Agroecological performances of low pesticide used grapevine systems adapted to six diverse regional contexts in France

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Research Paper

Agroecological performances of low pesticide used grapevine systems adapted to six diverse regional contexts in France

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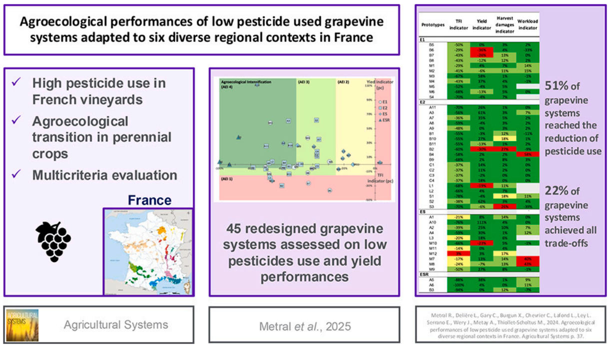
HIGHLIGHTS

- Prototyping method adapted to grapevine in six regional context in France.
- Redesign of 45 grapevine systems with low pesticide inputs.
- 22% of prototypes achieved both environmental and socio-economic sustainability.
- Relevant and regionally tailored grapevine systems fitted to reduce pesticide use.
- Pathways of agroecological transition for winegrowers and their vineyard.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Viticulture extensively employs pesticides to ensure its yield and quality targets. Vineyards are often characterised by low biodiversity and limited use of agroecological practices. The long-term sustainability of viticulture is dependent on the reduction of pesticide use. Designing and assessing innovative agroecological vineyards is a relevant approach to achieve this objective of french policies.

OBJECTIVES: The objectives of the study are: i) to develop a participatory method of cropping system prototyping to meet the agroecological challenges and particularly the reduction in pesticide use, ii) implement this method on grapevine systems at the national scale and iii) assess the agronomical and economical performances of the prototypes.

METHODS: This study presents an innovative methodology based on the **prototyping** of grapevine systems (GCS) with a participatory approach for knowledge-sharing. This approach was adapted to suit perennial crops and implemented through the EcoViti network of experimental sites located in six contrasted vineyards in France.

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The **Efficiency-Substitution-Redesign (ESR) framework** was used to categorise the 45 vineyard prototypes. Then, a **multi-criteria assessment method** encompassing agronomic, environmental, and socio-economic aspects was conducted to get a comprehensive analysis of the prototypes. From 2013 to 2018, data were collected to assess the 45 vineyard prototypes. To represent french vineyards, 93% of the vineyard prototypes were implemented on already planted vineyards, incorporating decision support tools, prophylactic practices, and biocontrol levers. And 7% of the vineyard prototypes were based on newly planted vineyards with innovative varieties (resistant to mildews).

RESULTS AND CONCLUSION: 45 grapevine systems across 27 experimental sites were prototyped with combined agroecological practices. The multi-criteria performance assessment revealed that all agronomic, environmental and socio-economic goals of the ESR rating scale could be attained, ensuring sustainability. Forty-one of the 45 prototypes exhibited a pesticide reduction exceeding 50% on average between 2013 and 2018. Moreover, 40 prototypes successfully met yield and harvest quality objectives, while 92% of the prototypes achieved the targeted workload goals.

SIGNIFICANCE: This study produced relevant and regionally tailored grapevine systems fitted to reduce significantly pesticide use. Our findings underscore the significance of knowledge-sharing in facilitating the overall redesign process. The vineyard prototypes presented herein are not prescriptive solutions but rather indicative of the avenues through which winegrowers can customise and devise their unique pathways of agroecological transition for their vineyard.

1. Introduction

The use of pesticides to control pests and diseases in cropping systems has undesirable side effects on human health and the environment (Enserink et al., 2013). Thus, the reduction of pesticide use in agriculture has been a major environmental and societal issue for the past two decades (Robertson and Swinton, 2005). Consequently, agriculture faces a major challenge in transitioning towards more sustainable systems capable of addressing the environmental and societal concerns related to pesticide use (Robertson and Swinton, 2005). The agroecological transition offers a promising pathway to reduce these impacts, but it requires profound changes in cropping systems, farming practices, and innovation strategies (Wezel et al., 2014). Prototyping methods, combining expert knowledge, experimental field trials, and multi-criteria assessment, have emerged as useful tools to design and evaluate such transitions in diverse contexts (Lançon et al., 2007; Keating et al., 2010). However, the effectiveness of available levers remains partial. Some strategies focus on improving efficiency (e.g., optimized spraying), while others promote the substitution of synthetic inputs by biocontrol solutions. The most transformative strategies aim to redesign the entire production system. This gradient of transition is well captured by the ESR framework (Efficiency – Substitution – Redesign), initially proposed by Hill and MacRae (1996), and later adapted to classify and assess agroecological innovations (Wezel et al., 2014; Merot et al., 2019). Despite promising results in annual crops, the application of this framework to perennial systems remains limited.

Viticulture provides a particularly relevant case to explore this transition, as vineyards are among the most pesticide-intensive cropping systems in Europe. French vineyard management relies on a large number of technical operations—up to 20 per year—including frequent pesticide applications (Christ and Burritt, 2013). A 2016 national survey by the French Ministry of Agriculture reported an average Treatment Frequency Index (TFI) of 15.3 in vineyards, with fungicides accounting for more than 80% of treatments, and biocontrol solutions representing a marginal share (Agreste, 2023). This high pesticide reliance persists despite ambitious public policies such as the Ecophyto plan, which aimed at reducing pesticide use in France by 50% (Hossard et al., 2017). Beyond pesticide use, vineyard systems also face structural constraints to agroecological transition: low agrobiodiversity due to the dominance of a few grapevine varieties (This et al., 2006) and simplified soil management practices (herbicides, tillage) that limit field biodiversity (Fried et al., 2022; Cohen et al., 2015). At the same time, grape production is driven by high expectations of product quality and profitability, increasing the complexity of change. Nevertheless, societal, regulatory, and market pressures are pushing winegrowers towards more sustainable systems (Jourjon et al., 2016; Renaud-Gentié et al., 2018).

Research initiatives have sought to develop low-input vineyard systems tailored to local conditions, as illustrated by the French Ecoviti project, which adapted prototyping methods—originally developed for annual crops—to the perennial context of viticulture through field experiments, participatory design, and multi-criteria evaluations (Lafond et al., 2013; Dardonville et al., 2021; Thiollet-Scholtus et al., 2021). However, three major knowledge gaps continue to hinder the development and dissemination of agroecological viticultural systems. First, although the ESR (Efficiency–Substitution–Redesign) framework has proven valuable for analyzing transitions in annual cropping systems, its application to perennial crops like vineyards remains scarce, limiting our capacity to understand and support transformative redesign in these complex and long-lived systems (Wezel et al., 2014). Second, prototyping approaches remain underdeveloped for perennial crops and have yet to be robustly tested across varied pedoclimatic contexts, restricting the emergence of context-specific, evidence-based strategies (Martinson et al., 2016). Third, while several agroecological levers exist to reduce pesticide use—such as biological monitoring, epidemic modelling, mechanical weeding, or mating disruption—their adoption is often constrained by technical, economic, and organizational barriers (Kuhfuss and Subervie, 2018; Dagostin et al., 2011). Furthermore, sustainability assessments frequently overlook the need for integrated, multi-dimensional evaluations that address agronomic, environmental, and socio-economic dimensions, limiting our ability to evaluate and scale up innovative systems (Renaud-Gentié et al., 2018). In Thiollet-Scholtus et al. (2021), a small number of regional prototypes are evaluated in detail. This study proposes a change of scale to the size of a country with a preliminary assessment of the broad sustainability dimensions of a larger number of prototypes with a view to adoption. In this way, prototypes are selected and a refined evaluation will be proposed to validate the adoption of these prototypes on a country-wide scale by commercial farms. This study addresses these gaps by applying the ESR framework to analyse and classify innovative grapevine systems, providing insights into their performance, feasibility, and potential for wider adoption.

Consequently, the objectives of this study are (i) to apply an adapted version of the prototyping method, initially developed for annual crop management systems (Lançon et al., 2007), to the specificities of grapevine systems in a large diversity of soil and climate locations in France, (ii) to characterise these new grapevine systems in term of agroecological transition, using the ESR framework and (iii) to assess the key agronomic, environmental and socio-economical performances of these systems.

2. Material and methods

2.1. *The national network of the EcoViti project*

The EcoViti Project involves the six of the major French wine-growing regions with (Lafond et al., 2013): Alsace, Bordeaux, Cognac, Loire Valley, Mediterranean and South West. These six regional sub-projects were coordinated by IFV (Cognac, Loire valley, South-West), INRAE (Alsace, Bordeaux) or the Regional Chamber of Agriculture (Mediterranean). In total, 36 partners were involved in the network: local Chambers of Agriculture, professional organisations, technical agricultural education, associations and private operators.

2.2. *Prototyping method adapted to perennial crops and multisite implementation*

2.2.1. *The prototyping framework adapted to perennial crops*

The prototyping method initially designed for annual cropping systems (Lançon et al., 2007) is based on previous and published results combining three methods which have been adapted to vineyard specificities (perennial, quality product, labour and pesticides intensive). Fig. 1 gives details of the three steps of the methodology:

Step 1: design. Before designing a prototype, a Set of Objectives (eg. Yield target) and Constraints (SOC) (eg. A maximal amount of labour hours per year) is defined with stakeholders in order to guide the design and further on to be used in step 3 to define assessment indicator. Each prototype of grapevine systems was then designed by a focus group of experts and then adapted for field experiments. This design phase was based on the mobilisation of a conceptual model of the agroecosystem (Lamanda et al., 2012) that synthesised the current knowledge about the functioning of the climate-soil-vine-pathogens system. While the SOCs were specific to a region the same conceptual model was used in all focus groups in order to build a common understanding of the grapevine system and improve knowledge sharing among regions and among experts and scientists involved in the workshop.

Step 2: test and adjustment loop. After implementation of these prototypes in field experiments, they are assessed using indicators for the assessment of the system's performance ("assessment" indicators), for the analysis of the behaviour of a component ("analysis" indicators) or as an input variable of a decision rule for the system's management ("assessment" indicator) (Rapidel et al., 2009). The prototypes which do not reach the targets for all assessment indicator defined in the SOC step back to step 1 in order to adjust (i) the SOC (i.e. the expected performances like for example the target yield and/or the constraints like for example the maximal workload) (ii) the cropping system changing its structure (e.g. adding a new component like a cover-crop) and/or it's input (e.g. reducing further pesticides spraying with a decision rule conditional to disease severity.

Two national workshops were held in Bordeaux and Angers to introduce the overall methodology and collaboratively develop a conceptual model of a grapevine system. These workshops provided the first examples of SOCs and theoretical prototypes. Building on this foundation, each region conducted specific prototyping workshops to adapt the theoretical prototypes to their own SOCs. These regional workshops brought together around 30 experts per session—grapevine professionals and scientists from various disciplines, including agronomy, plant protection, soil and nutrient management, genetics, machinery, and viticulture—amounting to a total of 63 participants.

Experts were selected based on the themes addressed in the national workshops, such as reducing fungicide doses for mildew control or introducing biocontrol products for pest and disease management. During the design workshops, participants were encouraged to think creatively about the structure and management of grapevine systems, while retaining only solutions that could realistically be implemented by

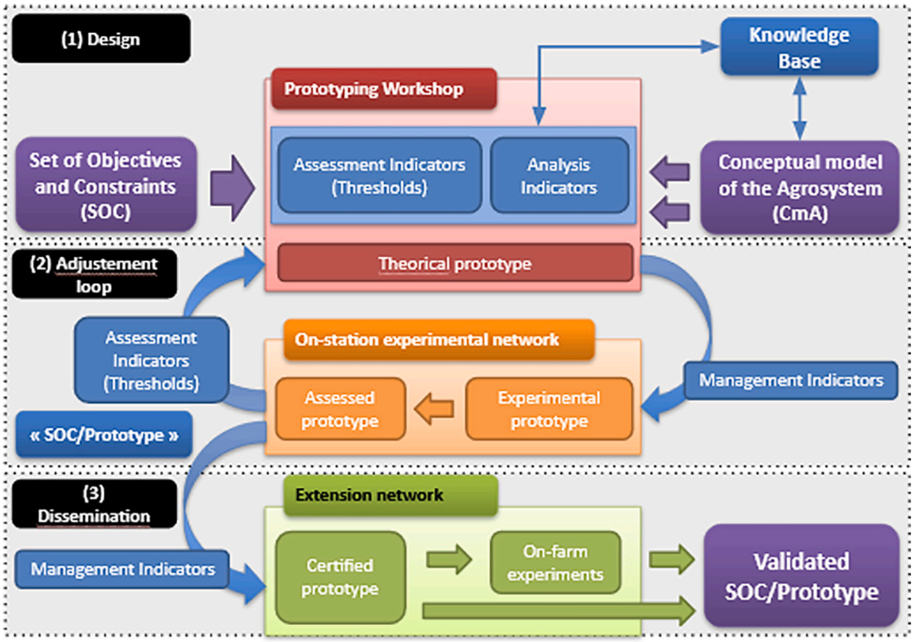


Fig. 1. Methodological framework developed for the prototyping of perennial cropping systems in the EcoViti project (Lafond et al., 2013), structured in three steps: design, test and adjustment loop, dissemination. Step 3 is not presented in the article.

- Step 1 (Design) = From 2012 to 2013 with two national workshops (for global strategies for pesticide reduction) and one regional workshop in each regional context. One national conference was organized in 2014 for dissemination of methods and results for Step 1.
- Step 2 (test and adjustement loop) = From 2013 to 2018 with annual assessment in the 7 regions of Ecoviti network for validation and adjustement of the prototypes.
- Step 3 (Dissemination) = Each region provides a technical paper to present the results (2018).

farmers. This process resulted in a "theoretical prototype," which was then adjusted to accommodate the constraints of the experimental farm (e.g., limited equipment), leading to the development of an "experimental prototype" that was tested in the field (Lançon et al., 2007). Each experimental prototype included a strategic component (e.g., grape variety, defined once) and a tactical component, consisting of decision rules applied annually or multiple times per year (e.g., fungicide treatments targeting specific diseases). The prototype was designed to align with a given SOC, combining the technical specifications of the regional appellation (production goals, grape varieties, planting density, training system) with the performance expectations of farmers and markets. For example, appellation requirements—particularly yield targets—influenced key strategic choices such as irrigation, fertilization, pruning, canopy management, and mechanical harvesting. Performance expectations also shaped tactical decisions, such as prioritizing biocontrol approaches, which led to banning herbicides and relying exclusively on biocontrol agents for pest and disease management (see Supp. Mat. Table S.1).

2.2.2. *Definition of the sets of objectives and constraints (SOC)*

31 sets of objectives and constraints (SOC) were built in the six wine-growing regions of the Ecoviti project (Table 1). The SOCs list, for each region, describes (i) the production objectives and expected performances in agronomic, technical, environmental, social and economic terms, and (ii) the climatic, biotic and technical constraints of the production area. Perennial cropping systems must address long-term issues (planting renewal time and plant life of several decades in viticulture) (Lafond and Metral, 2015). The SOC has to rank the objectives for the assessment of the prototypes and for multicriteria analysis (e.g. pesticide reduction, yield, gross margin, …). The readjustment of SOC can be done after the first tests of the prototypes (see adjustment loop in Fig. 1).

2.3. *Regional implementation of the prototyping method*

The network allowed the experimentation of 45 grapevine systems spread over 27 experimental sites. 14 systems were certified as Organic or potentially compatible with these specifications (non-certified farms, but exclusive use of natural products in experimentation). Organic systems are included in our study because they are agroecological systems. We have selected some organic systems because they benefit from an international certification system and a recognized supply chain in viticulture. The network of grapevine systems did not aim to be representative of the French vineyard. Nevertheless, it allowed the testing of "low input" systems in a wide variety of wine-growing regions (Table 2):

- soil and climate situations, with Mediterranean, continental and oceanic;
- types of production, with 73% of the systems in Protected Designation of Origin (PDO) (including 10% for the production of Brandy), 17% in Protected Geographical Indication (PGI) and 10% of Wine Without Geographical Indication (WWGI);
- planting densities, from 3000 to over 7000 plants/ha;
- yield targets between 5 and 18 tons/ha.

Table 1
Number of Set of Objectives and Constraints and experimental prototypes defined in the six grapevine production areas of the EcoViti project. One SOC led to one or more prototypes.

Grapevine production areas	Number of SOCs	Number of experimental prototypes
Alsace	6	11
Bordeaux	8	11
Cognac	3	4
Loire valley	3	3
Mediterranean	8	12
South-West	3	4
TOTAL	***31***	***45***

2.4. *Classification of the prototypes according to the efficiency substitution redesign framework*

The prototypes of the national EcoViti network were classified with the Efficiency-Substitution-Redesign framework which classifies combinations of technical changes in the transition pathway of a grapevine system (Merot and Wery, 2017):

- changes aimed at higher efficiency (E) of pesticide inputs, for example with the help of decision support tools (DSS);
- changes aimed at substituting (S) organic or biocontrol solutions for synthetic pesticides;
- full redesign (R) of the grapevine system, including the planting of disease-resistant varieties with new training systems, the use of cover-crops and the installation of agroecological infrastructures (such as hedgerows with pest suppressive impact).

2.5. *Overall assessment of the grapevine systems designed with the prototyping method*

Systems experiments (i.e. field testing and multi-criteria assessment of a prototype (Debaeke et al., 2009)) aims to test and compare specific combinations of techniques instead of a limited set of techniques in factorial experiments. Multicriteria assessment methods have been applied to viticulture (Beauchet et al., 2020; Pelzer et al., 2012; Renaud-Gentié et al., 2020; Thiollet-Scholtus and Bockstaller, 2015). These methods can assess a diversity of existing vine systems but are complex to implement for a large and diverse network of prototypes. The aim of the evaluation of the prototypes is to give a first view of some performances in every dimension of sustainability. It assumes that cropping systems performances are primarily dependent on interactions between several management techniques which are difficult to experiment in a factorial experiment necessarily restricted to a limited number of techniques (2 or 3 in most factorial experiments). Therefore, in a system experiment, the comparison of experimental treatments is only valid for the specific combinations of techniques and does not allow to assess the individual effect of a technique. On the other hand, in these experiments the comparison is done with a larger set of assessment indicators aimed to cover the biophysical and socio-economic dimensions of the targeted sustainability (defined by the SOC). The indicators and their interpretation thresholds (e.g. minimum desired yield) have been discussed in national prototyping workshops and have been decided during the definition of the SOCs. As a consequence, thanks to the very large number of prototypes throughout France, the number of indicators selected was more restricted than for a similar study based in a single vineyard (Thiollet-Scholtus et al., 2021), to make the evaluation feasible on a larger geographical scale. In addition, the indicators selected were identical to those used in previous studies (Aouadi et al., 2021; Wyler et al., 2023), to enable a discussion of the performance of our prototypes. All indicators were determined thanks to the conceptual model of the agroecosystem as defined in step 1 of the method. The objective of agroecological transition in the prototype design exemplifies the need to combine high ambitions both in terms of environmental performance and economic performance for example strongly reducing pesticide use and maintaining a high level of grape quality and the target yield necessary for farmers income**.** Based on the article *"The blurred boundaries of ecological, sustainable, and agroecological intensification: a review" by* Wezel et al. (2014), agroecological intensification refers to improving the performance of agriculture while minimizing environmental impacts and reducing dependency on external inputs, through the integration of ecological principles into farm and system management. It emphasizes a systemic approach, incorporates social and cultural dimensions, and promotes the use of local and traditional knowledge. We defined 4 levels of performance from AEI 1 (Low level of agroecological intensification)

Table 2
Description of the main characteristics of the six vine-growing regions contributing to the Ecoviti network.

Region	Climatic zones[2]	Type of production (PDO, PGI, WWGI[1])	Prototype ID[3]	Yield objective (t.ha^{-1})	Vine density (vines.ha^{-1})	Current TFI mean (2019)[4]
Alsace	Temperate continental climate, warm with moderate precipitation	PDO Alsace Grand Cru Osterberg	A1	10	4464	14,9
		PDO Alsace Grand Cru Osterberg	A2	10	4464	14,9
		PDO Alsace	A3, A4, A5, A6	13	4850	14,9
		PDO Alsace	A7, A8, A9	10,98	3922	14,9
		PDO Alsace	A10	12,55	5348	14,9
		PDO Alsace	A11	7,84	4167	14,9
Bordeaux	Warm oceanic climate, more rainy but fewer wet spring days	PDO Pessac-Leognan	B1, B2	7,50	6580	17,2
		Vin de France (WWGI)	B3	10	6580	17,2
		PDO Bordeaux	B4	8,40	3333	17,2
		PDO Bordeaux	B5, B6	7,15	3333	17,2
		PDI Atlantique	B7	10,40	3150	17,2
		PDO Montagne St Emilion	B8	6,90	5000	17,2
		PDO Sauternes	B9	2,60	6500	17,2
		PDO Saint Emilion	B10	6,90	6060	17,2
		PDO Bordeaux	B11	7,15	3636	17,2
Cognac	Warm oceanic climate, more rainy but fewer wet spring days	PDO Cognac	C1	16	3333	18
		PDO Cognac	C2, C3	16	4000	18
		PDO Cognac	C4	16	3000	18
Loire Valley	Temperate maritime-influence climate, warm with moderate precipitation	PDO Saumur rouge	L1, L2	7,3	6000	15
		PDO Muscadet	L3	8,8	5000	15
Mediterranean	North Mediterranean climate, warm and moderate precipitation	PDO Crozes Hermitage (Drôme)	M3	5,83	4630	13,6
		PDO Côtes de Rhône (South)	M4, M9	6,63	4444	12,7
		PDO Malepère (Aude)	M6, M10	7,14	5000	14
		PDO Côtes du Roussillon (Pyrénées Orientales)	M11	5	3333	10,4
		PDI Languedoc (Hérault)	M1, M2, M7, M8	12,80	4000	14
		Vin de France (WWGI) (Gard)	M5	12,30	4040	14
		PDI Languedoc (Pyrénées Orientales)	M12	10	4000	10,4
South-West	Warm oceanic climate, more rainy but fewer wet spring days	PDO Gaillac (Tarn)	S1, S2	7,15	4545	15,7
		PDI Comté Tolosan (Tarn)	S3	11,7	4545	15,7
		PDI Côtes de Gascogne (Gers)	S4	18	4000	18,9

[1] PDO: Protected Designation of Origin specification, PDI: Protected Geographical Indication, WWIG: Wine Without Geographical Indication.
[2] (Blenkinsop et al., 2008). Classification of the European region into 16 FOOTPRINT climatic zones.
[3] See Table 4 for Prototype ID descriptions.
[4] Agreste, 2021.

to AEI 4 (High level of agroecological intensification). Table 3 describes the criteria and the thresholds used for each indicator and their four AEI levels. **Agronomic performances** are assessed with two indicators:

- **Yield indicator**: a target yield was defined for each SOC (and its associated prototypes) and each year (especially for a young vine in the case of a new plantation). The following ratio was calculated with Eq. (1):

$$\text{Yield indicator} = (\text{Actual yield–Target yield})/\text{Target yield} \tag{1}$$

where Target yield = Minimum (Objective yield; Reference yield).

If a reference yield (control plot) is available and does not reach the objective yield (defined in the SOC), the yield indicator compares the actual yield to the reference yield. In that case, we assumed that as the reference yield did not achieve the objective yield, there were external factors to the tested cropping system that impacted the production (e. g. climatic incident). Otherwise, if the reference yield was over the objective yield, the yield indicator compared the actual yield to the objective yield. We considered that the prototype satisfied the objectives. The highest-level AEI 4 allowed a maximum yield loss of −5%. AEI 3 corresponded to a yield decrease between −15% and − 6% (no difference between EAEI 3 and AEI 2 according to the focus groups). Over −16% of yield loss, the yield performance was considered in the lowest level AEI 1.

- **Harvest damage indicator**: The reference was no damage on harvested grapes in order to maintain yield and quality. The highest-level AEI 4 is defined by damages below 10%, AEI 3 level between 11% and 15%, AEI 2 level between 16% and 25%. Over 25% of harvest damages, the performance is considered in the lowest level AEI 1.

Environmental performance was assessed with the Treatment Frequency Index as a proxy of an indicator of pesticides on the environment.

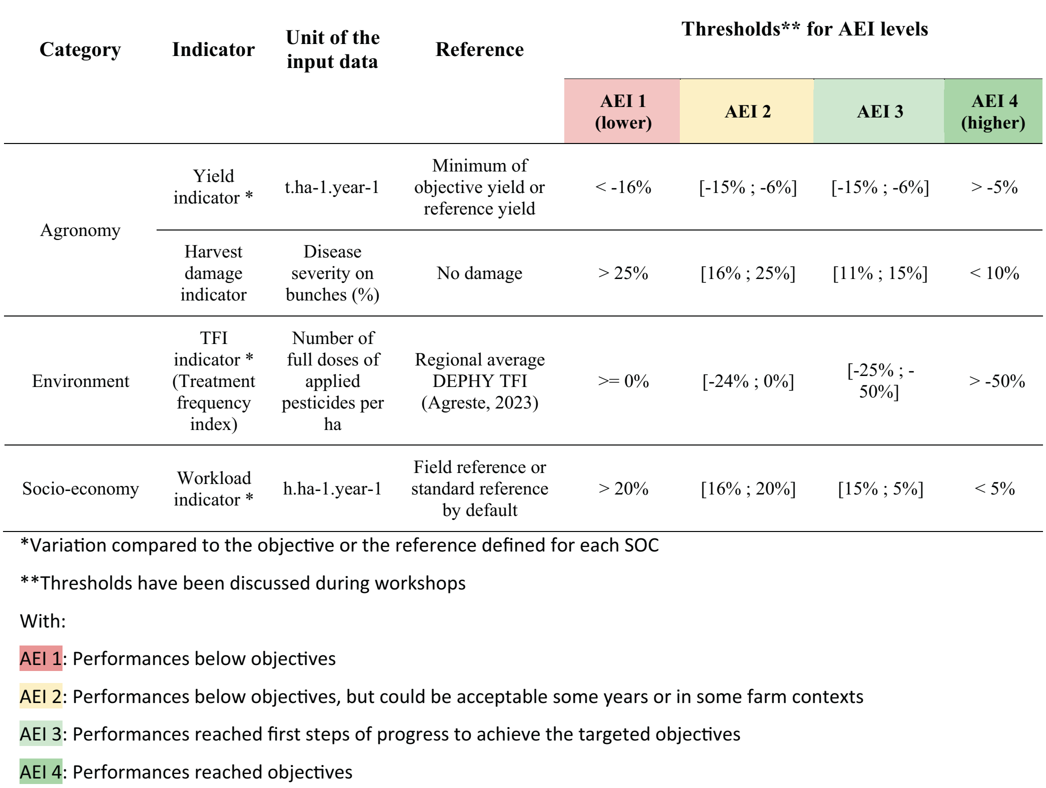
- **TFI Indicator**: Treatment Frequency Index (TFI, Eq. (2)) measures the quantity of product doses applied in comparison with the recommended official dose for each pesticide. TFI is the metrics to measure reduction and quantity of pesticide use. A TFI decrease is expected to limit the impact on the environment (Butault et al., 2010). This index was calculated annually for each plot.

$$\text{TFI} = \sum \left((\text{AR}_t/\text{HR}_t) \times (\text{TA}_t/\text{PA}) \right) \tag{2}$$

Eq. (2) Calculation of the TFI (Pingault et al., 2009) for a given year at the cropping system scale. The TFI equals the sum, for all treatments, of the TFI per treatment, where one treatment corresponds to one product t sprayed and one date of application, with AR_t the dose of product t applied HR_t the registered or recommended dose of the product, TA_t the area of the plot treated with product t, and PA the plot area.

Table 3

Assessment indicators, definitions and thresholds for interpretation depending on the agroecological intensification levels (AEI) for sustainability assessment.



Category	Indicator	Unit of the input data	Reference	Thresholds** for AEI levels			
				AEI 1 (lower)	AEI 2	AEI 3	AEI 4 (higher)
Agronomy	Yield indicator *	t.ha-1.year-1	Minimum of objective yield or reference yield	< -16%	[-15% ; -6%]	[-15% ; -6%]	> -5%
	Harvest damage indicator	Disease severity on bunches (%)	No damage	> 25%	[16% ; 25%]	[11% ; 15%]	< 10%
Environment	TFI indicator * (Treatment frequency index)	Number of full doses of applied pesticides per ha	Regional average DEPHY TFI (Agreste, 2023)	>= 0%	[-24% ; 0%]	[-25% ; -50%]	> -50%
Socio-economy	Workload indicator *	h.ha-1.year-1	Field reference or standard reference by default	> 20%	[16% ; 20%]	[15% ; 5%]	< 5%

*Variation compared to the objective or the reference defined for each SOC

**Thresholds have been discussed during workshops

With:

AEI 1: Performances below objectives

AEI 2: Performances below objectives, but could be acceptable some years or in some farm contexts

AEI 3: Performances reached first steps of progress to achieve the targeted objectives

AEI 4: Performances reached objectives

The assessment was based on the percentage of TFI reduction compared to a reference. The reference was the average of DEPHY TFI surveyed in a network of farmers' fields in 2013 and 2016 and published by the French Ministry of Agriculture (Agreste, 2023). DEPHY TFI is calculated at regional scale for each crop production. The average DEPHY TFI of the studied vineyards were: Alsace = 12.9, Bordeaux = 17.1, Cognac = 18.1, Loire Valley = 14.3, Mediterranean region = 13.6 (Languedoc) and 9.8 (Pyrénées-Orientales) and 13.2 (North Rhone valley), South-West = 15.6 (Gaillac) and 19.1 (Gers). In a vineyard with more than one data (Mediterranean and South-West), we average the data to get a reference for the vineyard. The TFI indicator is calculated with the following ratio (Eq. (3)):

$$\text{TFI indicator} = (\text{Prototype TFI} - \text{DEPHY TFI Reference}) / \text{DEPHY TFI Reference} \tag{3}$$

The thresholds of the French national Ecophyto 2 plan were used for the AEI ranking. Ecophyto 2 plan aims for a TFI reduction of 50% with an intermediate objective of 25% of TFI reduction.

The highest-level AEI 4 is achieved with a TFI indicator over −50%, AEI 3 level with a TFI indicator between −50% and − 25%, AEI 2 level with a TFI reduction between −24% and 0%. With no TFI reduction (TFI indicator >0%), the performance was considered in the lowest level AEI 1.

Socio-economic performance was assessed with the recorded workload of the experimental prototype. When restriction of number of indicators is needed, choosing the right indicator is crucial. Considering workload is an essential prerequisite when evaluating prototypes because it will be decisive for the validation and then dissemination of prototypes in commercial farms. Perinelle Edemetti et al. (2022) have clearly identified farmers' criteria for adopting more agroecological farming systems. Labour management is one of the 6 criteria identified. And workload is directly linked to labour management thanks to changes in practices in the prototypes. Consequently, this will influence the potential adoption of the prototypes by winegrowers. Aouadi et al., 2021 and Wyler et al., 2023 used workload indicator to evaluate existing inequalities in terms of workload between some vineyard plots. An increase of workload compared to the target was considered as a non-sustainable intensification trajectory of the cropping system. Then, workload indicator is considered in this study as a proxy of the socio-economic acceptability of the prototype by winegrowers. In addition, during the two national workshops held in 2012 and 2013, the actors suggested that the workload indicator is the first step of a potential acceptability of the innovative prototypes by farmers. Workload indicator calculates the variation of working time in hours per year between the tested prototype and the regional references. Our objective is to make a first and simple economic assessment as suggested in Finger et al. (2024) with the necessity for interdisciplinary approaches and improved policy analysis tools to better represent farmer behaviour and economic levers (e.g. profitability, revenues, costs). To conclude, we assume our approach as a preliminary assessment of socio-economic acceptability.

- **Workload indicator**: The workload indicator is calculated with the following ratio (Eq. (4)):

$$\text{Workload indicator} = (\text{Prototype workload} - \text{Reference workload}) / \text{Reference workload} \tag{4}$$

The reference was the workload of a control plot if it is available. Otherwise, the reference was given by regional figures of the extension and advisory viticultural services.

2.6. Data analysis

Data were collected in every studied region from 2013 to 2018 (Dataset is published and available at: https://doi.org/10.18167/DVN1/743UAT). As some data were missing, evaluation results were preferably presented as percentages (of the objective value) rather than absolute values. Then, the performance assessment was based on an evaluation of how the TFI reduction did or did not compromise each one of the other assessment indicators: the yield and the quality of the grapevine production (economic performance) and the social performance (with workload indicator). The bivariate performance TFI-other indicator of the grapevine systems was plotted in XY graphs, comparing (i) TFI indicator and Yield indicator, (ii) TFI indicator and Harvest damage indicator, (iii) TFI indicator and Workload indicator. We used the mean value of six-year experiments and an inter-annual variation. Because we considered that it is relevant for robustness of assessment results of grapevine systems to have both.

3. Results

3.1. Characteristics of the prototypes designed during the regional workshops

In relation with the local SOCs (see supplementary materials SOCs Ecoviti.xlsx), from four to twelve grapevine prototypes were designed by region, representing a total of 45 grapevine prototypes (Table 4).

The 45 grapevine prototypes mobilised various types of technical changes used separately or combined (See Supp. Mat. Table S.1 for the InnoBio prototypes). Organic practices are included in technical changes in 14/45 prototypes and aimed to take into account no use of synthetic pesticides or fertilizers.

With the operators of the experiments, the 45 grapevine prototypes were grouped in four types according to the different changes selected and their relative level in the ESR framework (Table 4):

- type E1 (24%; 11/45 prototypes) was close to conventional grapevine systems. The main technical change was the use of DSS for reducing the number and rate of pesticide spraying. No E1 grapevine prototypes was under organic label;
- type E2 (47%; 21/45 prototypes) was similar to E1 with several additional prophylactic practices to reduce pests and diseases pressure (e. g. disbudding, early leaf removal, export of winter pruning wood);
- type ES (22%; 10/45 prototypes) mobilised both DSS and biocontrol for reducing pesticide use with additional prophylactic practices. A majority of ES grapevine prototypes was under organic label (80% and 8/10 ES_prototypes);
- type ESR (7%; 3/45 prototypes) was mostly based on disease-resistant varieties to downy and powdery mildew, and on the installation of ecological infrastructures.

Our hypothesis was basically based on a deep redesign of the grapevine systems to implement agroecological transition for a perennial crop. However, only 7% of the grapevine prototypes were ESR type. The first explanation was the very low availability of resistant variety plants for new grapevine plantations at the beginning of the study (2012). And secondly, replantation of new resistant varieties could not be the main lever or solution for the vine and wine sector. We made the choice to deal with the redesign of the already planted vineyards which represent the huge part of the grapevine area in France. We wanted to explore and experiment how to redesign planted vineyards for agroecological transition.

Table 4

Main features of the 45 experimental prototypes of low pesticide-use wine growing cropping systems. Prototypes were named by a letter for the region and by a serial number; A: Alsace; B: Bordeaux; C: Cognac; L: Loire valley; M: Mediterranean; S: South-West France. In the DSS and biocontrol domains, the prototypes could mobilize a "low", "medium" or "high" number of technical lever (with Low = advice based on regional adviser surveillance network, Medium = one DSS (Mildium® or Optidose), High = monitoring + Mildium® + Optidose methods). In the soil surface management domain, when two techniques are indicated, they were applied alternately every other inter-row. Type definition from ESR typology (Merot and Wery, 2017): E1 = use of DSS for reducing the number and rate of pesticide spraying, E2 = E1 + additional prophylactic practices, ES = use of both DSS and biocontrol for reducing pesticide use with additional prophylactic practices, ESR = use of disease-resistant varieties to downy and powdery mildew, and installation of ecological infrastructures. Fourteen of the 45 prototypes follow organic specification recommendations practices for vineyard management.

Prototypes	DSS	Biocontrol	Organic	Resistant variety	Inter-row management	Under vine management	Type
B5 B6	high	low	no	no	perm/temp cover crop	herbicide	E1
M1 M2	high	low	no	no	temp cover crop	tillage	E1
M3 M4 M5 M6	high	low	no	no	temp cover crop / tillage	tillage	E1
B7	high	no	no	no	perm cover crop	perm cover crop	E1
B8	high	no	no	no	perm cover crop / tillage	tillage	E1
S4	high	no	no	no	temp cover crop	perm cover crop	E1
A10	high	medium	yes	no	perm cover crop	tillage	E2
B4	high	low	no	no	perm/temp cover crop	herbicide	E2
C1	high	low	no	no	perm cover crop/tillage	tillage	E2
A3	high	medium	no	no	temp cover crop / tillage	herbicide and tillage	E2
A8	high	low	no	no	perm cover crop	tillage	E2
B2 B10 S1 S2	high	low	yes	no	perm cover crop / tillage	tillage	E2
A11	high	low	yes	no	perm cover crop	tillage	E2
C2 C3 C4	high	no	no	no	perm cover crop	herbicide	E2
L1	high	no	no	no	perm cover crop	perm cover crop	E2
B1 B9 B11 L2	high	no	no	no	perm cover crop / tillage	tillage	E2
S3	high	no	no	no	perm cover crop / tillage	perm cover crop	E2
A9	medium	low	no	no	perm cover crop	tillage	E2
A7	no	low	no	no	perm cover crop	herbicide	E2
A2	high	high	yes	no	perm cover crop / tillage	perm cover crop	ES
M9 M10 M11 M12	high	high	yes	no	temp cover crop / tillage	tillage	ES
M7 M8	high	high	yes	no	temp cover crop	tillage	ES
A4	high	medium	yes	no	temp cover crop / tillage	Mulch and tillage	ES
A1	medium	medium	no	no	perm cover crop / tillage	herbicide	ES
L3	medium	medium	no	no	perm cover crop	temp cover crop	ES
B3	medium	no	no	yes	temp cover crop	tillage	ESR
A5	medium	no	no	yes	temp cover crop / tillage	herbicide and tillage	ESR
A6	no	low	no	yes	temp cover crop / tillage	tillage	ESR

See supplementary material (Table S.1) for an example of the InnoBio grapevine prototype.

In the Decision Support System (DSS) for **pest and disease control**, the grapevine prototypes mobilised a “low”, “medium” or “high” number of technical levers (with Low = advice based on regional adviser surveillance network, Medium = one DSS (Mildium® or Optidose), High = monitoring + Mildium + Optidose). These two DSS were based on decision rules based on disease monitoring and modelling. Mildium® aimed at reducing the number of pesticide sprayings by making each intervention conditional on various types of criteria being met. As a consequence, the time between two sprayings could be longer and some sprayings could be cancelled. Sprayings against powdery mildew were based on observations of symptoms in the field and of grapevine phenology. Optidose adjusted the pesticide doses applied according to the actual vine leaf area, the disease pressure and the grapevine phenology (Davy et al., 2010). Campos et al. (2020) confirmed that the “variable rate application” to reduce the sprayed-dose of pesticide can achieve the goal of TFI reduction and powdery mildew control. Our results with E1 and E2-prototypes based on use of DSS Optidose (spraying adapted to canopy characterization) shown the same conclusions. With DSS Mildium®, sprayings against downy mildew depended on observations of symptoms in the field, which is an indicator of risk at local scale and rain forecast (Deliere et al., 2015).

Fourteen grapevine prototypes had organic labels imposing to select pesticides only from a limited list. Biocontrol of pests and diseases consisted in combining preventive actions and use of alternative products in which the preferred active substances were microbial agents, or microorganism or plant extracts (Pertot et al., 2017). The grapevine prototypes combined practices such as mate disruption, biological control (e.g. the hyperparasite *A. quisqualis* for reducing the inoculum of powdery mildew), use of sulphur-based products, essential oils, and paraffin oil.

Three grapevine prototypes were based on the use of novel varieties resistant to downy and powdery mildew. These experimental varieties were provided by the Inrae-ResDur breeding program that aims at creating grape varieties with sustainable resistance to both downy and powdery mildew (Merdinoglu et al., 2018).

Soil surface management was mainly based on a combination of cover cropping and mechanical weeding. The area covered by cover-crops and the duration of its vegetation cycle varied according to the risk of competition for soil resources (especially water and nitrogen) with grapevine yield objectives and the ecosystem services expected from cover crops (Delpuech and Metay, 2018). Yet in 10 of the 45 prototypes, herbicides were still used under the vine row because mechanical weeding was difficult to manage. All prototypes avoided herbicides on the inter-row.

Each prototype included a strategic component and a tactical component made of decision rules. For example, the “InnoBio” strategy assessed in the Mediterranean region (prototypes M8 to M12) resulted from a SOC meeting both the specifications of the regional appellations (production objective, grape varieties, density and training system) and the priority given to biocontrol (See Supp. Mat. Table S.1). The specifications of the appellations (i.e. Protected Designation of Origin), in particular the yield objective, induced some strategic technical choices: irrigation, fertilization, pruning, canopy management and mechanical harvest. The priority given to biocontrol led to ban herbicides use and to use biocontrol agents to control pests and diseases, including some not allowed in organic farming. Within this strategic framework, tactical management was designed with decision rules that guided the day-to-day running of the experimental prototypes. For pest and disease management, decision rules were those described in Mildium® (Deliere et al., 2015) and Optidose (Davy et al., 2010) (see before in 3.1.).

3.2. *Multi-performances of the grapevine prototypes*

The performances of the grapevine prototypes were analysed using several bivariate approaches to analyse the mean performances over the 6 years of the projects. With the thresholds of each indicator, areas of agroecological intensification (AEI levels) have been drawn and helped for results analysis (Table 3). First, we analysed the potential trade-off between environmental indicator (TFI) and agronomic performance (yield and harvest damage) thanks to Fig. 2 and Table 6 during the 6 years, then, the potential trade-off between environmental indicator (TFI) and socio-economic indicator (workload) (Table 7), both during the 6 years. And finally, Table 8 illustrated the potential trade-off for all the performances together for the average of the 6 years.

3.2.1. *Pesticide reduction and yield*

The first bivariate approach analysed was **Yield and TFI performances** of the prototypes (Fig. 2 and Supp. Mat. Table S.2). The relationships between the two variables gave an indication of the trade-offs between agronomic performance (yield) and environmental performance related to the reduction of pesticides use (assessed with the TFI indicator). Firstly, 38% of the prototypes (17/45) corresponded to the **high-level AEI 4** of the agroecological intensification target (dark green zone of AEI 4 in Fig. 2). Their TFI reduction was below −50% and could reach −100% with the A6 ESR_prototype. Their yield reduction was over 5% (the Yield indicator = (Actual yield - Target yield)/Target Yield = −5%): A10 ES_prototype even achieved 111% over the objective yield. These high performance prototypes represented 27% of the E1 type (3/11), 40% of the E2 type (8/20), 18% of the ES type 2/11) and 100% of the ESR type (3/3). Secondly, 38% prototypes (17/45) corresponded to the **level AEI 3** of the agroecological intensification target (light green zone of AEI 3 in Fig. 2). At least one of the two indicators was under the AEI 4 objectives. Their TFI reduction was below −25% and could reach −70% with the S3 E2_prototype. Their yield reduction was over −15%: S2 E2_prototype achieved only 62% over the objective yield. Fifty-four percent of the prototypes E1 type (6/11), 45% percent of the prototypes E2 type (9/20), 18% of the prototypes ES type (2/11), and none ESR type (0/3) were in this intermediate area of performances (level AEI 3) that could be acceptable for a part of their results. Thirdly, 11% of the prototypes (5/45) were in the **level AEI 2** of the agroecological intensification target (yellow zone of AEI 2 in Fig. 2). In this zone, their TFI reduction was below 0% but did not reach the expected limit of −25%. However, the Yield indicator was at least at the AEI 3 level. All the 5 prototypes were of ES type. The minimum value of the TFI indicator was −14% for M11, and the maximum was −24% for M8. The minimum value of the Yield indicator was −7% for M8, and the maximum was 18% for L3. Finally, 13% of the prototypes (6/45) corresponded to the **level AEI 1** of the agroecological intensification target (red zone of the AEI 1 in Fig. 2). The M12 ES_prototype achieved the AEI 4 level for the yield indicator with a result of 3% but failed to reach it on the TFI indicator with a result of 3% (no reduction). The 5 other prototypes failed on the yield indicator: the minimum yield indicator is −36% for B6 E1_prototype and the maximum was −19% for L1 E2_prototype. However, these 5 prototypes reached the AEI level 3 for the TFI indicator: the minimum was −29% for B6 E1_prototype and the maximum was −68% for L1 E2_prototype.

Our results shown that some prototypes were able to provide a trade-off of a high yield (agronomic indicator) with a reduction of more than 40% of pesticide use (environmental indicator). To summarise, the joint analysis of yield and TFI performances shown that 76% of prototypes achieved AEI 3 level or more. In addition, we demonstrated trade-offs between yearly environmental (TFI) and agronomic (yield) performances exist in all the E1, E2, ES and ESR types. Finally, 64% of ES_prototypes were in the AEI 2 level and lower with insufficient results for the environmental (TFI) and agronomic (yield) trade-off.

3.2.2. *Pesticide reduction and vine health*

The second bivariate approach analysis was **harvest damage and TFI performances** of the prototypes with the pluri-annual results in Table 6 (See also Supp. Mat. Fig. S.2).

Firstly, 36% of prototypes (16/45) reached **the AEI 4 level** of agroecological intensification (dark green zone - level 4 in Table 6) with

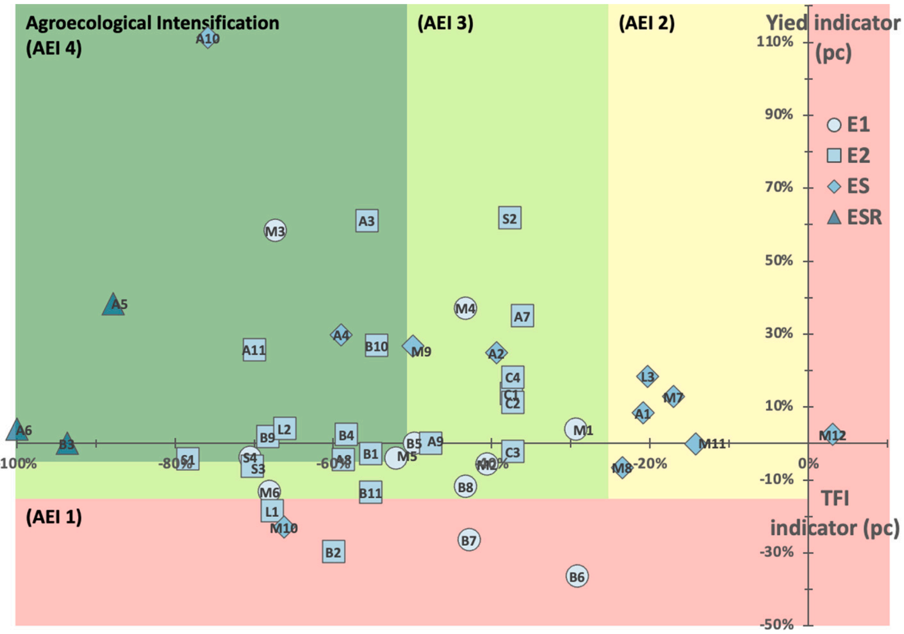


Fig. 2. ECOVITI Prototypes assessment (mean performance over 6 years) based on the coupled analysis of the Yield indicator (Y-axis) and TFI indicator (X-axis) (See Table 3 for agroecological intensification thresholds and levels).

TFI Indicator under −50% and a Harvest damage (HD) indicator under 10%. Four grapevine prototypes (4/16) (M3 (in E1_prototypes), A11 (in E2_prototypes) and A5 and A6 (in ESR_prototypes)) reached the AEI 4 level each year. Six grapevine prototypes (6/16) had annual performances between Level AEI 3 and AEI 4 (M5, M6 in E1_prototypes; A8, B11, L2 in E2_prototypes; M10 in ES_prototypes).

Five prototypes (5/16) had one year in AEI 2 Level, but reached AEI 4 Level at least one year in five (S4 in E1_prototypes; A3, B9 in E2_prototypes; A4, A10 in ES_prototypes). None grapevine prototypes could obtain the AEI 4 Level on annual average with at least one year in five with the lowest AEI 1 Level assessment.

Secondly, 42% of prototypes (19/45) reached the AEI 3 level (Light green zone - Level 3 in Table 6). Four grapevine prototypes (B5, M4 in E1_prototypes; A9, C1 in E2_prototypes) had every individual year performances over AEI 3 Level. Sixteen of these grapevine prototypes were in the E1 and E2_prototypes mainly based on the use of efficiency levers. Three grapevine prototypes (A2 and M9 in ES_prototypes; B3 in ESR_prototypes) reached the level AEI 3 with one or two annual performances in AEI 1 or AEI 2 level.

These 35 grapevine prototypes (16 + 19 in 45) (78%) shown a significant trade-off between environmental indicator, represented by pesticide reduction (TFI) and agronomic performance indicator represented by an acceptable threshold on harvest damages and as a consequence on agronomic performance.

22% of grapevine prototypes (10/45) had an overall assessment under AEI 2 level for the two indicators. Only one prototype (M12 in ES_prototypes) did not have at least one year with an assessment over AEI 3 level. B10, B2, S1 and S3 in E2_prototypes and A1, L3, M11, M7 and M8 in ES_prototypes had one or more years with the AEI 3 or AEI 4 level.

The results shown that there was more variability in environmental indicator (TFI) than in the agronomic indicator (harvest damage). The trade-off between the two indicators was not the same as between the environmental indicator (TFI) and yield (the second agronomic indicator). It seemed to reflect that depending on the prototype, the strategies adapted the level of pesticide use to maintain the damages in an acceptable range of values.

3.2.3. *Pesticide reduction and workload*

Finally, to assess the acceptability of prototypes from a third bivariate approach with pluri-annual variability, on environmental and socio-economic perspectives: we analysed the relationship between results of **TFI performances and workload** of the grapevine prototypes (Table 7 and Supp. Mat. Fig. S.3).

Firstly, 34% of prototypes (13/38) reached **the AEI 4 level** (dark green level 4 - Table 7) with a TFI Indicator under −50% and a workload indicator under 5% (no more than 5% of supplementary workload with the grapevine prototype). Tree grapevine prototypes (M3 and M6 in E1_prototypes; and A11 in E2_prototypes) reached AEI 4 level every year. Nine grapevine prototypes were over AEI 3 level every year (A8, B1, B10, B11, B2, B9 and S3 in E2_prototypes, and A10 and M10 in ES_prototype). B3 in ESR_prototypes reached the AEI 4 level, despite the AEI 1 level the first year.

Secondly, 55% of prototypes (21/38) reached AEI 3 level (Table 6). On the pluri-annual point of view, there were ten grapevine prototypes which improved their trade-off environmental/socio-economic performances between the beginning and the end of the experimentation (B5, B6 in E1_prototypes; A3, C2, C3, C4 and S1 in E2_prototypes, A4 in ES_prototypes; A5 and A6 in ESR_prototypes). Eight prototypes were quite stable during the experimentation (B7, B8, M4 in E1_prototypes; A7, A9, C1, S2 in E2_prototypes; M9 in ES_prototypes). Three prototypes decreased in their combined performance on environmental indicator (pesticide reduction though TFI) and socio-economic indicator (workload) (M1 and M2 in E1_prototypes and A2 in ES_prototypes).

Only, four prototypes (11%) (4/38) did not reach an acceptable level of performance in that socio-economical assessment even if the environmental indicator TFI) is acceptable. A1 (ES_prototypes) had the AEI 2 level. And three prototypes (B4 in E2_prototypes; M7 and M8 in ES_prototypes) havd the AEI 1 level with an environmental indicator (TFI) over 0% and a socio-economic indicator (workload) over 20%. This result meaned that there was no reduction of pesticides combined to a significant increase of workload. As a consequence, B4, M7 and M8 prototypes presented trade-off that went in the opposite direction to the wished agroecology transition of vineyards and should be presented as such to winegrowers.

Overall, a large number of prototypes (89%, 34/38) did not allow trade-off between the environmental indicator and the socio-economic

Table 6

ECOVITI Prototypes assessment level for TFI indicator and Harvest damage indicator: average value from 2013 to 2018 and for the 6 studied years. See Table 3 for agroecological intensification thresholds and levels. Overall ranking is based on the indicator average values.

Prototypes	TFI indicator (pc)		Harvest damage indicator (pc)		Agroecological intensification level *Harvest damage and TFI Indicator assessment*						
	Average	*sd*	Average	*sd*	2013	2014	2015	2016	2017	2018	Overall
E1											
B5	**-50%**	*11%*	**3%**	*3%*	4	4	3	3			**3**
B6	**-29%**	*8%*	**4%**	*7%*			2	2	3		**3**
B7	**-43%**	*12%*	**13%**	*17%*	3	3	4	1			**3**
B8	**-43%**	*25%*	**12%**	*13%*	1	3	2	3			**3**
M1	**-29%**	*23%*	**7%**	*4%*	3	4	2	2	3		**3**
M2	**-41%**	*22%*	**11%**	*6%*	2	3	3	2	4		**3**
M3	**-67%**	*5%*	**1%**	*2%*	4	4	4	4	4		**4**
M4	**-43%**	*18%*	**4%**	*6%*	4	3	3	3	3		**3**
M5	**-52%**	*19%*	**5%**	*7%*	3	3	3	4	3		**4**
M6	**-68%**	*10%*	**5%**	*7%*	3	3	4	4	4		**4**
S4	**-70%**	*3%*	**7%**	*7%*			2	4	4	4	**4**
E2											
A11	**-70%**	*9%*	**1%**	*1%*	4	4	4	4	4	4	**4**
A3	**-56%**	*35%*	**3%**	*0%*					3	2	**4**
A7	**-36%**	*9%*	**5%**	*10%*	3	3	3	2	1	3	**3**
A8	**-59%**	*13%*	**3%**	*5%*	4	4	4	3	3	4	**4**
A9	**-48%**	*7%*	**3%**	*5%*	3	3	4	3	3	3	**3**
B1	**-55%**	*7%*	**12%**	*15%*	4	3	4	1	4		**3**
B10	**-55%**	*12%*	**18%**	*32%*	1	3	4	4			**2**
B11	**-55%**	*8%*	**1%**	*1%*		4	3	3			**4**
B2	**-60%**	*9%*	**27%**	*32%*	3	1	4	1	3		**1**
B4	**-58%**	*8%*	**2%**	*1%*	3	4	4	4			**4**
B9	**-68%**	*7%*	**8%**	*13%*	4	4	2				**4**
C1	**-37%**	*8%*	**2%**	*2%*	3	3	3	3	3	3	**3**
C2	**-37%**	*16%*	**2%**	*1%*				2	4	3	**3**
C3	**-37%**	*16%*	**0%**	*0%*				2	4	3	**3**
C4	**-37%**	*16%*	**0%**	*0%*				2	4	3	**3**
L1	**-68%**	*8%*	**11%**	*16%*	1	4	4				**3**
L2	**-66%**	*11%*	**7%**	*7%*	3	4	4				**4**
S1	**-78%**	*9%*	**18%**	*15%*	1	1	4	4	4	1	**2**
S2	**-38%**	*7%*	**3%**	*6%*	1	2	3	4	4	1	**3**
S3	**-70%**	*20%*	**26%**	*25%*			3	3	3	3	**1**
ES											
A1	**-21%**	*12%*	**14%**	*19%*	1	2	2	2	3	2	**2**
A10	**-76%**	*18%*	**4%**	*10%*	3	4	4	2	4	4	**4**
A2	**-39%**	*15%*	**10%**	*12%*	1	3	3	3	3	2	**3**
A4	**-59%**	*37%*	**1%**	*2%*		4	4	4	3	2	**4**
L3	**-20%**	*5%*	**6%**	*1%*	3	2	2				**2**
M10	**-66%**	*10%*	**5%**	*7%*	3	3	4	4	4		**4**
M11	**-14%**	*18%*	**4%**	*5%*	3	2	2	1	3		**2**
M12	**3%**	*15%*	**17%**	*20%*	1	2	1	2	2		**1**
M7	**-17%**	*19%*	**14%**	*18%*	1	3	2	1	3		**2**
M8	**-24%**	*23%*	**13%**	*12%*	1	3	3	2	3		**2**
M9	**-50%**	*14%*	**8%**	*14%*	4	4	1	3	3		**3**
ESR											
A5	**-88%**	*8%*	**1%**	*1%*					4	4	**4**
A6	**-100%**	*0%*	**0%**	*0%*					4	4	**4**
B3	**-94%**	*4%*	**12%**	*17%*	3	1	4	4	4		**3**

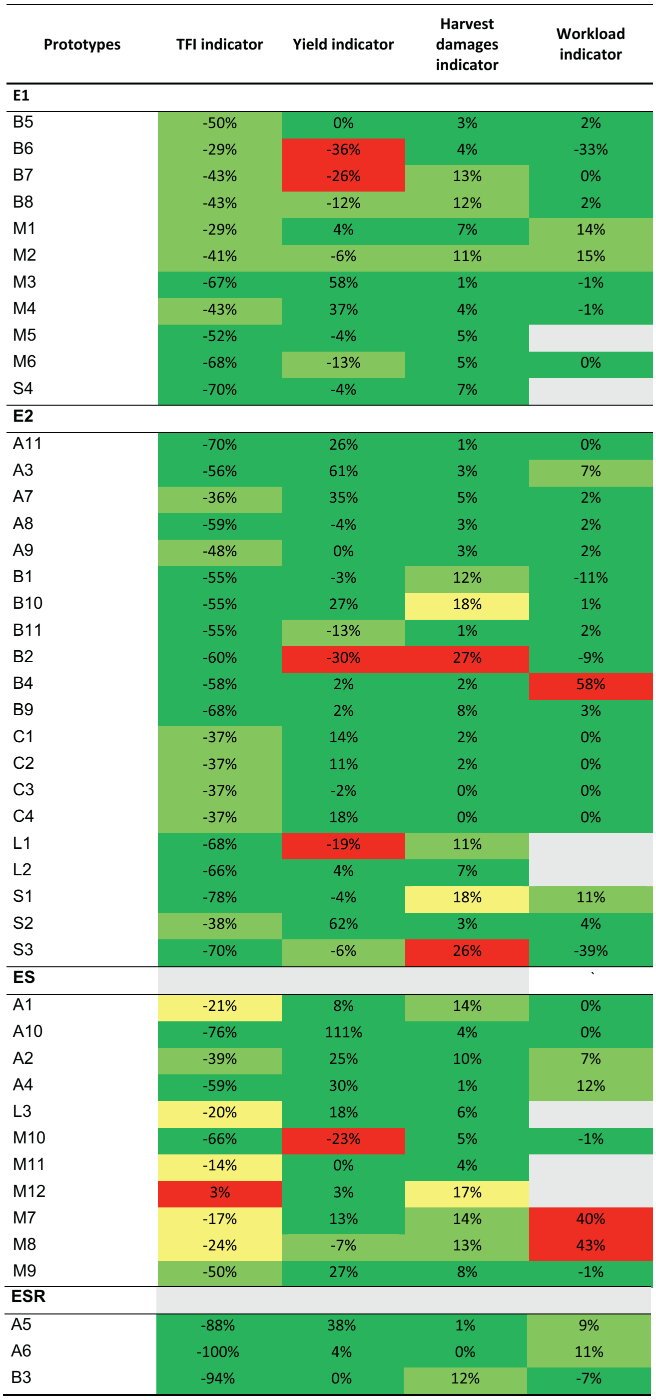
Table 7

ECOVITI Prototypes assessment level for TFI indicator and Workload indicator: average value from 2013 to 2018 and for the 6 studied years. See Table 3 for agroecological intensification thresholds and levels. Overall ranking is based on the indicator average values.

Prototypes	**TFI indicator (pc)**		**Workload indicator (pc)**		**Agroecological intensification level** ***Workload and TFI Indicator assessment***						
	Average	*sd*	**Average**	*sd*	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Overall**
E1											
B5	**-50%**	*11%*	**2%**	*32%*	1	2	3	3	4		**3**
B6	**-29%**	*8%*	**-33%**	*6%*			2	2	3		**3**
B7	**-43%**	*12%*	**0%**	*7%*	3	3	3	3			**3**
B8	**-43%**	*25%*	**2%**	*4%*	3	3	2	3	3		**3**
M1	**-29%**	*23%*	**14%**	*10%*	3	4	2	1	2		**3**
M2	**-41%**	*22%*	**15%**	*13%*	2	4	3	1	2		**3**
M3	**-67%**	*5%*	**-1%**	*0%*	4	4	4				**4**
M4	**-43%**	*18%*	**-1%**	*1%*	4	3	3	3	3		**3**
M5	**-52%**	*19%*									
M6	**-68%**	*10%*	**0%**	*4%*	4	4	4	4	4		**4**
S4	**-70%**	*3%*									
E2											
A11	**-70%**	*9%*	**0%**	*0%*	4	4	4	4	4	4	**4**
A3	**-56%**	*35%*	**7%**	*27%*		1	1	3	3	2	**3**
A7	**-36%**	*9%*	**2%**	*2%*	3	3	3	2	3		**3**
A8	**-59%**	*13%*	**2%**	*2%*	4	4	4	3	4		**4**
A9	**-48%**	*7%*	**2%**	*2%*	3	3	4	3	4		**3**
B1	**-55%**	*7%*	**-11%**	*17%*	3	4	4	3	4		**4**
B10	**-55%**	*12%*	**1%**	*3%*	3	3	4	4	4		**4**
B11	**-55%**	*8%*	**2%**	*8%*		3	3	3	4		**4**
B2	**-60%**	*9%*	**-9%**	*17%*	3	4	4	4	3		**4**
B4	**-58%**	*8%*	**58%**	*47%*	3	3	1	1	1		**1**
B9	**-68%**	*7%*	**3%**	*2%*	4	3	4				**4**
C1	**-37%**	*8%*	**0%**	*0%*	3	3	3	3	3	3	**3**
C2	**-37%**	*16%*	**0%**	*0%*				2	4	3	**3**
C3	**-37%**	*16%*	**0%**	*0%*				2	4	3	**3**
C4	**-37%**	*16%*	**0%**	*0%*				2	4	3	**3**
L1	**-68%**	*8%*									
L2	**-66%**	*11%*									
S1	**-78%**	*9%*	**11%**	*9%*	1	4	4	3	3	3	**3**
S2	**-38%**	*7%*	**4%**	*0%*	3	4	4	4	4	4	**3**
S3	**-70%**	*20%*	**-39%**	*11%*			3				**4**
ES											
A1	**-21%**	*12%*	**0%**	*0%*	2	2	2	2	3	2	**2**
A10	**-76%**	*18%*	**0%**	*0%*	3	4	4	4	4	4	**4**
A2	**-39%**	*15%*	**7%**	*14%*	3	2	1	3	2	2	**3**
A4	**-59%**	*37%*	**12%**	*23%*		1	1	3	3	2	**3**
L3	**-20%**	*5%*									
M10	**-66%**	*10%*	**-1%**	*7%*	4	3	4	4	4		**4**
M11	**-14%**	*18%*									
M12	**3%**	*15%*									
M7	**-17%**	*19%*	**40%**	*20%*	1	1	1	1	2		**1**
M8	**-24%**	*23%*	**43%**	*23%*	1	1	1	1	2		**1**
M9	**-50%**	*14%*	**-1%**	*1%*	4	4	4	3	3		**3**
ESR											
A5	**-88%**	*8%*	**9%**	*28%*		1	1	3	4	4	**3**
A6	**-100%**	*0%*	**11%**	*30%*		1	1	1	4	4	**3**
B3	**-94%**	*4%*	**-7%**	*27%*	1	4	4	4	4		**4**

Table 8

TFI, Yield, Harvest damages and Workload Indicators average values from 2013 to 2018 for the 45 grapevine prototypes experimented in the ECOVITI project. The colour indicates the level of AEI - See Table 3 for agroecological intensification thresholds and levels.



Prototypes	TFI indicator	Yield indicator	Harvest damages indicator	Workload indicator
E1				
B5	-50%	0%	3%	2%
B6	-29%	-36%	4%	-33%
B7	-43%	-26%	13%	0%
B8	-43%	-12%	12%	2%
M1	-29%	4%	7%	14%
M2	-41%	-6%	11%	15%
M3	-67%	58%	1%	-1%
M4	-43%	37%	4%	-1%
M5	-52%	-4%	5%	
M6	-68%	-13%	5%	0%
S4	-70%	-4%	7%	
E2				
A11	-70%	26%	1%	0%
A3	-56%	61%	3%	7%
A7	-36%	35%	5%	2%
A8	-59%	-4%	3%	2%
A9	-48%	0%	3%	2%
B1	-55%	-3%	12%	-11%
B10	-55%	27%	18%	1%
B11	-55%	-13%	1%	2%
B2	-60%	-30%	27%	-9%
B4	-58%	2%	2%	58%
B9	-68%	2%	8%	3%
C1	-37%	14%	2%	0%
C2	-37%	11%	2%	0%
C3	-37%	-2%	0%	0%
C4	-37%	18%	0%	0%
L1	-68%	-19%	11%	
L2	-66%	4%	7%	
S1	-78%	-4%	18%	11%
S2	-38%	62%	3%	4%
S3	-70%	-6%	26%	-39%
ES				`
A1	-21%	8%	14%	0%
A10	-76%	111%	4%	0%
A2	-39%	25%	10%	7%
A4	-59%	30%	1%	12%
L3	-20%	18%	6%	
M10	-66%	-23%	5%	-1%
M11	-14%	0%	4%	
M12	3%	3%	17%	
M7	-17%	13%	14%	40%
M8	-24%	-7%	13%	43%
M9	-50%	27%	8%	-1%
ESR				
A5	-88%	38%	1%	9%
A6	-100%	4%	0%	11%
B3	-94%	0%	12%	-7%

indicator. For the majority of the prototypes, a significant reduction of pesticide use included a significant increase in the workload. Other socio-economic indicators will have to be taken into account and shown to be sustainable to ensure that winegrowers accept to adopt the prototypes on their farms.

To conclude, the prototyping approach has enabled us to demonstrate that some trade-offs exist between indicator performances with producing breakthrough prototypes for each region that significantly reduce pesticide use without degrading agronomic and labour performance. 22% of grapevine prototypes have a trade-off between environmental, agronomic and socio-economic indicators (Table 8). Four prototypes (4/45; 9%) had all the indicators in the AEI 4 level (M3 in E1_prototypes; A11 and B9 in E2_prototypes, and A10 in ES_prototypes) (Table 8). And 18 prototypes (18/45; 40%) had good performances with only one indicator with the AEI 3 level (B5, M4, M6 in E1_prototypes; A3, A7, A9, B1, B11, C1, C2, C3, C4, S2 in E2_prototypes; A4, M9 in

ES_prototypes; and A5, A6, B3 in ESR_prototypes). Eleven prototypes (11/45; 24%) had only one indicator over acceptable objectives (B6 and B7 in E1_prototypes; B10, B4, L1, S1, S3 in E2_prototypes; A1, L3, M10, M11 in ES_prototypes). ES_prototypes (with the highest use of biocontrol and prophylactic practices) had more variability, the least TFI reduction, and the highest number of grapevine prototypes in AEI 2 and AEI 1 levels.

Our results shown that there were inter-annual variations between performances of grapevine prototypes according to the combination of pest pressure and pest management. These variations in TFI highlight the adaptive nature of the prototypes was a point that may emerge in the results. In Table 8, looking at trade-off between indicators, it was interesting to observe that environmental performance (TFI) was more variable than agronomic performance (harvest damages): the plant protection was adjusted to maintain a relatively good and stable sanitary state. However, agronomic performance (yield) shown significant variability, which was likely associated with factors other than sanitary conditions, such as climate. In terms of multi-criteria evaluation of prototypes performance sustainability, our results shown a majority of trade-offs between the four indicators calculated on average over 6 consecutive years (Table 8). The evaluation of a large number of prototypes at a country scale aimed to gain insight on trade-offs between environmental indicator (TFI), agronomic indicators (yield and harvest damage), and socio-economic indicator (workload) to take trade-off analysis one step further than authors focusing on one vineyard homogeneous area alone (Thiollet-Scholtus et al., 2021).

Performant grapevine prototypes existed for some trade-off considering together environmental (TFI), agronomic (yield, harvest damage), and socio-economic (workload) indicators at all levels of the ESR rating scale. In addition, there were grapevine prototypes with good performance for the 4 indicators in all the studied grapevine regions in France. And finally, there were grapevine prototypes with good performance that lasted over more than 4 consecutive studied years of measurements regardless of variations in pest pressure of the year.

4. Discussion

In this study, we successfully applied the prototyping method to design new grapevine systems with low pesticide use in France. These prototypes were first classified with the ESR framework to analyse how deep were the technical changes in their management compared to the current best practices in each region. We then assessed the trade-offs between the reduction of pesticides achieved and three key variables driving the economic performance (based on yield, grape damages and workload because we do not have financial and cost indicators recorded on the experimental platforms). Moreover, grapevine production value depends on the type of production (i.e. PDO or not) and the marketing circuit. The overall aim was to identify prototypes of agroecological intensification, meaning with a strong reduction of pesticide reduction with similar yield, grapevine damages and workload compared to the regional reference.

4.1. Diversity of codesigned grapevine systems prototypes with reduced rate of pesticide use adapted to the regional context

This study produced innovative grapevine systems with significant reduction of pesticide use and adapted to the major vineyards regions in France.

Interestingly, we observed that the redesigned grapevine prototypes were mainly based on E and S lever with a wide range of TFI reduction rates between −78% and 3%. This can be explained by the fact that the project deals with the agroecological transition of vineyards that were planted before prototyping, which represent the large majority of French vineyards in which only 5% are newly planted every year. Redesign of grapevine systems from plantation was therefore not our priority, except when it was possible with novel varieties resistant to disease, but for which the availability of plantlets was still very low during the project. A broad transformation of the French vineyards should therefore integrate E and S strategies first. The lever used in the grapevine prototypes were mainly based on DSS and observations, which is consistent for an "adaptive cropping system" in context with high variability in pest and disease pressures and potential yields. We observed fewer very innovative systems (ESR_prototypes) which corresponded to newly planted grapevine systems. Varieties resistant to powdery and downy mildews were integrated into three redesigned prototypes and played a pivotal role in high values of all performance indicators: TFI reduction, yield, harvest damages and workload.

E1 and E2 were performant regarding the TFI reduction but still involved synthetic products, which are considered to have a higher environmental and health impact than natural products and biocontrol solutions. The ES prototypes based on the biocontrol strategy were less performant regarding TFI reduction (+3% to - 76%); however, this assessment was based on global TFI calculation. In further studies, TFI should be calculated separately for synthetic products and biocontrol products to assess the real biocontrol effect (Fouillet et al., 2022). Fouillet et al. (2022) and Nefti et al. (2024) analysed data from a French farms network, including 244 cropping systems monitored during 10 years and spread across 12 winegrowing regions and used the TFI to assess the intensity of pesticide use. Mean pesticide uses within the network decreased over the 10-year period and mostly concerned fungicide use. By analyzing TFI per fungicide spraying, the authors identified some of the management options mobilised for achieving this pesticide reduction. The use of biocontrol products and the reduction of sprayed rates were often associated with a low TFI. The analysis of yield variation showed a significant mean reduction (19% of decrease of yield) (Fouillet et al., 2022). Although it was lower than the TFI reduction (33% of TFI reduction rate). This study shown that it is possible to commit French vineyards to an agroecological transition that will greatly reduce or even eliminate the use of synthetic pesticides, but maintaining socio-economic performance requires adaptive management with DSS, the use of biocontrol techniques and, where possible, the use of resistant varieties. Innovation could also imply plot and supra-plot diversification of the cropping system (Simon et al., 2019 – Z Project). During prototyping workshops with stakeholders, precision viticulture did not come to the fore. However, precision viticulture does exist and deserves to be tested and evaluated in future projects. The dissemination of these digital innovations is ongoing in France (Davy et al., 2010). Matese and Filippo Di Gennaro, 2015 and Edemetti et al., 2022 pointed to the necessity for training technicians to effectively utilise these technologies. Agroecological transition could benefit of precision viticulture. The hot issue for future remains the shared access to digital platforms for vineyards (Matese and Filippo Di Gennaro, 2015).

4.2. Performances of co-designed prototypes

Over the 6 years of the project, on the environmental point of view, the objective of 50% of pesticide use reduction were achieved for all grapevine systems (E1, E2, ES and ESR in Table 8) even if the annual analysis of the performances revealed an important year effect (Tables 6 and 7, Supp. Mat Table S.2). This questioned the long-term acceptability of the strategies of reducing the rate of pesticide use for the winegrower, particularly in the case of vine production systems which are supposed to be productive over several decades (Bou et al., 2019). The performances of the prototyped grapevine systems have to be considered at each age of the vineyard and allocated as a 'payback' impact to its whole lifetime, especially for environmental impact (Simon et al., 2017).

However, in this study, we assumed that the performance assessment based on the mean value of six-year experiments is relevant for a consistent assessment of these systems, prior to the third step for grapevine systems dissemination with on-farm assessment if needed. The necessary methodological investment was not feasible in this study for a life cycle assessment on a thirty years period for grapevine systems.

This allows to assume a form of resilience of these prototypes. Our environmental assessment remains with tackling dynamic aspects related to sustainability like resilience or vulnerability (Dardonville et al., 2021; Hercher-Pasteur et al., 2020). Our dynamic assessment during 6 years would also gain to be longer according to the long-term cultivation of vine as a perennial crop and to be adapted to statistical analysis (Dardonville et al., 2022a). One alternative would be to continue the shortage of data describing the prototypes with the best trade-off and to enrich assessment with resilience indicators adapted from cropping systems (Dardonville et al., 2022b). Another shortcoming of the study is that socio-economic and environmental performances were both calculated for one indicator, workload and TFI respectively. Using others complementary indicators to address environmental issues (Simona et al., 2024) and others socio-economic indicators, like soil carbon, gross margin could be included in the next data collected and then, could allow to implement resilience evaluation of grapevine prototypes before adoption by winegrowers (Soulé et al., 2023).We used a bivariate approach to assess whether environmental performance (measured by TFI reduction) compromises agronomic performance—namely yield, grape quality (including harvest-related damage), both of which indirectly influence economic performance—as well as socio-economic performance, evaluated through a workload indicator. A more detailed economic assessment was beyond the scope of the present study. However, previous research has shown that the economic sustainability of innovative grapevine systems can often be challenged, with prototypes that reduce chemical inputs sometimes experiencing a decrease in semi-net margin (Bonnet et al., 2021). Moreover, negative externalities must be accounted for in the calculation of production costs, considering disservices such as water, soil, and air pollution, along with impacts on human and wildlife health (Pretty et al., 2000).

4.3. Learnings, limitations and perspectives of the prototyping method

The prototyping method implemented in this study builds on earlier developments in system design approaches, particularly those applied to annual cropping systems (Debaeke et al., 2009; Meynard et al., 2012). In contrast, viticulture—being a perennial, pesticide-intensive system—has received less attention in terms of adapted system design methodologies. Our approach aimed to address this gap by proposing a structured, participatory, and context-specific method tailored to the complexity of vineyards (Rapidel et al., 2015; Metral et al., 2015). Key lessons learned include the ability of the method to integrate diverse types of knowledge—scientific, technical, and local—through prototyping workshops involving vineyard experts and multidisciplinary researchers, as described by Jeuffroy et al. (2022). These workshops fostered a shared understanding of plant-soil-climate-disease interactions and enabled the co-design of innovative, pesticide-reducing systems in six French winegrowing regions. The use of System Objectives and Constraints (SOCs), initially defined through a top-down stakeholder process (Duff et al., 2022), allowed for a broad characterization of viticultural diversity and provided a structured basis for designing regionally adapted systems. Local adaptations, such as distinctions between red and white wine production within the same region, further refined these SOCs. The participatory process drew upon other theoretical and practical frameworks for system design. For instance, Salembier et al. (2018) emphasised the value of tracking on-farm innovations, while incremental redesign approaches have been promoted as a complementary strategy (Meynard et al., 2012). Multi-actor platforms and exploration tools (Dabire et al., 2017) proved important for fostering dialogue, although stakeholder diversity—spanning farmers, advisers, researchers, policymakers, and consumers—could create tensions that require mediation and openness to disruptive thinking (Moneyron et al., 2017). From the evaluation side, our results confirmed the feasibility of agroecological redesign: out of 45 prototypes, 41 achieved more than a 50% average reduction in pesticide use over six years, with 40 maintaining yield and quality targets, and 92% meeting workload objectives. These outcomes aligned with other findings in vineyard innovation (Fouillet et al., 2022) and highlighted the transformative potential of combining efficiency, substitution, and redesign levers (Lançon et al., 2007; Guimier et al., 2019).

However, a first limitation was the initial SOCs were not dynamically updated based on prototype performance, which limited feedback integration during the experimentation phase. While multi-criteria assessments were performed using indicators from the national Ecoviti network (2013–2018), the evaluation did not go into a statistical analysis of temporal data and has only one environmental and one socio-economic indicator (Dardonville et al., 2021). Another limitation of the study was the actual implementation of prototypes at the field level often involved undocumented adaptations to the farm level, making it difficult to trace specific lever effects or propose “ready-to-use” systems to disseminate to winegrowers Participation imbalances were also noted: as in the study by Moneyron et al. (2017), farmers were underrepresented compared to other stakeholders, potentially reducing the relevance and scalability of the prototypes. Agronomists might benefit from creative design-support tools to avoid fixation (Agogué et al., 2014) and to stimulate exploration using methods such as the KCP® method (Hooge et al., 2016) or C-K theory (Hatchuel and Weil, 2003). Workshop facilitation and clarification of the role of scientific tools in the design process—experimentation, diagnosis, and collective workshops—were also essential, as highlighted by Berthet et al. (2018) and Quinio et al. (2022).

Looking ahead, the dissemination (third step represented in Fig. 1, not integrated in the present study) of innovative low-input viticultural systems should be guided by adaptive, winegrower-driven design principles. Rather than promoting fixed models, grapevine prototypes should be positioned as *exploration guides*—tools that inspire and support winegrowers and advisers in context-specific redesign efforts and at farm level. This implies a flexible decision-making framework, capable of evolving in response to winegrowers' priorities, technical constraints, early-stage outcomes, and climate variability. Such an iterative and situated approach is essential for enabling meaningful agroecological transitions (Altieri, 2002; Girard and Magda, 2020; Delmotte et al., 2016; Moraine et al., 2016). In parallel, evaluation methods must be expanded and refined. Moving beyond a limited set of validated indicators to assess a large number of prototypes (Aouadi et al., 2021; Wyler et al., 2023), future assessments should incorporate dynamic, region-specific performance metrics (i.e. climate and soil data). For example, evaluations conducted at the level of production basins (Thiollet-Scholtus et al., 2021) or based on farmers' own success criteria (Perinelle Edemetti et al., 2022) could provide a richer and more grounded understanding of system performance but for a smaller number of prototypes and ask the question of dissemination outside of the studied area. A more comprehensive socio-economic analysis was also needed to assess long-term viability and foster broader adoption across diverse viticultural contexts.

Moreover, recent literature offers valuable insighted into complementary dissemination pathways. First, promoting short supply chains and direct marketing channels could accelerate the adoption of fungus-resistant grapevine varieties by allowing producers to better communicate added value to consumers and capture higher margins (Finger et al., 2023). Second, designing *bundled policy instruments*—which integrate technical support, financial incentives, and regulatory tools—could effectively address multiple adoption barriers at once (Finger et al., 2024). Third, incorporating behavioural insighted into policy design is crucial: recognizing how farmers perceived risk and innovation could significantly enhance the effectiveness of interventions (Zachmann et al., 2024). Lastly, improving monitoring and evaluation frameworks would be a key to understanding both the environmental impacts of low-input systems and the risks borne by pioneering farmers.

Together, these avenues underscored the importance of flexible design, regionally adapted evaluations, supportive policies, and behaviourally informed interventions to scale up agroecological innovations in viticulture. Based on the results of this study, we recommend that future studies on agroecological vineyard, such as policy-makers, pay attention to (i) the spatial and temporal scales of studies (characteristics of production areas) that determine their SOC and the results, (ii) the need to analyse more than one indicator for every dimension of sustainability evaluation to embrace the complexity of viticulture (more than TFI, yield harvest damage and workload), (iii) the need to go further in evaluation of the prototypes with including farmers' success criteria and criteria of dynamics of the chosen performance attributes. This study could be identified as a first step analysis of performance of new-designed agroecological viticultural prototypes tested in real soil-climate conditions at a country scale, and quantitative analysis and updated in future studies based on new results. Designing and adapting methods for assessing prototypes should not stop there, and we expect a significant increase in the number of studies with a design-assessment approach in the future.

5. Conclusion

To conclude, the prototyping method developed in this study has demonstrated that it is possible to reduce the use of pesticides significantly in vineyard while maintaining good agronomic performance and with sometime increasing working time, in the main French production regions and even on vines that have already been planted. First, there are variations of intensity of redesign in the practices of the new grapevine prototypes according to the ESR rating scale. In addition, there are inter-annual variations between performances of grapevine prototypes according to the combination of pest pressure and pest crop management system. Furthermore, grapevine prototypes that demonstrate strong performance across coupled indicators such as yield, TFI, crop damage, and workload, exist at all levels of the ESR rating scale. And finally, there are grapevine prototypes with good performance that last over more than 4 consecutive years regardless of variations in pest pressure. This allows to expect adoption of reduction of pesticide use by winegrowers.

CRediT authorship contribution statement

R. Métral: Methodology, Conceptualization, Writing – original draft, Formal analysis, Writing – review & editing, Data curation. **L. Delière:** Methodology, Data curation. **C. Gary:** Conceptualization, Writing – review & editing, Methodology, Writing – original draft. **X. Burgun:** Methodology, Data curation. **C. Chevrier:** Data curation, Methodology. **D. Lafond:** Methodology, Data curation. **L. Ley:** Methodology, Data curation. **E. Serrano:** Methodology, Data curation. **J. Wery:** Writing – review & editing, Conceptualization, Methodology. **A. Metay:** Writing – original draft, Methodology, Writing – review & editing, Conceptualization. **M. Thiollet-Scholtus:** Methodology, Conceptualization, Writing – original draft, Data curation, Writing – review & editing, Formal analysis.

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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.

Declaration of generative AI in scientific writing.

During the preparation of this work, the author(s) used Chat-GPT to translate French text into English, or detect English language errors. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.104690.

Data availability

Data set available here: https://doi.org/10.18167/DVN1/743UAT or upon request at raphael.metral@institut-agro.fr

References

Agogué, M., Kazakçi, A., Hatchuel, A., Le Masson, P., Weil, B., Poirel, N., Cassotti, M., 2014. The impact of type of examples on originality: explaining fixation and stimulation effects. J. Creat. Behav. 48 (1), 1–12.

Agreste, 2021. Enquête Pratiques culturales en viticulture en 2019 - IFT et nombre de traitements. Disponible sur. https://agreste.agriculture.gouv.fr/agreste-web/disaron/Chd2119/detail/.

Agreste, 2023. Enquête Pratiques culturales en viticulture en 2019 - IFT et nombre de traitements. Available at: https://agreste.agriculture.gouv.fr/agreste-web/download/publication/publie/Chd2304/cd2023-4_PKViti2019.pdf.

Altieri, M.A., 2002. Agroecology: the science of natural resource management for poor farmers in marginal environments. Agric. Ecosyst. Environ. 93 (1), 1–24.

Aouadi, N., Macary, F., Delière, L., Roby, J.-P., 2021. New scenarios for a shift towards agroecology in viticulture. Agric. Sci. https://doi.org/10.4236/as.2021.1210065, 121003-1033.

Beauchet, S., Cariou, V., Renaud-Gentié, C., Meunier, M., Siret, R., Thiollet-Scholtus, M., Jourjon, F., 2020. Modeling the grape quality by multivariate analysis of viticulture practices, soil and climate. Oeno One 54 (3), 601–622. https://doi.org/10.20870/oeno-one.2020.54.3.1067.

Berthet, E.T., Hickey, G.M., Klerkx, L., 2018. Opening design and innovation processes in agriculture: insights from design and management sciences and future directions. Agric. Syst. 165, 111–115.

Blenkinsop, S., Fowler, H.J., Dubus, I.G., Nolan, B.T., Hollis, J.M., 2008. Developing climatic scenarios for pesticide fate modelling in Europe. Environ. Pollut. 154 (2), 219–231.

Bonnet, C., Gaudio, N., Alletto, L., Raffaillac, D., Bergez, J.-E., Debaeke, P., Gavaland, A., Willaume, M., Bedoussac, L., Justes, E., 2021. Design and multicriteria assessment of low-input cropping systems based on plant diversification in southwestern France. Agron. Sustain. Dev. 41 (5), 65.

Bou, Nader K., Stoll, M., Rauhut, D., Patz, C.-D., Jung, R., Loehnertz, O., Schultz, H.R., Hilbert, G., Renaud, C., Roby, J.-P., Delrot, S., Gomès, E., 2019. Impact of grapevine age on water status and productivity of Vitis vinifera L. cv. Riesling. Eur. J. Agron. 104, 1–12.

Butault, J., Dedryver, C., Gary, C., Guichard, L., Jacquet, F., Meynard, J., Nicot, P., Pitrat, M., Reau, R., Sauphanor, B., et al., 2010. Ecophyto R&D, quelles voies pour réduire l'usage des pesticides. *Synthèse du rapport d'étude*. INRA Éditeur, France.

Campos, J., Gallart, M., Llop, J., Ortega, P., Salcedo, R., Gil, E., 2020. On-farm evaluation of prescription map-based variable rate application of pesticides in vineyards. Agronomy 10 (1), 102.

Christ, K.L., Burritt, R.L., 2013. Critical environmental concerns in wine production: an integrative review. J. Clean. Prod. 53, 232–242.

Cohen, M., Bilodeau, C., Alexandre, F., Godron, M., Andrieu, J., Grésillon, E., Garlatti, F., Morganti, A., 2015. What is the plant biodiversity in a cultural landscape? A comparative, multi-scale and interdisciplinary study in olive groves and vineyards (Mediterranean France). Agric. Ecosyst. Environ. 212, 175–186.

Dabire, D., Andrieu, N., Djamen, P., Coulibaly, K., Posthumus, H., Diallo, A.M., Karambiri, M., Douzet, J.-M., Triomphe, B., 2017. Operationalizing an innovation platform approach for community-based participatory research on conservation agriculture in BURKINA FASO. Exp. Agric. 53 (3), 460–479.

Dagostin, S., Schärer, H.-J., Pertot, I., Tamm, L., 2011. Are there alternatives to copper for controlling grapevine downy mildew in organic viticulture? Crop Prot. 30 (7), 776–788.

Dardonville, M., Bockstaller, C., Therond, O., 2021. Review of quantitative evaluations of the resilience, vulnerability, robustness and adaptive capacity of temperate agricultural systems. J. Clean. Prod. 286, 125456.

Dardonville, M., Bockstaller, C., Villerd, J., Therond, O., 2022a. Resilience of agricultural systems: biodiversity-based systems are stable, while intensified ones are resistant and high-yielding. Agric. Syst. https://doi.org/10.1016/j.agsy.2022.103365, 197103365.

Dardonville, M., Legrand, B., Clivot, H., Bernardin, C., Bockstaller, C., Therond, O., 2022b. Assessment of ecosystem services and natural capital dynamics in agroecosystems. Ecosyst. Serv. https://doi.org/10.1016/j.ecoser.2022.101415, 54101415.

Davy, A., Raynal, M., Vergnes, M., Remenant, S., Michez, A., Claverie, M., Codis, S., Bernard, F.M., Colombier, L., Davidou, L., Girard, M., Mornet, L., Perraud, J.-P., Rives, C., Vergnes, D., 2010. Trials results of the "Optidose" method using an adjustment of the pesticide dose for control of downy and powdery mildew. In: Proceedings of the 6th International Workshop on Grapevine Downy and Powdery Mildew, pp. 123–125.

Debaeke, P., Munier-Jolain, N., Bertrand, M., Guichard, L., Nolot, J.-M., Faloya, V., Saulas, P., 2009. Iterative design and evaluation of rule-based cropping systems: methodology and case studies. A review. Agron. Sustain. Dev. 29 (1), 73–86.

Deliere, L., Cartolaro, P., Leger, B., Naud, O., 2015. Field evaluation of an expertise-based formal decision system for fungicide management of grapevine downy and powdery mildews. Pest Manag. Sci. 71 (9), 1247–1257.

Delmotte, S., Barbier, J.-M., Mouret, J.-C., Le Page, C., Wery, J., Chauvelon, P., Sandoz, A., Lopez, Ridaura S., 2016. Participatory integrated assessment of scenarios for organic farming at different scales in Camargue, France. Agric. Syst. 143, 147–158.

Delpuech, X., Metay, A., 2018. Adapting cover crop soil coverage to soil depth to limit competition for water in a Mediterranean vineyard. Eur. J. Agron. 97, 60–69.

Duff, H., Hegedus, P.B., Loewen, S., Bass, T., Maxwell, B.D., 2022. Precision agroecology. Sustainability 14 (1), 106.

Edemetti, et al., 2022. Vineyard digital twin: construction and characterization via UAV images-DIWINE proof of concept. In: 2022 IEEE 23rd International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM). IEEE, pp. 601–606.

Enserink, M., Hines, P.J., Vignieri, S.N., Wigginton, N.S., Yeston, J.S., 2013. The Pesticide Paradox. Science 341 (6147), 728–729.

Finger, R., Zachmann, L., McCallum, C., 2023. Short supply chains and the adoption of fungus-resistant grapevine varieties. Appl. Econ. Perspect. Policy 45 (3), 1753–1775.

Finger, R., Sok, J., Ahovi, E., Akter, S., Bremmer, J., Dachbrodt-Saaydeh, S., de Lauwere, C., Kreft, C., Kudsk, P., Lambarraa-Lehnhardt, F., McCallum, C., Oude Lansink, A., Wauters, E., Möhring, N., 2024. Towards sustainable crop protection in agriculture: a framework for research and policy. Agric. Syst. 219, 104037.

Fouillet, E., Delière, L., Chartier, N., Munier-Jolain, N., Cortel, S., Rapidel, B., Merot, A., 2022. Reducing pesticide use in vineyards. Evidence from the analysis of the French DEPHY network. Eur. J. Agron. 136, 126503.

Fried, G., Blanchet, C., Cazenave, L., Bopp, M.-C., Kazakou, E., Metay, A., Christen, M., Alard, D., Cordeau, S., 2022. Consistent Response of Weeds According to Grime's CSR Strategies along Disturbance and Resource Gradients in Bordeaux Vineyards. Weed Research.

Girard, N., Magda, D., 2020. The interplays between singularity and genericity of agroecological knowledge in a network of livestock farmers. J. Rural. Stud. 73, 214–224.

Guimier, S., Delmotte, F., Miclot, A.S., Fabre, F., Mazet, I., Couture, C., Schneider, C., Delière, L., 2019. OSCAR, a national observatory to support the durable deployment of disease-resistant grapevine cultivars. Acta Hortic. 1248, 21–34. https://doi.org/10.17660/ActaHortic.2019.1248.4.

Hatchuel, A., Weil, B., 2003. A new approach of innovative design: an introduction to CK theory. In: The International Conference on Engineering Design.

Hercher-Pasteur, J., Loiseau, E., Sinfort, C., Hélias, A., 2020. Energetic assessment of the agricultural production system. A review. Agron. Sustain. Dev. 40 (4), 29. https://doi.org/10.1007/s13593-020-00627-2.

Hill, S.B., MacRae, R.J., 1996. Conceptual framework for the transition from conventional to sustainable agriculture. J. Sustain. Agric. 7 (1), 81–87.

Hooge, S., Béjean, M., Arnoux, F., 2016. Organising for radical innovation: the benefits of the interplay between cognitive and organisational processes in kcp workshops. Int. J. Innov. Manag. 20 (04), 1640004.

Hossard, L., Guichard, L., Pelosi, C., Makowski, D., 2017. Lack of evidence for a decrease in synthetic pesticide use on the main arable crops in France. Sci. Total Environ. 575, 152–161.

Jeuffroy, M.-H., Loyce, C., Lefeuvre, T., Valantin-Morison, M., Colnenne-David, C., Gauffreteau, A., Médiène, S., Pelzer, E., Reau, R., Salembier, C., Meynard, J.-M., 2022. Design workshops for innovative cropping systems and decision-support tools: learning from 12 case studies. Eur. J. Agron. 139, 126573.

Jourjon, F., Chou, H.-C., Gezart, A., Kadison, A., Martinat, L., Pomarici, E., Vecchio, R., 2016. Wineries evaluation of costs and benefits of sustainability certification program: the case of Terra Vitis in France. Recent Pat. Food Nutr. Agric. 8 (2), 138–147.

Keating, B.A., Carberry, P.S., Bindraban, P.S., Asseng, S., Meinke, H., Dixon, J., 2010. Eco-efficient agriculture: concepts, challenges, and opportunities. Crop Sci. 50 (Supplement 1) p. S-109-S-119.

Kuhfuss, L., Subervie, J., 2018. Do European Agri-environment measures help reduce herbicide use? Evidence from viticulture in France. Ecol. Econ. 149, 202–211.

Lafond, D., Metral, R., 2015. Concevoir en partenariat une EcoViticulture ECOnomiquement viable et ECOlogiquement responsable par rapport aux pesticides (EcoViti).

Lafond, D., Coulon, T., Metral, R., Merot, A., Wéry, J., 2013. EcoViti: a systemic approach to design low pesticide vineyards. IOBC-WPRS Bull. 85, 77–86.

Lamanda, N., Roux, S., Delmotte, S., Merot, A., Rapidel, B., Adam, M., Wery, J., 2012. A protocol for the conceptualisation of an agro-ecosystem to guide data acquisition and analysis and expert knowledge integration. Eur. J. Agron. 38, 104–116.

Lançon, J., Wery, J., Rapidel, B., Angokaye, M., Gérardeaux, E., Gaborel, C., Ballo, D., Fadegnon, B., 2007. An improved methodology for integrated crop management systems. Agron. Sustain. Dev. 27 (2), 101–110.

Martinson, T.E., Mansfield, A.K., Luby, J.J., Gartner, W.C., Dharmadhikari, M., Domoto, P., Fennell, A., 2016. The northern grapes project: integrating viticulture, enology, and marketing of new cold-hardy wine grape cultivars in the Midwest and Northeast United States. Acta Hortic. 1115, 3–12. https://doi.org/10.17660/ActaHortic.2016.1115.2.

Matese, A., Filippo Di Gennaro, S., 2015. Technology in precision viticulture: a state of the art review. Int. J. Wine Res. 69–81.

Merdinoglu, D., Schneider, C., Prado, E., Wiedemann-Merdinoglu, S., Mestre, P., 2018. Breeding for durable resistance to downy and powdery mildew in grapevine. OENO One 52 (3), 203–209.

Merot, A., Wery, J., 2017. Converting to organic viticulture increases cropping system structure and management complexity. Agron. Sustain. Dev. 37 (3), 19.

Merot, A., Alonso, Ugaglia A., Barbier, J.-M., Del'homme B., 2019. Diversity of conversion strategies for organic vineyards. Agron. Sustain. Dev. 39 (2), 16.

Metral, R., Rapidel, B., Delière, L., Petitgenet, M., Lafond, D., Chevrier, C., Bernard, F.-M., Serrano, E., Thiollet-Scholtus, M., Wéry, J., 2015. A Prototyping Method for the Re-Design of Intensive Perennial Systems: The Case of Vineyards in France.

Meynard, J.M., Dedieu, B., Bos, A.P., 2012. Re-design and co-design of farming systems. An overview of methods in practices. In: Farming Systems Research into the 21st Century: The New Dynamic, pp. 405–429.

Moneyron, A., Lallemand, J.F., Schmitt, C., Perrin, M., Soustre-Gacougnolle, I., Masson, J.E., LMC, Westhalten Group, 2017. Linking the knowledge and reasoning of dissenting actors fosters a bottom-up design of agroecological viticulture. Agron. Sustain. Dev. 37 (5), 41.

Moraine, M., Grimaldi, J., Murgue, C., Duru, M., Therond, O., 2016. Co-design and assessment of cropping systems for developing crop-livestock integration at the territory level. Agric. Syst. 147, 87–97.

Nefti, O., Chartier, N., Merot, A., Peyrard, T., Delière, L., 2024. To what extent can a phase-out of pesticides in viticulture be achieved? Learning from the efforts of a large farm network after 10 years. Oeno One. https://doi.org/10.20870/oeno-one.2024.58.2.7885.

Pelzer, E., Fortino, G., Bockstaller, C., Angevin, F., Lamine, C., Moonen, C., Vasileiadis, V., Guérin, D., Guichard, L., Reau, R., Messéan, A., 2012. Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. Ecol. Indic. 18171–18182. https://doi.org/10.1016/j.ecolind.2011.11.019.

Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., Grando, M.S., Gary, C., Lafond, D., Duso, C., Thiery, D., Mazzoni, V., Anfora, G., 2017. A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. Crop Prot. 97, 70–84.

Pingault, N., Pleyber, E., Champeaux, C., Guichard, L., Omon, B., 2009. Produits phytosanitaires et protection intégrée des cultures: l'indicateur de fréquence de traitement. In: Notes et études socio-économiques, 32, pp. 61–94.

Pretty, J.N., Brett, C., Gee, D., Hine, R.E., Mason, C.F., Morison, J.I.L., Raven, H., Rayment, M.D., van der Bijl, G., 2000. An assessment of the total external costs of UK agriculture. Agric. Syst. 65 (2), 113–136.

Quinio, M., Jeuffroy, M.-H., Guichard, L., Salazar, P., Détienne, F., 2022. Analyzing co-design of agroecology-oriented cropping systems: lessons to build design-support tools. Agron. Sustain. Dev. 42 (4), 72.

Rapidel, B., Traoré, B.S., Sissoko, F., Lançon, J., Wery, J., 2009. Experiment-based prototyping to design and assess cotton management systems in West Africa. Agron. Sustain. Dev. 29 (4), 545–556.

Rapidel, B., Ripoche, A., Allinne, C., Metay, A., Deheuvels, O., Lamanda, N., Blazy, J.-M., Valdés-Gómez, H., Gary, C., 2015. Analysis of ecosystem services trade-offs to design agroecosystems with perennial crops. Agron. Sustain. Dev. 35 (4), 1373–1390.

Renaud-Gentié, C., Perrin, A., Rouault, A., Garrigues-Quéré, E., Renouf, M., Julien, S., Czyrnek-Delêtre, M., Jourjon, F., 2018. Eco-quali-conception©: Agroecological Transition in Viticulture through Life Cycle Assessment. OENOVITI International Network, p. 7.

Renaud-Gentié, C., Dieu, V., Thiollet-Scholtus, M., Merot, A., 2020. Addressing organic viticulture environmental burdens by better understanding interannual impact variations. Int. J. Life Cycle Assess. 24 (25), 1307–1322. https://doi.org/10.1007/s11367-019-01694-8.

Robertson, G.P., Swinton, S.M., 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Front. Ecol. Environ. 3 (1), 38–46.

Salembier, C., Segrestin, B., Berthet, E., Weil, B., Meynard, J.-M., 2018. Genealogy of design reasoning in agronomy: lessons for supporting the design of agricultural systems. Agric. Syst. 164, 277–290.

Simon, S., Lesueur-Jannoyer, M., Plénet, D., Lauri, P.-É., Le Bellec, F., 2017. Methodology to design agroecological orchards: learnings from on-station and on-farm experiences. Eur. J. Agron. 82 (Part B), 320–330.

Simon, S., Alaphilippe, A., Borne, S., Penvern, S., Dufils, A., Ricard, J.M., Lauri, P.É., 2019. Methodology to co-design temperate fruit tree-based agroforestry systems: three case studies in Southern France. In: Book of abstracts 4th World Congress on Agroforestry, 20-22 May 2019, Montpellier, p. 601. https://agroforestry2019.cirad.fr/replay/book-of-abstracts.

Simona, C., Nicola, F., Micol, M., Carmen, M.R., Raffaella, M., Daniele, P., Andrea, V., Roberto, Z., 2024. A multi-indicator approach to compare the sustainability of organic vs. integrated management of grape production. Ecol. Indic. 158, 111297.

Soulé, E., Charbonnier, R., Schlosser, L., Michonneau, P., Michel, N., Bockstaller, C., 2023. A new method to assess sustainability of agricultural systems by integrating ecosystem services and environmental impacts. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2023.137784, 415137784.

Thiollet-Scholtus, M., Bockstaller, C., 2015. Using indicators to assess the environmental impacts of wine growing activity: the INDIGO® method. Eur. J. Agron. 6213–6225. https://doi.org/10.1016/j.eja.2014.09.001.

Thiollet-Scholtus, M., Muller, A., Abidon, C., Chaumonnot, S., Grignion, J., Keichinger, O., Klein, C., Koller, R., Langenfeld, A., Ley, L., Lemarquis, G., Nassr, N., Nibaudeau, R., Rabolin-Meinrad, C., Ribeiro, S., Weissbart, J., Wohlfahrt, J., 2021. Multidimensional assessment demonstrates sustainability of new low-input viticulture systems in North-Eastern France. Eur. J. Agron. https://doi.org/10.1016/j.eja.2020.126210, 123126210.

This, P., Lacombe, T., Thomas, M.R., 2006. Historical origins and genetic diversity of wine grapes. Trends Genet. 22 (9), 511–519.

Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. Agron. Sustain. Dev. 34 (1), 1–20.

Wyler, L., Conedera, M., Tanadini, M., Krebs, P., 2023. Relating the management difficulty to the abandonment rate of traditional mountain vineyards. J. Rural. Stud. https://doi.org/10.1016/j.jrurstud.2023.103072, 102103072.

Zachmann, L., McCallum, C., Finger, R., 2024. Determinants of the adoption of fungus-resistant grapevines: evidence from Switzerland. J. Wine Econ. 1–33.