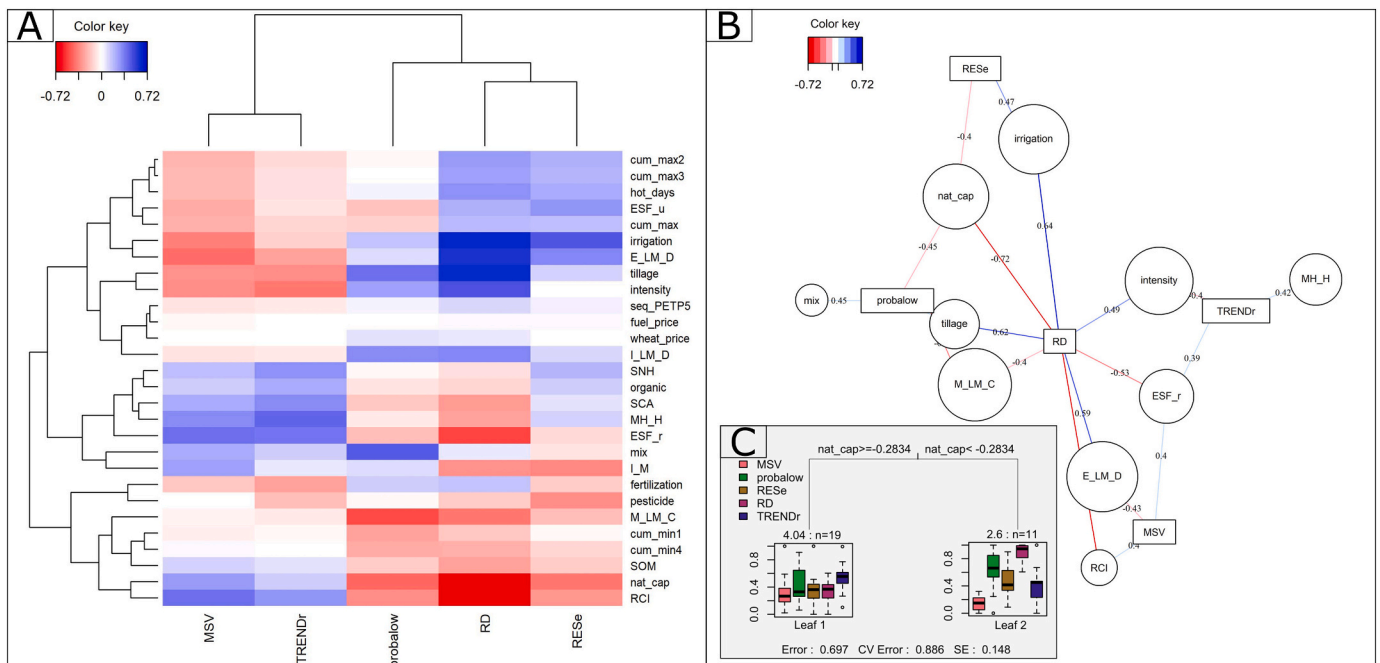


**Fig. 1.** (A) Clustered Image Map and (B) network representation of the partial least squares regression of metrics for energy yield on explanatory variables (see Table 1 for definitions of variable abbreviations), showing positive (blue) and negative (red) correlations with the criteria of dynamics. (C) Multivariate regression tree based on criteria of dynamics (normalized) for energy yield on explanatory variables. It results in two patterns of dynamics, which indicate two types of resilience situations depending on the value of the explanatory variable. The tree is evaluated using the residual error (Error), the mean residual error of a 10-fold cross-validation procedure (CV Error) and its standard error (SE). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

acceptable predictive quality (cross-validated error of 0.76; i.e. the tree explained 24% of the variance) (Fig. 1C). Natural capital dynamics, with a threshold of  $-0.23$ , was selected to split the two leaves, which represented two main types of resilience situations. The 12 agroecosystems with natural capital  $< -0.23$  had relatively high yield and resistance, but low stability (Leaf 2), while the 18 others had more homogenous pattern of dynamics, with higher stability and lower level and resistance

(Leaf 1). Comparing the criteria for this split revealed significant differences between the two groups (Supplementary material 14).

When analysing wheat yield (for the 27 agroecosystems with wheat in their rotations (all but #10\_2, 5\_2, 8\_1)), dynamics followed the same pattern with less confidence (Supplementary material 15). Intensive systems had higher levels of wheat yield, while diversified (organic, crop diversity in the rotation and SNH) systems had lower levels.



**Fig. 2.** Same as Fig. 1, but for gross margin.



### 3.2. Gross margin

The relative distance to the regional gross margin (RD), stability (MSV), resistance to 2016's conditions (RESe), resistance to unspecified events (probalow) and trend (TRENDr) were used to describe gross margin (€/ha) dynamics. Three PLS components were acceptable: the first component represents level (mainly), the second is a combination of all metrics and the third one is the resistance to unspecified events (Supplementary materials 16 and 17). Like for energy yield, level was positively related to intensity of cropping practices, particularly irrigated and tillage-intensive systems (Fig. 2A and B). It was also positively related to the "Efficient use of Low-to-Medium ESF capacity, with Depletion of natural capital" (E\_LM\_D) model, which referred mainly to irrigated and intensive maize monocropping systems. However, level was negatively related to natural capital dynamics, crop diversification, real ESF capacity and the "Medium use of Low-to-Medium ESF capacity, with Capitalization" model (M\_LM\_C). Natural capital dynamics was negatively related to resistance to unspecified events and 2016's conditions. The irrigated system resisted 2016's conditions better, even though it was not a strong drought year (Supplementary material 3). Tillage intensity and species mixture management was positively related to resistance, in general (probalow). Stability, crop diversification and real ESF capacity (and to a lesser extent, the "Medium-high use of High ESF capacity" (MH\_H) model and natural capital dynamics) were positively related, unlike E\_LM\_D (and to a lesser extent, irrigated systems), which were negatively related. Trend was also positively related to the MH\_H model and real ESF capacity but negatively related to intensity.

The MRT was organised into two levels and two leaves with acceptable predictive quality (cross-validated error of 0.88; i.e. the tree explained 12% of the variance) (Fig. 2C). Natural capital dynamics, with a threshold of -0.28, was selected to split the two leaves to consider two situations. The 11 agroecosystems with natural capital < -0.28 had a gross margin much higher than the regional mean (RD > 0, Supplementary material 18) and greater resistance to 2016's conditions and to unspecified events, but less stability, while the 19 others had a more homogenous pattern of dynamics, with higher stability and lower level and resistance. Comparing criteria for this split revealed significant differences between the two groups (Supplementary material 18).

### 3.3. Workload

Level, stability (MSV), resistance to workload peak intensity (probahigh) described workload (h/ha) dynamics. Three PLS components were acceptable: the first component represents the level (mainly) and stability, the third one is the resistance to unspecified events (Supplementary material 19 and 20). Unlike for gross margin and energy yield, level (specifically, the inverse) was positively related to natural capital dynamics, crop diversification, real ESF capacity and the "Inefficient use of Medium ESF capacity" (I\_M) model (Fig. 3A and B). It was negatively related to intensity of cropping practices, especially irrigated and tillage-intensive systems. It was also negatively related to the "Efficient use of Low-to-Medium ESF capacity, with Depletion of natural capital" (E\_LM\_D) model, which referred mainly to irrigated and intensive maize monocropping systems. Natural capital dynamics and crop diversification were also positively related to workload stability, unlike irrigated systems, which had more variable workload. Pesticide use and mineral fertilisation were positively related to resistance to a high peak in workload intensity, while organic systems were negatively related.

The MRT was organised into two levels and two leaves with acceptable predictive quality (cross-validated error of 0.88; i.e. the tree explained 12% of the variance) (Fig. 3C). Crop diversification, with a threshold of 4.357, was selected to split the two leaves to consider two situations. The 16 agroecosystems with RCI > 4.357 had lower workload levels, high resistance to a high peak in workload intensity and workload stability over the eight years (Leaf 2). Comparing criteria for this split revealed significant differences between the two groups (Supplementary material 21).

### 3.4. Positive deviants

Pareto ranking identified two positive deviant agroecosystems in the group that had the best performance dynamics without compromising the other performances (Supplementary material 22). Agroecosystem #1 had an average performance for all attributes, but high stability in working time and little probability of peaks in intensity. Agroecosystem #5.2 had high yields and gross margins, without much working time, despite variability in performances.

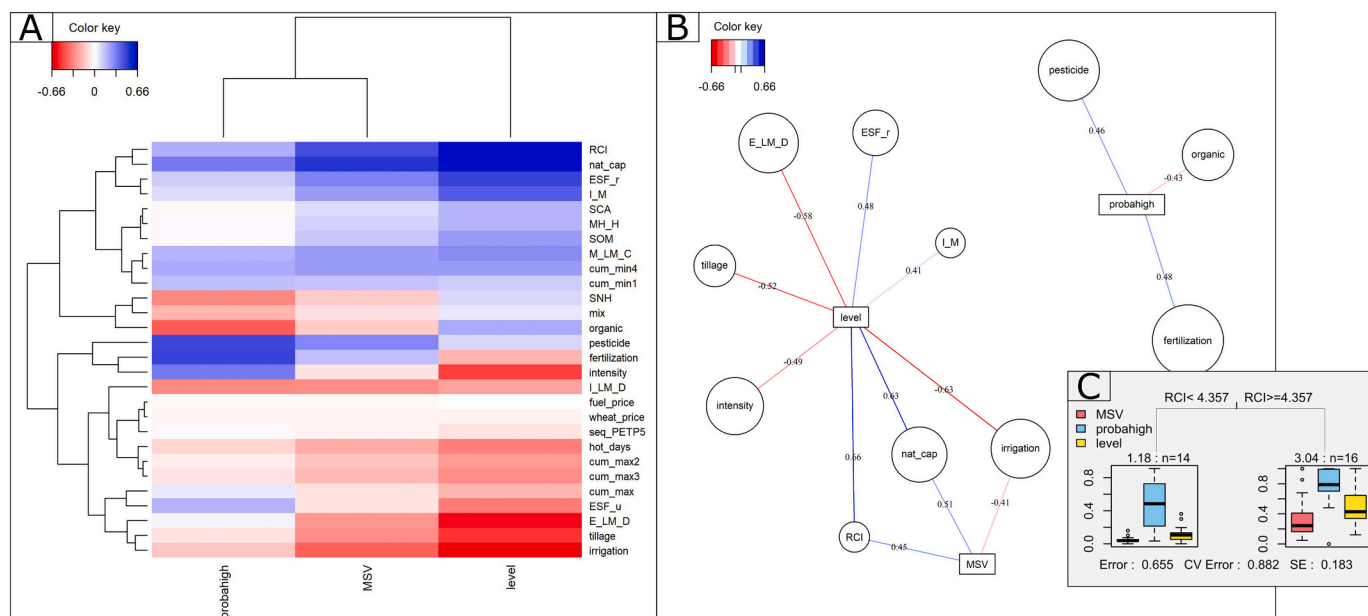


Fig. 3. Same as Fig. 1 but for workload.

#### 4. Discussion

We assessed the resilience of 30 agroecosystems that represented agriculture models along a gradient of level and use of ESF and natural capital dynamics. The multicriteria analysis of dynamics (level, stability, resistance and trend) of the multi-performances (energy yield, gross margin and workload) of these contrasting systems helped to identify system characteristics that explain resilience.

Analysis of the relationship between performance dynamics and exogenous explanatory factors (with PLS) showed that the observed dynamics were related primarily to endogenous characteristics, as observed by Martin et al. (2017). The variability in wheat and fuel prices seemed to have little influence on the dynamics of gross margin (Fig. 2A), perhaps because there was not sufficient variation or due to compensation between crop and input prices. Spatial differences in annual weather patterns can influence performances, but less so than farm characteristics. The MRTs did not identify climatic variables as main predictors. Consequently, farmers are able to manage the mechanisms that improve system resilience.

##### 4.1. Biodiversity at the hub of resilience

Our results show two main types of resilience situations (Table 3). Systems based on biodiversity (crop diversification, SNH and species mixtures), ESF and increasing natural capital tend to be more stable for the three performances investigated. These systems also require less work than intensified systems and have lower gross margin. Conversely, intensified systems, especially irrigated and tillage-intensive ones, have higher yield and gross margin performances and are relatively more resistant to major (2016) impacting disturbances. Using a species mixture, although a strategy to promote biodiversity, is also related to economic resistance to unspecified disturbances. Organic farming has a greater likelihood of workload peaks, which can be due to mechanical weeding emergencies (Chikowo et al., 2009), while diversified crop systems have fewer workload peaks.

Our results suggest that systems with a high ESF capacity and a constant or increasing natural capital have more stable performances than simplified systems. Biodiversity (in a broad sense, such as crop diversity, SNH, use of cover crops, species mixtures, non-crop plants) is a major determinant of ESF (Kleijn et al., 2019) and underpins natural capital dynamics (Dardonville et al., 2021b; González-Chang et al., 2020). Therefore, the stability of these systems seems to be related to their biodiversity. In the literature, when ESF-based systems are suggested as being more resilient (Elmqvist et al., 2003), the justifications often focus on their biodiversity aspects and clearly identified processes, such as complementary-function redundancy and synergistic interactions (Tschamtkke et al., 2005). Conversely, similarly to intensified systems, our results also show that systems that use ESF effectively have relatively high performances but are less stable. However, with a few exceptions (#25, 28, 16, Box 1), the agroecosystems that used the most ESF were not those that had the highest ESF capacity overall.

More generally, our case study results agree with the extensive literature on biodiversity-stability relationships for production (Craven

et al., 2018; McCann, 2000; Tilman et al., 1994) due to the buffering effect predicted by the insurance hypothesis (Yachi and Loreau, 1999). This relationship depends on the intensity and type of climate events and the random or non-random assembly of species (De Boeck et al., 2017). Its relevance for grasslands is strongly debated due to the diversity of results observed (Wang et al., 2019), which can be explained by composition effects (Dardonville et al., 2020) or species asynchrony (Craven et al., 2018). For crops, results are more consistent (Bowles et al., 2020; Gaudin et al., 2015; Renard and Tilman, 2019), likely due to farmers selecting complementary species (unlike for non-seeded grasslands).

##### 4.2. Multifaceted dynamics

While stability is an interesting characteristic of dynamics, it is not sufficient alone and must be combined with a sufficient level of production to ensure agricultural system sustainability. Our results suggest a possible trade-off between these two facets of resilience (i.e. criteria of dynamics) which are “unlikely to be independent” (Donohue et al., 2016). This could be due to our focus on cash crops, without considering diversification of other types of agricultural production, such as livestock production. In our case study, crop-intensification strategies effectively decreased yield and economic gaps (Van Dijk et al., 2017). In addition, using inputs to control production factors (e.g. water, nutrients, crop health) can be effective during episodes of intense disturbance, as in 2016. Conversely, systems based on biodiversity, and more in line with environmental and ESF conservation, reach stable performances more effectively but have lower productivity and economic return. The issue is thus whether this level is sufficient for farmers. This highlights the potential trade-off between the aspects of dynamics that are important to farmers (e.g. economic return) and to society (e.g. food security (Godfray et al., 2010), biodiversity conservation (Brussaard et al., 2010)). Farmers themselves must define their objectives in terms of dynamics in order to become resilient (Córdoba Vargas et al., 2019). Their interests may diverge depending on their risk aversion, financial commitments, work values or family situation (e.g. the entire family works on the farm, complementary activities) (Darnhofer, 2014; De Roest et al., 2018).

Nevertheless, the choice between performance level and stability is not dichotomous: Pareto ranking helped to identify positive deviant agroecosystem #1, which had high performance levels, stability, resistance and an increasing trend of all attributes. This agroecosystem is diversified, with a high ESF level, but intensive use of pesticides and mineral fertilisers, and achieves adequate agronomic and economic performances. By combining a high real ESF capacity due to having many crops in rotation, organic fertilisation, SNH around fields and adjusted inputs, agroecosystem #1 has an interesting combination of characteristics (Box 1). Interestingly, it uses irrigation and combines livestock and cropping systems at the farm level. However, its natural capital is decreasing (i.e. depleted), which could influence its performance dynamics over the long term.

Natural capital was twice the determining factor that distinguished dynamic patterns (for energy yield and gross margin (MRT)).

**Table 3**

Summary of results for two categories of systems: those based on ecosystem services provided to farmers (ESF), biodiversity, and natural capital or intensified systems (irrigation and tillage, and to a lesser extent, pesticide or fertiliser).

Systems	Energy yield			Gross margin					Workload		
	Level	Stability	Resistance 2016	Level	Stability	Resistance 2016	Trend	Resistance unspecified	Level	Stability	Resistance unspecified
ESF, biodiversity, organic, and natural capital based systems	-	+	-	-	+	-	+	+/-	+	+	+/-
Anthropic input based systems	+	-	+	+	-	+	-	-	-	-	(+)

A “+” indicates a resilient system, “-” indicates a non-resilient system, “+/-” indicates a variable system and “(+)” indicates a specific relationship to criteria of dynamics.

Consequently, whether dynamics are observed in the short term - as in this study - or in the long term influences the results strongly. Natural capital is degraded by agricultural practices which are currently harmful and which will continue to have effects in the future. While we assessed natural capital dynamics through four components (i.e. biodiversity, phosphorus balance, carbon storage and sensitivity to erosion), further analysis could explore which dimension influences the performance dynamics the most.

#### 4.3. Use of high ESF levels: A way to reach resilience?

Our results suggest that hosting biodiversity is a successful strategy to ensure stable performances, while the actual use of the ESF provided by this biodiversity is an alternative strategy to intensification to ensure an acceptable performance level and resistance. Because intensification in our case study was not related to the level of actual ESF use (Supplementary material 23), maximising real ESF capacity and actual ESF use could be a way to address the apparent trade-off between performance level and stability. In our case study, however, agroecosystems with the highest combination of real capacity and actual use of ESF (#25, 28, 16) were not the positive deviants identified earlier (#1). They had relatively low energy yields and gross margins or required more working time (Supplementary material 22). These systems belong to the MH\_H agriculture model, which has lower mean yields than at least two other agriculture models (Supplementary Material 13), probably because these systems are not intensive (similar to organic agriculture and no-till practices) and do not have sufficient real ESF capacity (i.e. ca. 0.50–0.75) to achieve the high yields of input-intensive systems.

Thus, to ensure a sufficient yield and gross margin while controlling workload and achieving resilience of these performances through stable, increasing and resistant performances, the most effective strategy is to have both high levels of ESF and actual use of them, and to complement them with a parsimonious supply of anthropic inputs to decrease the yield gap without depleting natural capital. The challenge is thus to use anthropic inputs while minimising negative impacts on associated biodiversity that supports short- and long-term ESF supply (Duru et al., 2015), such as integrated pest management (Holland et al., 1994). Beyond the utility of preserving ESF and the natural capital dynamics that support them, the strong decrease in environmental impacts of agricultural inputs can also be managed to preserve biodiversity itself. If the objective is to cease anthropic inputs due to their impacts on the environment, human health and the climate, another strategy is to develop policies that provide economic support to diversified farming systems that use no anthropic inputs (Bennett et al., 2015; Larsen and Noack, 2020). Payments for environmental services is a well-known option to support such systems (Bowman and Zilberman, 2013) by going further than agri-environmental schemes for including agroecological practices on crop farms (Burton and Paragahawewa, 2011).

#### 4.4. Specific characteristics of irrigated systems

Irrigation played an important role in the dynamics observed. Irrigation can counteract spring and summer droughts and increases yields. Unlike Renard and Tilman (2019), we observed that irrigation was not always accompanied by greater production stability. Conversely, the two studies agree that diversifying the system is the best strategy to stabilise yield. Importantly, beyond its potential positive influence on dynamics, intensive irrigation can result in water shortage issues for agriculture and society (Mazzega et al., 2014; Murgue et al., 2015), as well as for downstream ecosystems, especially during low-water periods (Gordon et al., 2010). In Alsace, a sub-region of the Grand Est which contains most of the region's irrigated maize systems, public water-resource managers must increasingly set pumping limits in summer on the edges of the plain ([www.haut-rhin.gouv.fr](http://www.haut-rhin.gouv.fr)). More generally, the decrease in availability of water resources in agricultural regions and of fossil resources (e.g. petroleum, phosphorus; Ellis, 2015) could

compromise agriculture models based on anthropic inputs in the long term. Rist et al. (2014) warn against the “coerced” resilience of input-based systems that maintain the systems in an artificial state that “mimic the response of resilient natural ecosystems”.

#### 4.5. Workload, an original attribute of performance

In agreement with the incentives of Dardonville et al. (2021a), we considered social performance in addition to the traditionally investigated agronomic and economic performances. We chose work hours, as variability in workload is a key issue for farmers (Hostiou and Dedieu, 2012). Our analysis determined that diversification, increase in natural capital, high real ESF capacity and organic agriculture are mechanisms to achieve a homogenous interannual distribution and low level of workload. Two hypotheses can emerge. The first hypothesis was that systems based on biodiversity and associated ESF reduce the need for farmers to manage their systems intensively (i.e. alter the agroecosystem) (Dardonville et al., 2021b). Thus, for a given production level, some of the work required in intensified systems is “ensured” by the ESF. The second hypothesis was that in biodiversity-based systems, farmers manage each crop less intensively due to the diversity of crops or less risk of a crop failing at farm level due to ecological insurance. In our study, the correlation between level of workload (not reversed) and level of actual ESF use was significantly positive (Pearson correlation,  $r = 0.43$ ,  $p < 0.05$ ), i.e. the more the systems are observed/analysed by the farmers to maximise ESF use, the higher the workload. Thus, in this study, we cannot demonstrate that using and observing the ESF level before implementing crop management allows workload to be reduced.

#### 4.6. Methodological advances and issues

As Dardonville et al. (2021a) recommended, we combined a multi-performance approach using the multiple and complementary dynamics criteria selected to be adapted to the performances analysed. By considering more than agronomic, economic and social performances, our study goes beyond those conducted to date. However, it would be interesting to study the environmental aspect as the third pillar of sustainability (Purvis et al., 2019), such as the system not harming the environment over time and remaining within sustainable ecological boundaries. Donohue et al. (2016) recommended choosing criteria of dynamics that make sense from a performance viewpoint and considering the multi-dimensional aspect of system dynamics. Thus, we identified determinants of resilience individually (PLS; Martin et al., 2017) and in bundles, considering compensation among responses (MRT; Obiang-Ndong et al., 2020). We also used Pareto ranking to identify positive deviants (Steinke et al., 2019), even if, because of the large number of variables to be explained, this approach does not add much to the analysis. These three steps of analysing the relationship between agroecosystem characteristics and performance dynamics allow one to deeply analyse and highlight the complexities of intricate explanatory factors of resilience in agricultural systems.

Throughout our analysis, we were aware that analysing the yield requires taking major precautions, especially when comparing systems along an intensification gradient. A large amount of literature focuses on the level and stability of agricultural yields, especially when comparing organic vs. conventional systems (Knapp and van der Heijden, 2018). Döring et al. (2015) showed that there are many stochastic and/or agronomic relationships between the level and standard deviation of crop yield due to Taylor's Power Law, which can bias comparisons. Assessing this relationship in our data following their method indicated that our results for yield stability are robust (Supplementary material 24).

Resilience is tested on disturbances of the same type for the different agroecosystems. We chose to exclude particular fields (e.g. flood-prone) from the analysis of agroecosystems because they were isolated (i.e. few in number) and could induce noise in the results without being

representative to generate sound knowledge on the effect of these particularities or specific perturbations (e.g. flood).

## 5. Conclusion and perspectives

In this study, we presented an original quantitative multi-performance, multi-criteria and multi-method approach to identify relationships between characteristics of agricultural systems and multiple facets of resilience. Agronomic, social and economic performances were analysed in the context of climatic and economic disruptions for agroecosystems with a wide variety of crops and management practices. We show that cropping practices and the spatiotemporal structure of plant cover in agroecosystems can influence resilience strongly. While our results agree with studies that show the benefits of relying on biodiversity to stabilise system performances, we highlight a potential trade-off between performance level and stability and a potential way to overcome it and make it bearable for the farmer. Our results criticise an anthropic input-based strategy in the short-term, which performs well but consumes large amounts of time and resources. Systems based on biodiversity seem promising for resilience, for their lower environmental impacts and as an alternative to intensified agriculture. Avoiding anthropic inputs and coerced resilience, and developing systems with high ESF levels and actual ESF use, provided that natural capital is preserved, seems a promising way to increase resilience. In these systems, natural capital will have still to be restored and improved to increase and maintain ESF levels. This emphasises the relevance of understanding relationships between agricultural practices and ecological processes and the natural capital that underpins ESF and agroecosystems. Optimising the actual use of ESF requires advances in detection technologies and especially in training farmers to assess field ESF levels and apply adapted agroecosystem management strategies. These are the conditions required to fill the yield gap while strongly decreasing the use of anthropic inputs and achieving food security and sustainability.

## Contributions

Conceptualization : MD, OT ; Data curation : MD; Formal analysis : JV, MD, OT; Funding acquisition : OT; Investigation : CB, JV, MD, OT; Methodology : JV, MD, OT; Project administration : OT; Resources: OT; Software : JV, MD; Supervision : OT; Validation : JV, OT; Visualization : MD; Writing – original draft : MD, OT; Writing – review & editing : CB, JV, MD, OT.

## 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.

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