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# Multidimensional assessment demonstrates sustainability of new low-input viticulture systems in north-eastern France

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## Abstract

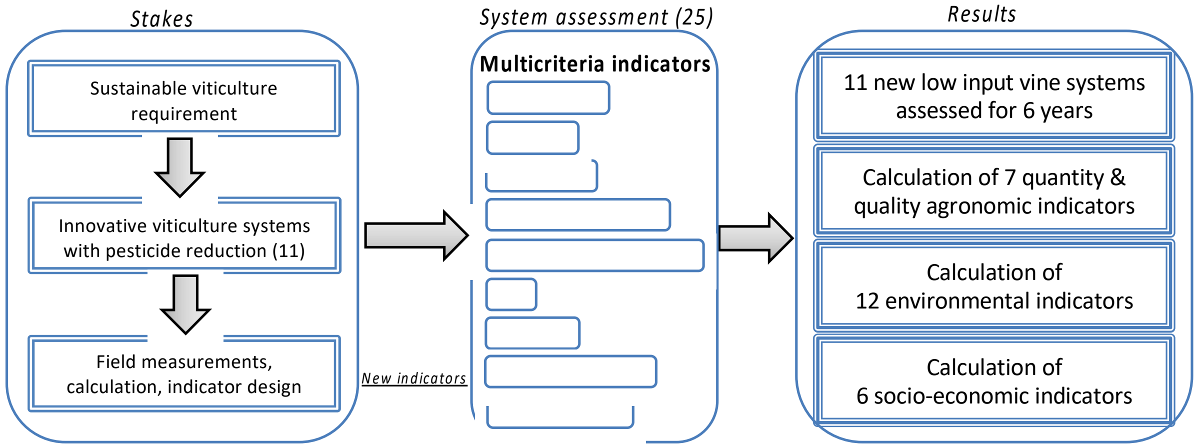
Current demand for more environmentally, socially, and economically sustainable farming practices requires multicriteria assessment of innovative agricultural systems to help enhance cropping systems. We assessed the sustainability of 11 systems intended to substantially reduce inputs, especially pesticides, to viticulture systems. Pesticide use was reduced using three methods: (i) technical (e.g., essential oils instead of some copper use, 100% soil covering applied); (ii) organizational (e.g., new spraying decision rules, decision aid tools); and (iii) redesign of the entire system (e.g., resistant grape varieties planted). Sustainable performance of the new low-input vine systems (NLIVS) was assessed over 6 years (2013–2018) based on 25 indicators. They covered all aspects of system sustainability: environmental, agronomic, economic, and social. This included the evaluation of human capital and the quality of the wines produced. The results showed that it is possible to combine good environmental performance, such as reducing treatment frequency by up to 89%, with good agronomic and wine quality performances. The socio-economic performance of these NLIVS was more moderate. Nonetheless, the results demonstrated that the NLIVS are sustainable according to many diversified indicators. NLIVS are also resilient, as shown by the consistent sustainability results over six consecutive years. They are a realistic tool enabling winegrowers to consider reducing viticulture inputs.

## Highlights

- 11 low-input viticulture systems were implemented and assessed over six years.
- Multi-dimensional indicators were used to assess sustainability.
- Agro-environmental and socio-economic performance levels were identified.
- Low-input vine systems are agronomically and qualitatively efficient.

**Key words** (**max 6**): grapevine, multi-performance, evaluation, pesticide reduction, long-term

## Graphical abstract



## 1. Introduction

Grapevine (*Vitis vinifera* L.) is the topmost cash crop worldwide, being cultivated on 7.5 million hectares in 2015 (OIV, 2017), producing nearly 74 million tons of fruit per year (FAOSTAT, 2017). However, grapevine production has many negative environmental effects, mainly due to pesticide impacts on water quality (Fiener et al., 2005), air quality (Otto et al., 2018), soil quality (Klik, 1994) and biodiversity (Thomson et al., 2007).

It is important to reduce these negative impacts while maintaining grape yield, grape quality, social sustainability, and profitability of the farms (Dantsis et al., 2010; Lichtfouse, 2009), while embracing the principles of sustainability. To address these issues, new low-input vine systems (NLIVS) that can achieve all these goals are required. NLIVS are co-conceived with winegrowers based on a range of agro-ecological principles and share the goal of reducing dependence on external inputs (Wezel et al., 2015). NLIVS are thus diverse in their pesticide reduction levels and strategies. Pesticide reduction strategies in the assessed systems are based on the single or combined activation of three approaches: (i) technical (i.e., using essential oils to reduce copper use, 100% soil covering applied); (ii) organizational (i.e., new decision rules to spray, decision aid tools); and (iii) redesign of the entire system (resistant grape varieties planted). Once conceived, these NLIVS must be assessed (Pelzer et al., 2012) in terms of all dimensions of sustainability. Moreover, their resilience, or temporal performance stability, must also be evaluated.

A recent research on the Web of Science with the keywords “vine” * ”long term” * ”experiment” (http://apps.webofknowledge.com/; accessed on 25 Nov. 2019) shows that very few (15) long-term sustainability assessments of viticulture systems have been reported. Most of them were performed at only one experimental site, and none performed broad multifactorial analysis to assess a diversity of systems (Morlat, 2008).

Multicriteria assessment methods for viticulture have been developed (Pelzer et al., 2012). These methods can assess existing vine systems, including integrated and organic management, but do not accommodate new, very low-input approaches. Methods for use in such systems are needed. Existing assessments also consider few indicators simultaneously, such as those in which one quality and one life cycle assessment (LCA) indicator are calculated for each system (Beauchet et al., accepted; Beauchet et al., 2016; Fermaud et al., 2016; Merot and Belhouchette, 2019; Thiollet-Scholtus and Bockstaller, 2015).

The main goal of this study was to assess the sustainability and performance of several new low-input viticulture systems over an extended period and a broad range of indicators. We assessed 11 new low-input viticulture systems using 25 indicators over six years to provide generalizable knowledge about the impacts of these systems to enable potential adopters to evaluate them.

## 2. Material and methods

### 2.1 Case study

The 11 NLIVS case studies took place in Alsace, a wine region in north-eastern France (48°19'5.446"N, 7°26'29.847"E). Alsace is one of the top four French regions exporting white wines (FranceAgriMer, 2018). Grapes are the largest single French plant product in terms of value, at €11.2 billion of the €41.1 billion national total excluding subsidies (Lubatti et al., 2018). Alsace has a temperate, maritime climate that is warm with moderate precipitation (Blenkinsop et al., 2008). Its climatic conditions combine moderate precipitation with temperatures influenced by oceanic air currents. This combination tends to reduce the survival of otherwise winter-resistant grapevine pathogens, and thus may be a favourable environment for experiments of very low pesticide use.

The 11 systems were studied over six years (2013-2018). This extended period was essential to test the robustness and resilience of the studied systems to multiple pathogen pressures related to varying climatic conditions.

The 11 NLIVS cover a range of biophysical and agronomic conditions (Table 1), representing winegrowers’ practices in the territory. Each of the participating winegrowers designed an NLIVS adapted to their objectives, constraints, and opportunities using or combining the three pesticide-reduction methods described above. The NLIVS were labelled A to K, with A being the least different from conventional viticulture and K the vine system requiring the most structural and management changes (e.g. resistant vine variety). NLIVS A to E reduce pesticide use through technical changes, F to I through organizational changes and J and K through redesigning the entire system (Table 2).

### 2.2 Indicator data collection

Twenty-five quantitative sustainability indicators were calculated for each of the six growing seasons in each NLIVS. Results were converted into mean values across the studied years for each indicator. They represented a broad spectrum of viticulture system sustainability dimensions, including agronomic criteria such as grape and wine quality, environmental, social, and economic elements (Table 3).

Indicators were calculated using data from two sources. First, information was collected during vineyard surveys undertaken annually, after each vine-growing season. This was used to calculate treatment frequency indexes (TFIs), I-Phy, copper usage rate, and socio-economic indicators (described below). These data included all the recorded management practices along with general information about the farm (number of hectares, number of workers, field size). Second, on-field measurements were taken several times over the years covering biodiversity indicators, soil compaction, bacterial activity and biomass in soil, damage caused by fungi, vine vigour and yield, and juice sugar and total acidity, depending on each indicator. All measurements and visual notations were made on ten groups of ten vines per NLIVS.

#### 2.2.1 Environmental sustainability indicators

The pressure of plant protection products is assessed using the **Treatment Frequency Index** of each plot (TFIp) (OECD, 2001) :

$$TFIp = \sum_{t} \frac{ARt}{HRt} * \frac{TAt}{PA}$$

with ARt the applied dose of product t, HRt the registered rate of product t; TAt the area of the plot treated with product t and PA, the plot area.

TFIp was calculated for all pesticide applications on each plot (TFI-total) and also for each pesticide category considered separately (TFI-total and TFI-fungicides).

We also calculated a **TFI-biocontrol** because substitution of chemical fungicide practices by biocontrol fungicide practices (i.e. using copper instead of folpel and sulphur instead of cyproconazol) is an important lever to reduce pesticide use in vine. While biocontrol fungicide practices are less harmful to the environment than chemical fungicide practices, they are nonetheless not harmless for some environmental compartments, such as soil accumulation of copper.

TFI calculation for studied systems was compared to the local reference based on a 2013 national survey (Pujol, 2017). Reference values are 10.9 for TFI-total and 9.8 for TFI-fungicides. TFI-biocontrol reference is the TFI-biocontrol calculated for each studied system in 2013.

**Copper rate** is the indicator that reports the level of copper used on each NLIVS. It is calculated as the amount of copper applied per hectare each year. Copper is an active ingredient for many biocontrol fungicides authorized in organic and biodynamic viticulture. Intensive use of copper might lead to soil pollution. Yearly copper rate is compared to the European authorized limit of 4 $kg.ha^{-1}.year^{-1}$ and also to the local (i.e. northern France) practice **reference** of 1.5 $kg.ha^{-1}.year^{-1}$ (Pujol, 2017).

**TFI** measures only the reliance and dependence on pesticides. In addition to the TFIs, the environmental exposure to pesticides is assessed with the **I-Phy indicator**. This indicator assesses the pesticide exposure of groundwater, surface water, air, and beneficial organisms induced by agricultural practices (Thiollet-Scholtus and Bockstaller, 2015; van der Werf and Zimmer, 1998). I-Phy indicator scores are based on a fuzzy decision tree aggregating system and are expressed on a scale of 0 (unacceptable risk) to 10 (no risk). The reference value 7 corresponds to an acceptable risk to the environment.

**Soil compaction** was assessed by root percentage and soil settling level in soil cultivation profiles that were obtained once, in 2015, for each NLIVS (Lagacherie et al., 2003). Results were expressed as percentages from 0 (no soil settling, with pores and roots, i.e., no soil compaction) to 100 (total soil settling without lacunae or roots, i.e., totally compacted soil). Acceptable soil settling was defined as less than 20%. This level of soil compaction corresponds to the minimum space that allows vine root development. This indicator thus provides an overall measure of the impact of soil management practices. As vine plots typically include three different zones that reflect soil maintenance practices (Lagacherie et al., 2003), soil profiles were assessed in each of these three zones: under vine rows (0.3 m wide), ploughed inter-row areas (0.5 m wide), and cover-crop inter-row areas (0.5 m wide). For each profile, soil compaction was assessed at two depths: 0-0.2 and 0.2-0.6 m. Thus, six soil compaction assessments were obtained per system.

**Bacterial activity in soil** was estimated by measuring the optical density of bacterial concentration in soil suspension able to degrade 31 sources of carbon over 48 h.

**Bacterial molecular biomass** is measured by quantitative PCR to extract soil DNA. The DNA bacterial biomass is used to evaluate the effect of soil management on the total soil microbial biomass. Soil samples were incubated at 28°C. $NH_4$ and $NO_3$ concentrations were measured after 0, 7, 14, 28, and 56 days to obtain the rate of nitrogen mineralization in the soil. The available nitrogen in the soil was represented by the quantity of nitrogen mineralized in 15 days. This duration under controlled laboratory conditions is equivalent to 4 months in the vineyard; 4 months is the time required for grape bunches to mature, accumulating sugar and acids in the process.

The two indicators selected to assess biodiversity in the NLIVS were number of species present, or **specific floristic richness**, and **relative pollination value**, which provides information about this ecosystem service. Botanical surveys were performed three times per year from 2014 to 2018 at grapevine budburst, flowering, and bunch closure in each of the 11 systems. We measured floristic richness as the number of plant species present on a 500 $m^2$ plot. All test areas were located centrally within the system area in order to avoid edge effects (Geiger et al., 2010).

The relative pollination value was calculated based on the pollination values of the species identified in the botanical survey. These were assigned following Ricou et al. (2014), in which a score of 0 represents a plant with no pollination value and 10 represents high pollination value, based on the domestic bee. The reference value of 3.5 is specified as representing acceptable pollination interest. The indicator was calculated as the percentage of the species found in each botanical survey that had a pollination value greater than 3.5.

### 2.2.2. Agronomic quantitative and qualitative indicators

**Vine vigour** was measured by weighing winter-pruned wood. In each NLIVS and for each year, the grapevines of four sub-plots were hand-pruned in December. Each sub-plot is a 10-vine-group. The sub-plots were selected according to resistivity (e.g. water supply in soil) map of the plot to represent the intra-plot variability in vine phenology according to potential water stress. The cut branches were collected and weighed immediately according to the method used by Ripoche et al. (2011). The **yield** per vine was measured at harvest in each NLIVS. The system yield per hectare was then calculated using the actual planting density recorded for that NLIVS and year.

**Damage caused by fungi** on grapes at harvest is a good proxy for the effectiveness or failure of the plant protection strategy and is connected to the TFI and I-Phy indicators (section 2.2.1). Experts from local extension services assessed damage to grape bunches due to powdery mildew and grey rot at harvest by visual observation. The damage rating for each of these two diseases consisted of the number of bunches with any damage due to that disease as a percentage of the total bunches on that vine. Then, again for each disease separately, the percentage of damage was assessed within each damage cluster. For each cluster, the intensity was multiplied by the relevant frequency rating to yield the powdery mildew and grey rot intensity indicators as percentages.

The reference for acceptable **powdery mildew and grey rot intensity** was defined as a maximum of 10% per cluster. The means across all ten-vine-groups in each NLIVS were then calculated to obtain a single value per system for each year.

**Sugar content and total acidity** were measured in the juice of the same 10-vine-groups at harvest. The sensory indicator, here used to measure overall wine quality, was based on conventional descriptive analysis as described by Cadot et al. (2012). The assessment was performed by an expert sensory panel composed of an average of 17 judges connected to the wine research sector, who were selected based on their availability and interest. A simplified set of sensory descriptors was predefined using the descriptors of Jourjon et al. (2005). Wines were assessed in duplicate in a Williams Latin Square arrangement to capture presentation order and carry-over effect. Wines were assessed by comparing them to the Alsace wine reference. Testing was performed blind. The reference sensory indicator value used was 5/10, corresponding to the quality required for the Protected Designation of Origin (PDO) wine standard, which uses a scale from 0 (unacceptable) to 10 (very good). This measure is a summary of the agronomic performance result of the studied systems, i.e., quantity and quality of juices to make PDO wines.

### 2.2.3 Costs and social indicators

The **economic assessment** was based on the profitability of the grapevine system before winemaking. This indicator, semi-gross margin, was calculated per NLIVS per hectare as grape sales revenue minus the cost of production, including workforce, pesticides, fertilisers, and equipment, in euros (Keichinger and Thiollet-Scholtus, 2017; Meylan et al., 2013). Vineyard profitability, which is the net economic result including farm costs. The reference value of this economic indicator is that of a field of the vineyard without pesticide reduction, for each NLIVS. It is also important to evaluate economics at the vineyard scale in order to judge and discuss the adoptability of NLIVS by winegrowers. Vineyard profitability is expressed in euros. There is no reference at this scale because of the very large diversity of the studied systems.

The **human capital indicator** assesses social factors relating to vineyard workers. It has three components: (i) labour-intensiveness: arduousness of the labour involved; (ii) pesticide risk: the health risks of the relevant pesticide; and (iii) occupational health: safety at work. The labour element is measured as the mean time spent in repetitive work, painful postures and subject to mechanical vibration, compared to a reference from the French health system. EUROPOEM data (Van Hemmen, 2001) were used to evaluate health risks by estimating exposure during pesticide preparation and spraying, considering whether personal protection equipment was used. Pesticide sub-indicator considers only risk to the operator. Finally, the safety element uses measures of worker education and protection while using mechanical equipment. The human capital indicator result aggregated these three risks using fuzzy-logic decision trees, producing a scale value from 0 (unacceptable) to 10 (fully acceptable) (Thiollet-Scholtus and Bockstaller, 2015). More details about this indicator calculation are available in Keichinger and Thiollet-Scholtus (2017). This indicator was calculated for only one year (2015) because the practices do not change every year. This indicator was not calculated for E, F, J, or K NLIVS because their vines were planted in 2014.

The reference for the human capital indicator is the value for a field of the farm without pesticide reduction. Considering human capital is essential when evaluating systems because it will be decisive for the dissemination of NLIVS after validation of their performance.

## 2.3 Statistical analysis

For indicators determined more than once during the six-year experimental period, means were calculated to compare the NLIVS and the assessment criteria, producing a single value per NLIVS for the 2013-2018 period. A boxplot was used to show the distribution of the annual data for each indicator and each NLIVS. Judges and replicates of the sensory data are described by Thiollet-Scholtus et al. (2020). For sensory data, one-way analysis of variance was performed, with wine as the factor and judges as replicates. For sensory attribute with an effect of wine, a Newman-Keuls test was used to determine the significance of differences between group means (P = 0.05) according to the method described by Cadot et al. (2012).

Statistical analysis was performed using XLSTAT-Pro software (ver. 2009; Addinsoft, Paris, France).

## 3. Results: NLIVS sustainability results according to targeted goals

There was a very clear decrease in **TFI-total** (i.e., both total pesticide used and biocontrol inputs used) for all NLIVS, compared to the local mean of 10.9 (Pujol, 2017). Only 4 of the 54 values obtained exceeded this value. The overall mean of TFI-total scores for all systems and all years was only 5.5. Five NLIVS (C, H, I, J and K) had a TFI-total less than 5.5 for several consecutive years (Fig. 1-A). Individually, fungicide and biocontrol TFI performance lay below the local mean value for all NLIVS (Fig. 1-B). The TFI-biocontrol and TFI-total indicators were close to zero for systems J and K because they used resistant grape varieties, which were associated with minimal pesticide and biocontrol management (Fig. 1-C).

The **I-Phy** indicator results were satisfactory for all of the systems studied. Mean I-Phy ranged from 9-10 for all NLIVS (Fig. 1-D), which lay above the acceptable value of 7/10. All results for individual years exceeded 7, varying from 7.3 (system D in 2014) to 10 (systems H, I and K). This confirms that winegrowers are minimizing the environmental risk of pollution by pesticides (Fig. 1-D).

Levels of **copper** use in the NLIVS were low, with an overall mean of 0.74 $kg.ha^{-1}.y^{-1}$, and a maximum of 3.04 $kg.ha^{-1}.y^{-1}$, compared to the maximum authorized use in Europe of 4 $kg.ha^{-1}.y^{-1}$. This confirms that our NLIVS managed to substantially reduce all vine-protection inputs including copper (Fig. 1-E).

The **soil compaction** results suggested that annual ploughing does not lead to high compaction of the soils of the NLIVS (Fig. 2-A). Under the rows, the topsoil (0-0.2 m) in all NLIVS had a compaction indicator of less than 20%, which was thus considered not compacted and satisfactory. In the topsoil of ploughed inter-rows, soils were compacted only in systems D and B, which had 40% and 80% soil compaction, respectively. These systems retained some herbicide spraying; more frequent spraying using tractors may have caused this additional compaction. The topsoil of the cover-crop inter-rows was not compacted (less than 20%), except in systems A, B, F and I. In F, it was due to spraying protection productions on vines planted in 2014, which required heavy tractor traffic. In I, it was due to spraying frequently with low doses of pesticides. In A and B, where compaction was the highest (80%), it was due to optimizing pesticide spraying, i.e. dividing the total amount of pesticide sprayed among several applications, which increased the frequency of tractor passes. The deeper soil layer (0.2-0.6 m) under the vine rows was more compacted than the topsoil; only systems F, I, and J systems had less than 20% compaction. Deep soil compaction was due to specific vine management activities such as grubbing-up and planting. As there were no clear relationships between deep soil compaction and NLIVS, and our NLIVS were based more on yearly management changes than on these practices, we assumed that this deep soil compaction is not directly related to the NLIVS types but with agricultural practices before 2013 (Fig. 2-A).

Indicator results for **bacterial activity** in the soil and **bacterial biomass** were satisfactory for all NLIVS (Fig. 2-B, 2-D), as were those for the **speed of nitrogen mineralization** in the soil (Fig. 2-C). In the first year of measurement (2014), the **rate of available nitrogen** was approximately 13 mg $kg^{-1}$ in all systems. In 2015, systems E and F had higher values, and system G had an atypically high value (greater than 65 mg $kg^{-1}$). We hypothesized that this was due to mulching with hardwood chips under the rows in October 2014. Systems E and F continued to show similar values in 2016 and 2018. The 2018 measurement in systems B and G indicated an increasing rate of nitrogen mineralization (Fig. 2-E).

The mean **relative pollination value** was 42%, ranging from 24-58% (Fig. 3-A). Mean **floristic richness** was 65 species, varying from 39-94 species. There were no significant differences among the 11 systems studied, suggesting that none of the NLIVS had a direct effect on these indicators (Fig. 3-B).

**Vine vigour** was satisfactory for all NLIVS, with a mean score of 0.63 kg $vine^{-1}$ (Fig. 4-A) compared to the national average of 0.3-0.7 kg $vine^{-1}$ in 2018, as was **vine yield**, with a mean yield of 12,058 kg $ha^{-1}$ (Fig. 4-B).

**Disease indicators** were also satisfactory for all NLIVS. For powdery mildew, all indicator values lay below 11% of bunches (Fig. 5-A), which corresponds to winegrowers' production objectives. For grey rot, the indicator values lay below 12% of bunches, which corresponds to winegrowers' production objectives, in 51 of the 54 measurements (Fig. 5-B). Winegrowers were able to minimize risk to quality; thus, the risk taken in adopting NLIVS did not decrease crop quality.

The **juice sugar**, at 119-240 g $L^{-1}$ (Fig. 6-A), and the **total juice acidity**, at 3.1-10.2 g $H_2SO_4$ per L (Fig. 6-B), were both satisfactory for all NLIVS according to the PDO specification.

The **sensory evaluation** of wines from the NLIVS was also sufficient to meet the PDO standard. Every wine studied scored from 4/10 to 6/10 (Fig. 6-C). It suggests that none of the NLIVS had a direct effect on this outcome.

The **semi-gross margins** at the system scale varied greatly among systems, ranging from a loss of €9000 to a gain of €6585 per year (Fig. 7-A).

**Vineyard profitability** also varied greatly for the annual periods measured, ranging from a loss of €12,000 to a gain of €3000 per year (Fig. 7-B). The NLIVS were found to be labour-intensive, with unsatisfactory typical indicator values of approximately 5 on a scale of 0-5. Innovations related to the decrease in pesticide spraying appear to have increased the labour needed to change viticulture practices. However, the human working time of NLIVS remained within the average working time of viticulture systems without innovation. Thus, the results suggest that this should not prevent implementing NLIVS in vineyards.

The **arduousness risk indicator** results were unsatisfactory. Almost all NLIVS scored zero, except for system B (Fig. 8), which scored 10. System B reduced all of the factors considered in the arduousness risk indicator (noise, low back pain, and musculoskeletal disorder) due to more frequent use of mechanization than the other NLIVS.

The **pesticide risk indicator** results were unsatisfactory, 0-4.3 on a scale of 0-10, compared to the reference value of 7. Systems A and D scored 0 (high pesticide risk to the operator) due to the toxicity of active ingredients used in these systems. The unsatisfactory scores of systems B (4.29), C (4.00), and G (4.86) were due to the rates of pesticide sprayed, while the scores of systems H (3.67) and I (1.33) were due to the frequency of pesticide spraying (Fig. 8). These results show that the intensity of pesticide use remains a danger for the operator who runs the viticultural system, even in very low-input systems. Even if pesticide rates are decreased and pesticides are approved by environmental certifications, there is a risk to the operator.

The **security risk indicator** results were satisfactory. All NLIVS scored from 8 to 10. Due to the unsatisfactory scores of most systems for pesticide risk and arduousness risk, results of the aggregate **human capital indicator** were not very satisfactory, as all ranged from 2.4-4.6, except for system B, which scored 9.1, compared to the reference value of 7 on a scale of 0-10. This suggests a risk of decreasing the acceptability of most NLIVS (Fig. 8).

## 4. Discussion

### 4.1 Relative sustainability performances of NLIVS

Encouragingly for NLIVS, the four indicators that varied along the NLIVS gradient are environmental indicators: **TFI-total**, **TFI-fungicides**, **bacterial biomass,** and **bacterial activity** in soil (Fig. 2-B). The TFI-total results confirmed the reduction in overall pesticide use in our system classification (Table 2), from 7.69 (system A) to 0 (system K) (Fig. 1-B). The TFI -biocontrol indicator values increased with the gradient of NLIVS, from 4% (system A) to 84% (system H) or 74% (system I). **Bacterial biomass in the soil and bacterial activity** in soil increased with the NLIVS gradient, from 0-1.4 × $10^{12}$ DNA copies per g of soil per second, and from 0-1.1 (no unit), respectively.

This result is consistent with the assumption that reducing pesticide inputs has increasingly positive impacts on environmental indicators. It is consistent with the results of Lechenet et al. (2014) and Reeve et al. (2005). Conversely, it does not agree with those of Döring et al. (2019), who found no environmental difference between organic and biodynamic viticulture systems; this may be due to the few sustainability indicators they used, none of which measured bacterial activity in the soil.

Another notable result is that the **copper rate** decreased according to the NLIVS gradient. Systems I, J and K depended little on copper input, at 0.42, 0.08, and 0.0 kg $ha^{-1}$ $y^{-1}$, respectively, which remained stable over time. In contrast, systems A, B, C, D, F, and G depended more on copper input, with higher variability (Fig. 1-E).

Other environmental assessment results, even if they do not clearly discriminate among the NLIVS, were also satisfactory for NLIVS sustainability, as mentioned.

The results for **growth and yield** (Fig. 4), **disease incidence** (Fig. 5), **juice quality**, and wine **sensory characteristics** (Fig. 6) did not discriminate among the NLIVS. These results are consistent with the assumption that decreasing environmental impacts of a system does not decrease the quantity and quality of the grapes and wine produced. This contrasts with results of Döring et al. (2019), who reported a decrease in vine yield and more grey rot attacks in organic systems than in conventional ones.

**Economic indicator** variation along the NLIVS gradient showed that semi-gross margin and vineyard profitability increased from systems G to K. The results suggest that the least cost-effective NLIVS are the intermediate systems B, C, and D, in which only technical changes were implemented rather than a complete redesign of the system. These systems can be considered hybrids, in which the transition toward very low-input is incomplete. They relied mainly on reducing the rate of and dividing pesticide applications (i.e., increasing pesticide efficiency) to decrease pesticide use, rather than whole-system redesign, including organizational changes, which characterized systems F to K (Hill and MacRae, 1995) (Fig. 7).

The **human capital indicator** did not clearly improve among NLIVS. Except for the pesticide risk indicator, arduousness and security did not seem to vary much among the systems (except for system B). While replacing conventional pesticide practices with more environmentally friendly ones reduces environment impact, it does not seem to reduce risks to the operator. As all of the NLIVS still use some kind of pesticide, they still present a risk to the operator.

### 4.2. Benefits of the NLIVS

With the growing evidence of pesticide toxicity (Damalas, 2009) and overall societal distrust in such agricultural practices, winegrowers should rapidly transition towards drastically reducing pesticide use. Assessing and comparing these NLIVS allows a range of pesticide-reduction solutions to be proposed to winegrowers. The relative performances of these NLIVS highlight that progressive and radical pesticide reduction is possible without large loss of yield or quality. However, one should recall that pesticide reduction is most effective when the entire farming system is redesigned. Our study showed that systems J and K, the redesigned systems, are those that have the best environmental performances while keeping production and quality performances at an acceptable level and ensuring good economic results. With their very low use of synthetic pesticides, copper, and machinery, these systems are also more resilient to economic and climatic changes (Dardonville et al., 2020).

Redesigning vine growing production systems is not easy, as the complexity of system management generally increases (Merot and Wery, 2017), as does the load or arduousness of the work. The results tend to show that using resistant grape varieties eases management of these NVLIS. This genetic innovation seems to be a good mechanism for transitioning towards agro-ecological vine systems.

### 4.3 Which indicators to assess NLIVS sustainability?

Agronomic performance indicators (i.e. yield and vigour) and qualitative wine performance (i.e. juice sugar, juice total acidity, and wine sensory characteristics) seemed to describe the winegrowers well. The results showed that NLIVS achieved the standards required by the PDO specification for the area in which they were implemented. Thus, they support the hypothesis that NLIVS can produce grapes that can claim an Alsace PDO.

Two indicators seem questionable for assessing NLIVS sustainability. Their lack of variation may indicate that they have limited sensitivity and may not reflect an absence of effects. For example, the complex aggregate indicator I-Phy, developed in the 2000s to assess diverse existing viticulture systems, was unable to discriminate among the NLIVS, all of which scored above 7. Most of these sustainability indicators were developed to discriminate between conventional and more sustainable cropping systems. Thus, they might be under-equipped to discriminate among different strong "alternative" viticulture systems. To discriminate among NLIVS now and in the future, indicators should be adapted and improved. Indicators could be adapted and improved by redefining their thresholds, references, and limits, which are parameters that greatly influence their sensitivity (Bockstaller et al., 2017). New indicators may also need to be built that consider new properties of future NLIVS. For example, from a cost perspective, the high variability in economic performance suggests that not all of the NLIVS in our study are sustainable. This instability could hinder adoption of NLIVS by winegrowers. However, a simple economic assessment may be insufficient to assess the economic viability of NLIVS. Future economic assessments could benefit from additional detail and a wider range of factors, such as investment and depreciation rates.

### 4.4. Generality of NLIVS and assessment results

The NLIVS within this study were designed and experimented with in Alsace. Generally, as pesticide reduction can be a shared goal, agricultural production systems should be designed for local contexts (Meynard et al., 2017). Because of its soil and climatic context, Alsace has wine production conditions that lay between those of regions with a very strong oceanic influence (e.g. Loire valley in France, Porto area in Portugal) and those with a strong continental influence (e.g. Tokay area in Hungary). These NLIVS could be developed in other regions by adapting them to the local soil and climatic conditions. In an oceanic climate, the main changes would be to maintain higher rates of copper application, as winegrowers may be less inclined to decrease it due to the higher pathogen pressure. In a continental climate, winegrowers could opt for more inter-row cover-crops in winter only, as the water stress is stronger in the summer. (R1-1)

Regarding the socio-technical context, Alsace benefits from a PDO defined by a set of characteristics that include authorized vine varieties and the trellis system. When exporting a specific vine system, one should be aware of the consistency of these socio-technical characteristics, especially when using pathogen-resistant varieties. These new varieties may not be eligible in other PDOs or specific wine appellations (e.g. Vin de France). Using a specific vine variety (e.g. Chardonnay) more sensitive to fungi may require more pesticide spraying, which would worsen environmental assessment results (e.g. TFIs, I-Phy, copper rate). Nonetheless, other practices, such as the type of trellis (e.g. pergola, buckets) may not be large obstacles to generalizing NLIVS, as they do not influence pathogen pressure.

## 4. Conclusion

The assessment of NLIVS performance covered all aspects of system sustainability: environmental, agronomic, social, and economic. The results demonstrate that it is possible to combine good environmental and agronomic performances, with a TFI reduced by up to 89% and more moderate socio-economic performance. NLIVS are thus sustainable according to many diverse indicators and can also remain resilient over six consecutive years.

Assessing NLIVS with a large number of indicators is useful. Such sustainability assessment, simultaneously considering agronomy, environment, social factors, and economic performance, is essential for identifying obstacles and mechanisms that influence adoption of NLIVS by winegrowers. Social and economic assessment needs further improvement to encourage broad and sustainable adoption of NLIVS by winegrowers while maintaining a high level of agronomic and environmental performance. The information obtained contributes to winegrower assessments of potential risks of transitioning their systems to agro-ecological viticulture.

Consequently, **NLIVS have multiple benefits**: i) they decrease environmental impacts while maintaining the profitability and agronomic performance of the system; ii) they are essential for adapting viticulture to pesticide regulations; and iii) the diversity of the 11 NLIVS, from efficiency to redesign, makes it possible to disseminate them to other vineyards using feasible adaptations.

## Author contributions

M. Thiollet-Scholtus: Conceptualization, Validation, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition. A. Muller, C. Abidon, J. Grignion, C, Rabolin-Meinrad, O. Keichinger, R. Koller, A. Langenfeld, L. Ley, N. Nassr, R Nibaudeau: Data curation, Investigation, Resources, formal analysis. J. Wohlfahrt: Writing - Review.

## Declaration of Competing Interest

None.

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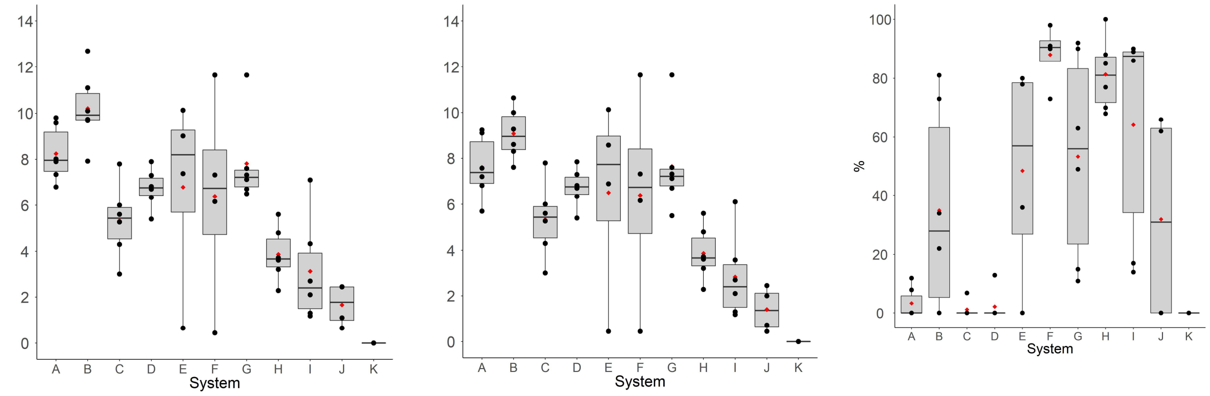
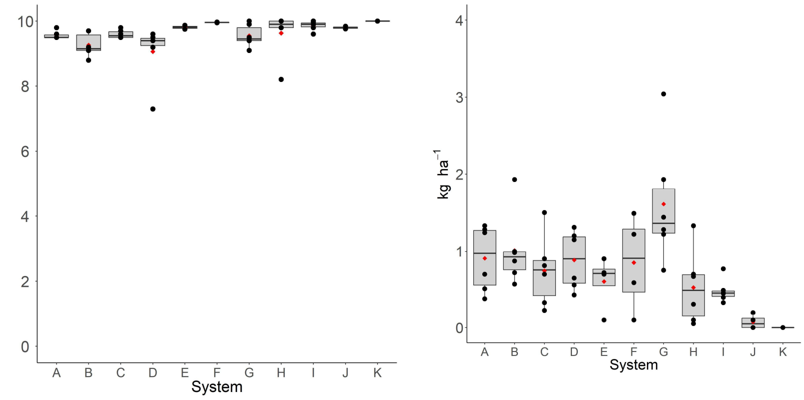


A TFI-total (no unit)

B TFI-fungicide (no unit)

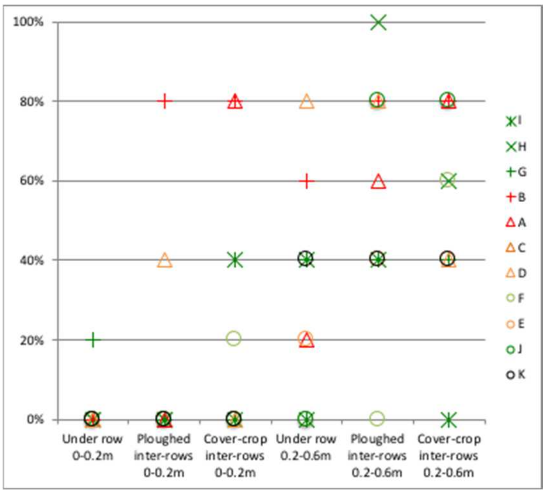
C TFI-biocontrol / TFI-total (%)



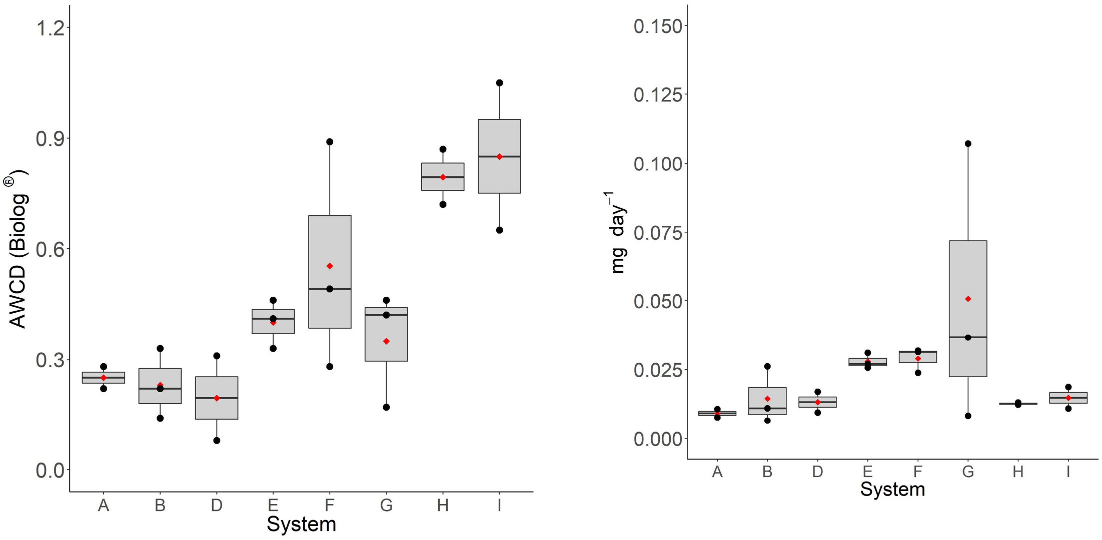
D I-Phy (no unit)

E Copper rate (kg ha$^{-1}$)

**Figure 1. Environment assessment (A, B, C, D, E).** For each indicator and new low-input vine system: dots show the distribution of annual observations, red diamonds show means, and whiskers show the minimum and maximum.

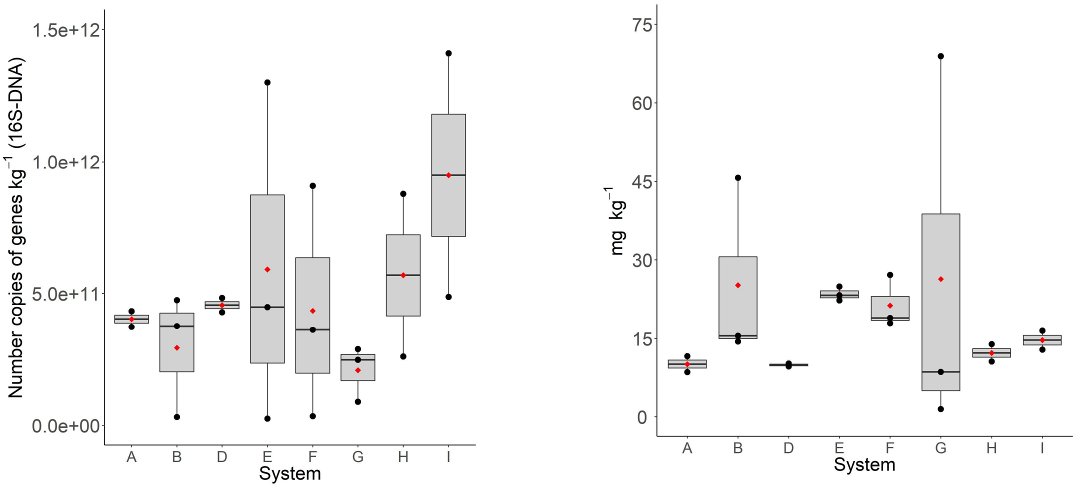


A Soil compaction (2015)



B Bacterial activity in soil with average well-color development, AWCD, Biolog®)

C Speed of nitrogen mineralization rate in the soil speed expressed in mg day$^{-1}$ (Thiollet-Scholtus *et al.*, 2020)

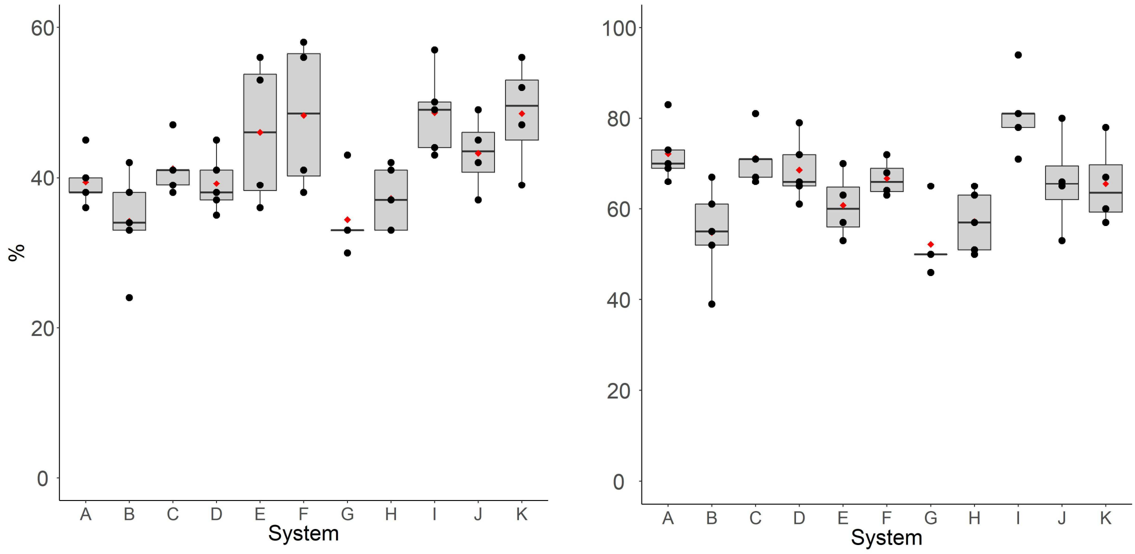


D Bacterial biomass in soil in number copies of genes kg-1 (16S-DNA)

E Nitrogen potentially available in soil in mg kg$^{-1}$

**Figure 2. Soil assessment (A, B, C, D, E).** For each indicator and new low-input vine system: dots show the distribution of annual observations, red diamonds show means, and whiskers show the minimum and maximum.

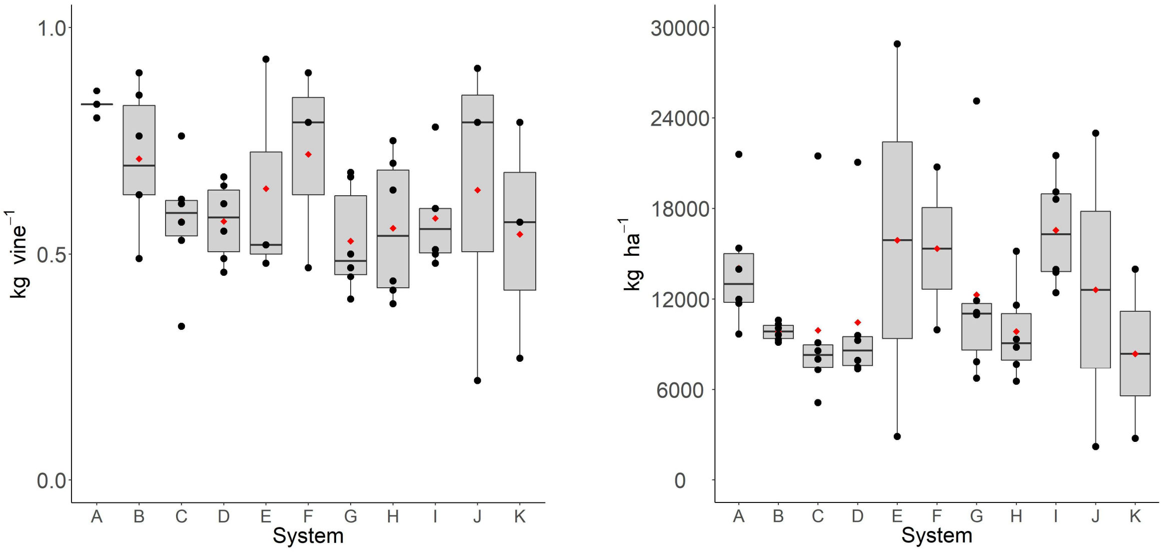
Thiollet-Scholtus, M., Muller, A., Abidon, C., Grignion, J., Keichinger, O., Koller, R., Langenfeld, A., Lemarquis, G., Ley, L., Rabolin-Meinrad, C., & Nassr, N. (2020). Assessment of new low input vine systems : dataset on environmental, soil, biodiversity, growth, yield, disease incidence, juice and wine quality, cost and social data. *Data in Brief* 31105663. https://doi.org/10.1016/j.dib.2020.105663



A Relative pollination value in %

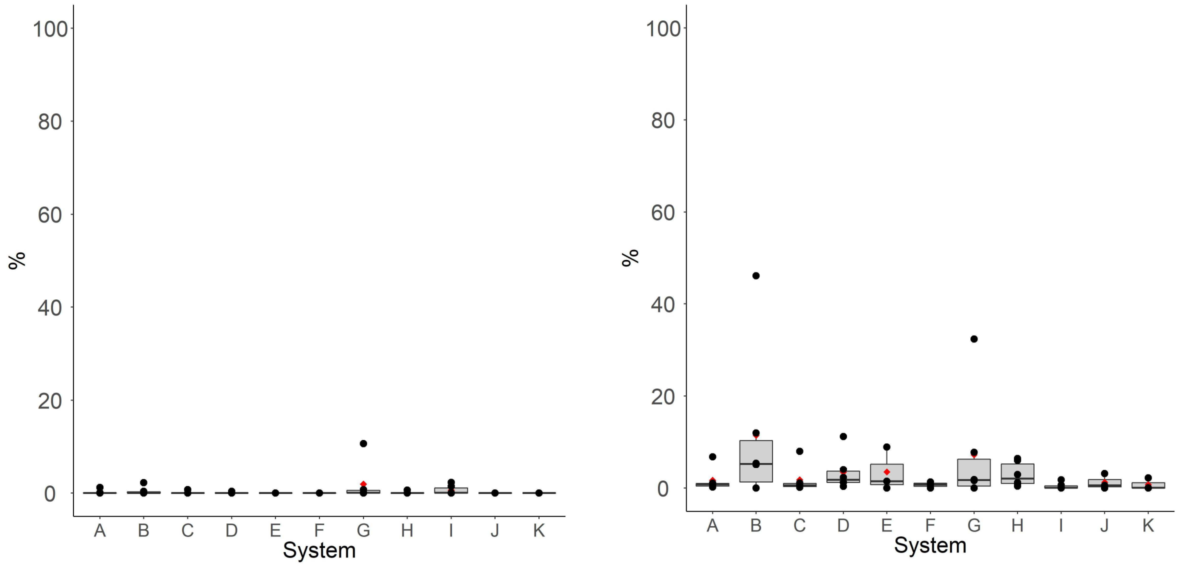
B Number of total floristic species found in tie fields to evaluate richness

**Figure 3. Biodiversity assessment (A, B).** For each indicator and new low-input vine system: dots show the distribution of annual observations, red diamonds show means, and whiskers show the minimum and maximum.



A Vine vigour in kg vine$^{-1}$ of winter pruning wood B Yield in kg ha$^{-1}$

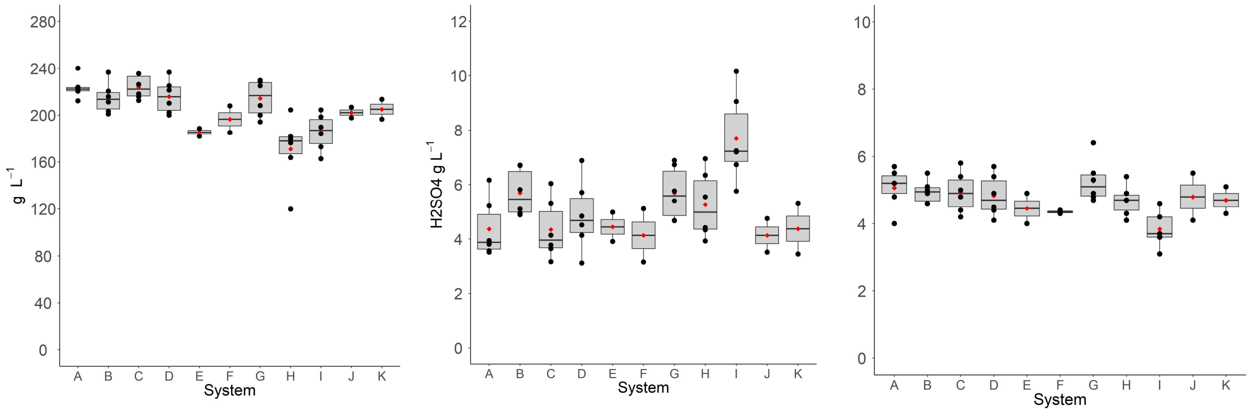
**Figure 4. Growth and yield assessment (A, B).** For each indicator and new low-input vine system: dots show the distribution of annual observations, red diamonds show means, and whiskers show the minimum and maximum.



A Powdery mildew (*Erysiphe necator*) intensity on bunches in %

B Grey rot (*Botrytis cinerea*) intensity on bunches in %

**Figure 5. Disease incidence assessment (A, B).** For each indicator and new low-input vine system: dots show the distribution of annual observations, red diamonds show means, and whiskers show the minimum and maximum.

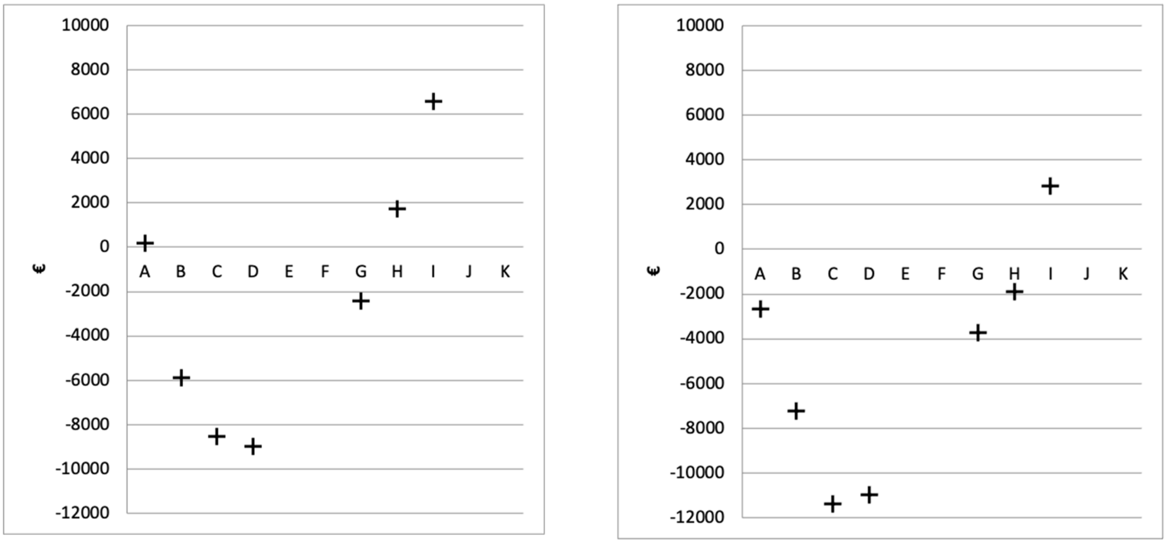


A Juice sugar in g L$^{-1}$

B Juice total acidity in $H_2SO_4$ g L$^{-1}$

C Wine sensory characteristics (no unit)

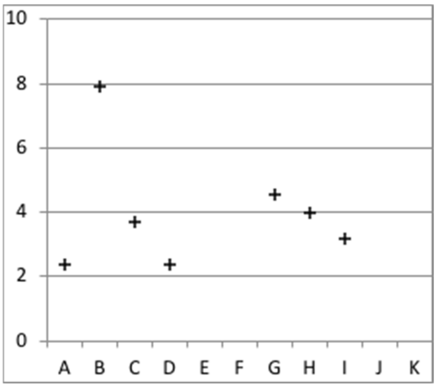
**Figure 6. Juice quality and sensory characteristics assessment (A, B, C).** For each indicator and new low-input vine system: dots show the distribution of annual observations, red diamonds show means, and whiskers show the minimum and maximum.



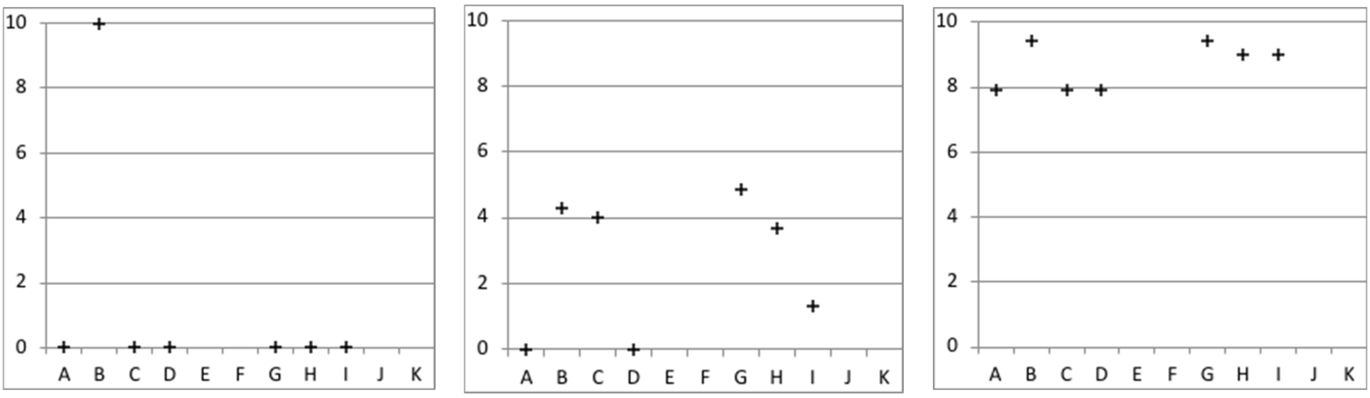
A Profitability 1: Semi-gross margin at the system scale in euros

B Profitability 2: Net economic result (including farm costs) in euros

**Figure 7. Cost assessment (A, B).** For each indicator and new low-input vine system: dots show the distribution of annual observations, red diamonds show means, and whiskers show the minimum and maximum.



A Human capital



B Arduousness C Pesticides D Security

**Figure 8. Social acceptability assessment (A, B, C, D).** For each indicator and new low-input vine system: black crosses show the distribution of observations in 2015.

**Table 1. Characteristics of New Low Input Vine Systems.**

| Characteristics | Nature |
|---|---|
| Variety | Riesling, pinot blanc, pinot gris or resistant varieties |
| Root stock | SO4, 3309, or 161-49 |
| Vine age | From 5 to 42 years-old |
| Winter pruning practice | Double Guyot |
| Slope | From 0% to 15% |
| Soil type | Brown soil, granite alluvium soil, stony and silt clay soil, clay loam soil or loamy sandy soil |
| Environmental specification | Integrated, organic or biodynamic |
| PDO certification | ‘Alsace’, ‘Crémant’ or ‘Grand Cru’ |

**Table 2. Gradient of intended reduction in pesticide use in new low input vine systems (NLIVS).** For ‘herbicides’, there is a decrease in their use on the surface of the plot, starting with use everywhere (xxx), then removing use on half of the inter-rows (xx), then on all inter-rows (x), and ending with no use (_). The gradient of notation is reversed for ‘plowing’ and for ‘crop soil cover’. For ‘copper’, there is a decrease of rate use on the surface of the plot, starting with the reference rate (xxx) according to E-phy database, then by dividing the reference rate by at least 2 (xx), then by dividing the reference dose by at least 5 (x), and finally by completely eliminating the use of copper (_). The gradient is the same for ‘Sulfur’ and ‘Chemical’. Tek: technical, Org: organizational, Re: redesign.

| | | **Gradient of new low input vine systems (NLIVS)** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** |
| **Nature of changes** | | Tek | Tek | Tek | Tek | Tek | Org | Org | Org | Org | Re | Re |
| **Details of changes** | | | | | | | | | | | | |
| Soil management | Herbicides | xxx | xxx | xxx | xxx | xx | x | _ | _ | _ | _ | _ |
| | Plowing | x | x | x | x | x | xx | xx | x | x | x | x |
| | Crop soil cover | x | x | x | x | x | xx | xx | xxx | xxx | x | x |
| Fungicides | Copper | xxx | xxx | xx | xx | xx | x | xx | x | x | x | _ |
| | Sulfur | xx | xxx | xx | xx | xx | xx | xx | x | x | x | _ |
| | Chemical | xxx | xxx | xxx | xxx | xx | x | _ | _ | _ | _ | _ |
| Variety | Resistant variety | _ | _ | _ | _ | _ | _ | _ | _ | _ | yes | yes |
| | | 🟥 | 🟥 | 🟧 | 🟧 | 🟧 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

## Table 3. Characteristics of assessment indicators.

| Indicators | Reference | Reference comment | Unit | Variation range | Number of original measures |
|---|---|---|---|---|---|
| TFI-total | Local average: 10.9 in 2013. National average: 14.7 in 2013. | National survey every 6 years gives the local and national averages. | no unit | 0 to 12.7 | 11 systems, 6 years, 51 scores |
| TFI-fungicides | Local average: 9.8 in 2013 | National survey every 6 years gives the local and national averages. | no unit | 0 to 11.7 | 11 systems, 6 years, 51 scores |
| TFI-biocontrol/TFI-total |  | – | % | 0 to 100% | 11 systems, 6 years, 51 scores |
| I-Phy | Integrated viticulture: 7/10 | INDIGO(R) scale | no unit | 0 to 10 | 11 systems, 6 years, 45 scores |
| Copper rate | Local average: 1.6 kg.ha-1.year.-1 in 2013 | European and French authorized maximum is 4 kg.ha-1.year-1 | kg.ha-1.year-1 | 0 to 3.0 | 11 systems, 6 years, 51 scores |
| Soil compaction | No local average | Scale from 0 (no settling) to 100% of compacted soil (correspondgin to ro vine root in the soil). | no unit | 0 to 100% | 11 systems, 1 year (2015), 60 scores |
| Nitrogen bacteria activity in soil |  |  |  | 0.1 to 1.1 | 11 systems, 3 years (2014, 15, 18), 20 scores |
| Nitrogen bacteria biomass in soil |  |  |  | 1,4E+12 to 2,6E+10 | 11 systems, 3 years (2014, 15, 18), 28 scores |
| Speed of nitrogen mineralization in the soil at veraison |  |  | mgN.kgDM-1 | 0.0 to 0.1 | 11 systems, 3 years (2014, 15, 18), 28 scores |
| Amount of available nitrogen in soil at veraison |  |  | mgN.kgDM-1 | 1.5 to 69.0 | 11 systems, 3 years (2014, 15, 18), 28 scores |
| Relative pollination value |  |  | no unit | 24.4 to 58.0 | 11 systems, 6 years, 51 scores |
| Total floristic richness |  |  | no unit | 39.0 to 94.0 | 11 systems, 6 years, 51 scores |
| Vine vigor | Winemaker personnal goal | no PDO specification | kg.vine-1.year-1 | 0.2 to 1.0 | 11 systems, 6 years, 47 scores |
| Yield | Winemaker personnal goal | PDO specification is the maximum | kg.ha-1.year-1 | 2240.7 to 28913.3 | 11 systems, 6 years, 43 scores |
| Powdery mildew intensity on bunches (%) at harvest | Local pest pressure | No regulatory reference | % | 0% to 10.7% | 11 systems, 6 years, 47 scores |
| Grey rot intensity on bunches (%) at harvest | Local pest pressure | No regulatory reference | % | 0% to 46.2% | 11 systems, 6 years, 47 scores |
| Juice sugar rate | Winemaker personnal goal | PDO specification is the maximum | g.L-1 | 119.9 to 240.2 | 11 systems, 6 years, 43 scores |
| Juice total acidity | Winemaker personnal goal | no PDO specification | H2SO4 g.L-1 | 3.1 to 10.2 | 11 systems, 6 years, 43 scores |
| Wine sensory characteristics | Alsace PDO average (5/10) | no PDO specification | no unit | 0 to 11.7 | 11 systems, 6 years, 43 scores |
| Profitability1 | Winemaker personnal goal | Semi gross margin at system scale | euros | _9000 to 6585 | 11 systems, 1 year (2015), 11 scores |
| Profitability2 | Winemaker personnal goal | Net economic result including farm costs | euros | _11387 to 2813 | 11 systems, 1 year (2015), 11 scores |
| Human capital | No reference | _ | no unit | 0 to 10 | 11 systems, 1 year (2015), 11 scores |
| Penibility | No reference | _ | no unit | 0 to 10 | 11 systems, 1 year (2015), 11 scores |
| Pesticides | No reference | _ | no unit | 0 to 10 | 11 systems, 1 year (2015), 11 scores |
| Security | No reference | _ | no unit | 0 to 10 | 11 systems, 1 year (2015), 11 scores |