Analysis of the socio-economic and environmental sustainability of a network of zero-pesticide cropping systems (Rés0Pest) after 10 years of experimentation

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Abstract.

Reducing dependence on pesticides in agricultural systems is a priority due to their proven negative impacts on agroecosystems and human health. We present here the results of a ten years of experimental network (2013-2022), assessing the sustainability[1] of eight pesticide-free cropping systems in field and mixed cropping, in different pedoclimatic and socio-economic contexts in France. The contribution to sustainable development of the eight systems tested ranges from "medium to high" to "very high". Environmental sustainability is "very high" for all systems. Profitability varies widely from "very low" to "very high", in a context where no specific economic reward was considered for pesticide-free cropping systems preserving the environment and human health. No deterioration in the production capacity or sanitary quality of the crops was observed over the long term, and we show that it is possible to produce without pesticides if there is added value for harvest sold. These results confirm that crop diversification and cultivation practices are effective levers for ensuring the sustainability of cropping systems.

Keywords : Cropping system, Trial network; System experiment; Agroecology; Cropping system design; Cropping system assessment; Biological regulations.

1 Rés0Pest: a network of zero-pesticide cropping systems trials in arable and mixed farming (2013-2022)

The DEPHY EXPE programmes, conducted over the period 2012-2017 and 2018-2023, funded the setting up of a network of nine long-term trials in mainland France. These trials have been carried out at farm plot level and aim to test cropping systems that use no pesticides and are built according to the principles of integrated crop protection in order to limit biotic pressures. As these experiments represent a major

[1] Sustainability was assessed using Criter 5.4 and MASC 2.0

break with conventional farming practices, they are being carried out on experimental stations. The reasons justifying the interest of such an experimental network, the description of the cropping systems, the objectives pursued, the specifications and the genesis of this original network, as well as an initial assessment of the network were detailed in an article published at the end of the first DEPHY EXPE project 2012-2017 (see Cellier et al. Innovations Agronomiques 70, 273-289), which is recommended reading to facilitate understanding of the points presented here. The project and the Rés0Pest sites also have presentation pages on the EcophytoPIC website (https://ecophytopic.fr/dephy/conception-de-systeme-de-culture/projet-res0pest).

1.1 Changes to the network structure

Compared with the first DEPHY EXPE project, the network has been enriched by an experimental site run by the PURPAN Engineering School, which is located on the Lamothe estate, 20km from Toulouse, and whose main characteristics are detailed in Appendix 1. As it only joined the network in 2018 and its system had to be modified in the first few years, it was not possible to take it into account in the multi-criteria evaluation. As the Auzeville site left the network to join the DEPHY EXPE REDUCE project from 2018, only the results for the 2013 to 2017 campaigns will be presented here. Finally, for the Grignon site, the experiment was stopped after the 2020 campaign.

1.2 Changes in Rés0Pest cropping systems

At the start of the Rés0Pest project in 2012, the cropping systems were designed by combining alternative techniques, either tried and tested or suggested by the literature and current knowledge of the life cycles of pests and diseases, in order to reduce the risk of their development and encouraging the implementation of biological regulations. These combinations have been designed at the level of each crop, but also at the level of the crop succession as a whole, including the area around the plots (see Cellier et al. Innovations Agronomiques 70, 273-289).

Following the results of the first DEPHY EXPE Rés0Pest project (2012-2017), changes were made to the successions tested on the sites, in order to take account of certain difficulties encountered and to try to improve the performance of the cropping systems tested. The main adaptations and their justifications are presented in Table 1 below:

Table 1 Main adaptations of Rés0Pest cropping systems during the experiment

WEBSITE	ADAPTATION CARRIED OUT	JUSTIFICATION
BRETENIERE	Replacing hemp with sunflower at the end of the trial	Increasing the system's range of validity in the absence of a local outlet for hemp
ESTREES-MONS	Introduction of table potatoes	Integration of a spring crop between two winter crops, demand from local farmers due to the frequent presence of table potatoes in succession in the region.
MAUGUIO	Transition from growing alfalfa for fodder (hay) to growing it as a seed-bearing crop	Increase economic results, as seed-bearing crops are fairly widespread in the small region and justify irrigation.
NOUZILLY	Interversion between silage maize and soft winter wheat after temporary grassland	Limitation of nitrogen leaching linked to turning over if destruction takes place in the spring, more possibility of combating dock in the meadow (long intercropping), possibility of hoeing meadow grass regrowth.
PURPAN	Replacing alfalfa with Sainfoin	Soil too acidic for good alfalfa growth

Figure 1 below shows the crop successions for the various Rés0Pest sites over the period 2018-2023, after application of the changes presented above.

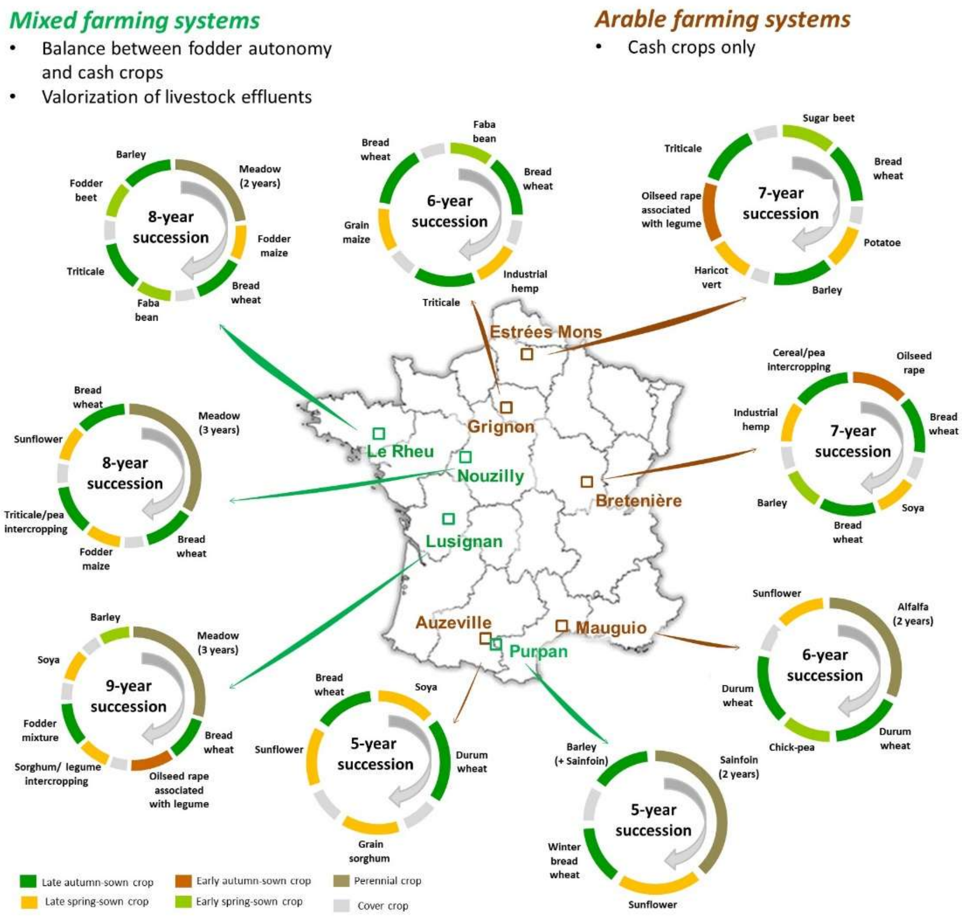

Figure 1 Cropping successions at the various Rés0Pest sites over the period 2018-2023

2 Multi-criteria sustainability assessment

Analysis of Rés0Pest system data using the Criter 5.4 and MASC 2.0 tools[2] reveals their levels of contribution to sustainable development according to each of the three pillars traditionally considered (social, environmental and economic pillars), with generic ordinal scales represented by a colour gradient (Figure 2).

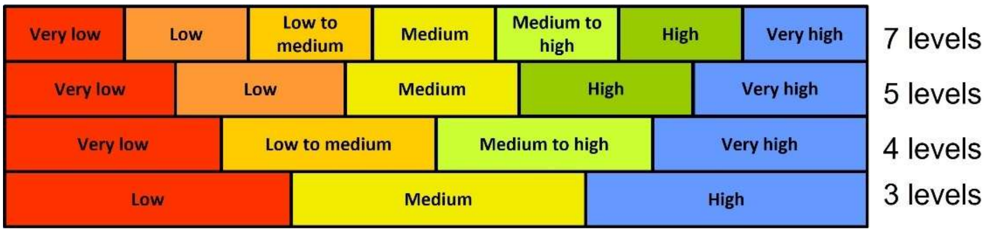

Figure 2 Generic ordinal scales to characterise sustainability according to 3, 4, 5 or 7 levels.

In the presentation of the results of the multi-criteria assessment, the weightings assigned to each sustainability attribute are shown in red and the number of levels of the scale used is shown to the right

[2] More information on Criter 5.4 and MASC 2.0: http://wiki.inra.fr/wiki/deximasc/Main/WebHome

of the wording. The filling of the boxes corresponds to the colour of the MASC 2.0 generic ordinal sustainability rating scales (Figure 2). Site names are abbreviated as follows: Auzeville (Au), Mauguio (Ma), Bretenière (Br), Grignon (Gr), Estrées-Mons (Mo), Lusignan (Lu), Nouzilly (No), Le Rheu (Rh). The complete evaluation tree is available in appendix 5.

2.1 Contribution to sustainable development

After ten seasons - with the exception of Auzeville (5) and Grignon (8) - the overall sustainability is 'medium to high' to 'very high' depending on the system (Figure 3). Two out of eight systems have 'very high' sustainability, three others have 'high' sustainability and the last three have 'medium to high' sustainability. It is the contributions of the economic and social dimensions that show the greatest differences between systems, with all systems having a "very high" contribution to sustainability for the environmental dimension.

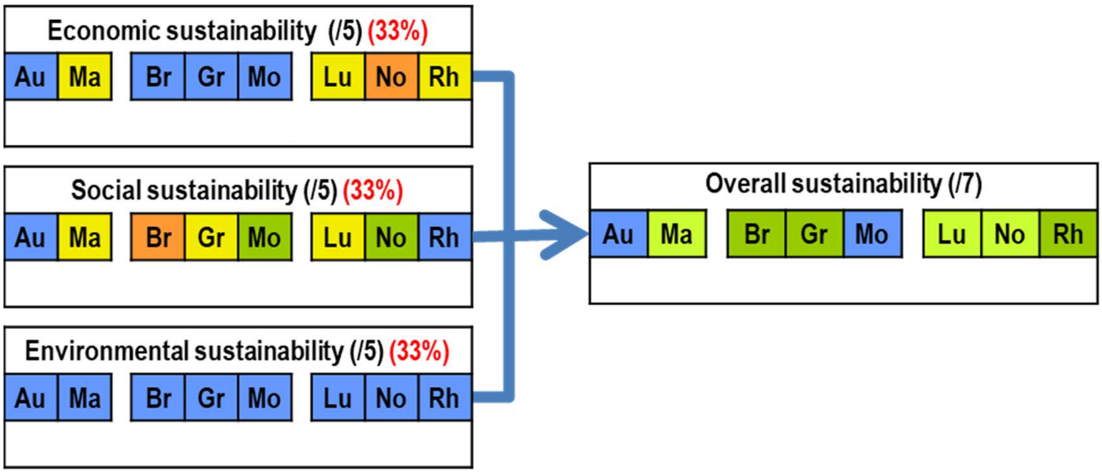

Figure 3 Overall contribution to sustainable development of eight Rés0Pest cropping systems (2013-2022).

2. Economic sustainability

Economic sustainability is 'very high' for four cropping systems, 'medium' for three others and 'low' for the last (Figure 4). There is no deterioration in long-term productive capacity after ten years of experimentation, and there is no deterioration in the quality of the products harvested (see 2.2.1 Yield and quality of the main crops, below).

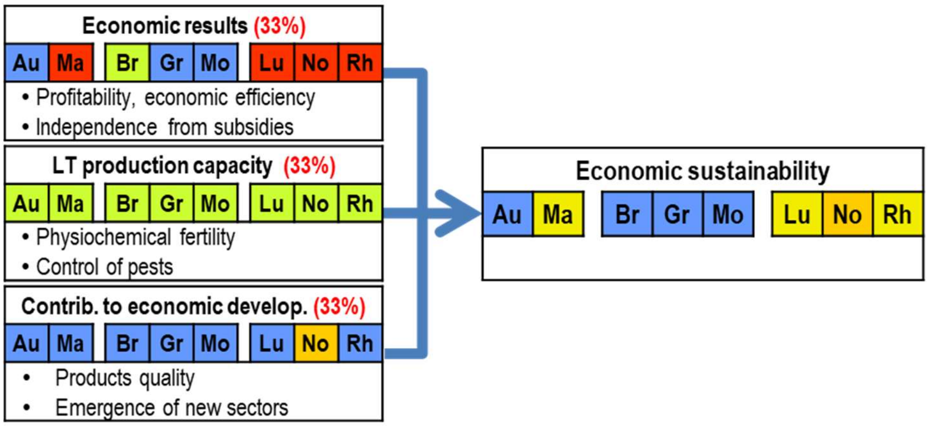

Figure 4 Contribution to the economic sustainability of eight Rés0Pest cropping systems (2013-2022).

2.2.1 Yield and quality of main crops

The yield of each of the crops in the Rés0Pest systems **should not be interpreted in isolation, as it is the performance of the whole cropping system that should be considered**. Nevertheless, it does allow us to see the level of production achieved and to compare it with the objective set by the experimenter and with the yields observed in conventional agriculture in the small farming area where the cropping system was tested.

In cereals, oilseed rape and beetroot, yields were often lower than with conventional methods, but higher than expected at the start of the project for crops grown without pesticides (see table 2 below). This in itself is a very important result of this experiment. Rapeseed yields were high, especially as the 2013 Estrées-Mons rapeseed suffered hail damage estimated at at least 5.0 q.ha^{-1} . At Bretenière, the oilseed rape was destroyed twice by autumn pests, but was replaced by spring barley (50 q.ha^{-1}) the first time, and by camelina (9.4 q.ha^{-1}) the second time. These adjustments to the crop succession limited economic losses. The table potato, introduced at the Estrées-Mons site from 2019, also performed well, although batches were sometimes downgraded on visual grounds. Good results have also been observed for sugar beet, where manual weeding has stabilised at around 20h.ha .$^{-1}$

Table 2 Yield levels for the main crops (q.ha^{-1}) and satisfaction levels of experimenters. In brackets, conventional yield in the small area or on the experimental field if available. The colour code indicates the experimenter's level of satisfaction (achievement of the yield objective or yield equivalent to those in the small region). Not all crops are present on a site in a given year. Au: Auzeville; Ma: Mauguio; Br : Bretenière; Gr: Grignon; Mo: Estrées-Mons; Lu: Lusignan; No: Nouzilly; Rh: Le Rheu; Pu: Purpan. DM: dry matter.

Crop	Target yield* q.ha^{-1}	Site	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Winter durum wheat	55	Au	37,6 (51)	34,8 (56)	42,4 (65)	28,8 (50)	48,7 (65)	37,8 (48)	37,7	28	31,6	-
	40	Ma	47	16,5	-	33,8	59	51	54	51,4	-	44
Soft winter wheat	65	Au	46,2 *(85)*	48,5 *(83)*	55,8 *(86)*	43,8 *(84)*	53,0 *(83)*	52,8	46,7	41	46,9	-
	70	Br	56,1 (70)	56,1 (56)	68,6 (72)	-	61,8 (75)	65 (79)	61,9	37,6	50,5	60,1
	70	Mo	-	-	64,2 (112)	44,3 (56)	-	67	-	-	78,5	75,4
	55	Gr	-	71,7 (86)	81,5 (87)	42,5 (50)	57,8 (80)	54,3	-	46,1		
	45	Lu	-	-	51,2 (75)	10,4 (40)	-	48,9	-	38,8	-	-
	60	No	53,6 (63)	36,4 (82)	61,0 (85)	-	76,3 (91)	45,2	52,7	56,1	57,7	-
	40	Pu						0	26	14 sorghum	-	-
	60	Rh	-	51,4	-	29,9	-	37,5	52,6	-	-	52
Triticale	70	Mo	70,7	82,2	-	40,3	-	-	70,6	89	-	-
	50	Gr	58,6 (65)	39,8 (65)	-	-	-	55,3	86,6	65,9		
	65	Rh	33,1	-	-	67,7	-	21,9	-	26	49	-
Winter barley	65	Mo	69,5	-	-	45,1	59,7	-	-	75,8	-	-
	35	Pu						-	40	9	37,5	-
	50	Rh	-	46	67,5	-	-	56,7	-	55	-	57
Spring barley	50	Br	-	38,7 (38)	58,6 (37)	25,0 (39)	-	46,0 (57)	55	-	61	53,8
	30	Lu	-	30,0 (45)	-	19,9 (30)	-	-	-	0	12,8	-

Crop	Target yield* q.ha-1	Site	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Winter rape	30	Br	-	30,7 (40)	-	-	35,8 (44)	23,0 (29)	-	16,7	9.4 camelina	-
	30	Mo	23,3 (40)	-	40,7 (43)	-	-	28	34	-	-	55,4
	20	Lu	-	-	-	18,8 (33)	17,0 (40)	-	8.7 tDM	-	28,1	-
Sunflower	22	Au	26,2 (21)	25,2 (25)	29,1 (21)	18,2 (25)	36,8 (29)					
	25	Br										20,8
	20	Ma	8,5 (20)***	13,0 (22)***	13,8 (21)***	-	7,7 (12,3)***	-	-	-	14,6 (26)***	-
	30	No	-	13,6 (29)	-	-						
	15-20	Pu						13 (22)	13,5	-	-	-
Soya	20	Au	24,1 (26)	43,2 (37)	33,0 (35)	20,9 (29)	31,2 (30)					
	25	Br	25,0 (36)	25,3 (25)	-	28,7 (30)	-	-	17,7	5,2	-	12,5
	20	Lu	70 (MS)**	*	50 (MS)**	*	-	-	Not harvested (15.5q/ha)	8,9	-	-
Sugar beet	500	Mo	-	1120 (1000)	726 (990)	-	993 (1010)	-	-	327	896	-
Fodder beet	150 (MS)	Rh	124	147	-	-	115	-	145	-	148	115
Potatoes	300	Mo							359	-	-	404

Satisfaction: Satisfactory / Moderately satisfactory / Unsatisfactory

Trial completed/not started or crop not included in the succession for this cropping season

* The yield target is determined by the experimenter on the basis of the soil and climate characteristics of the trial and the potential of the plots, the level of biotic pressures (diseases, pests and weeds) and taking into account the non-use of pesticides.

** Poorly emerged and weed-infested →harvested as silage.

*** in brackets, the yield excluding bird damage due to the peri-urban location of the Mauguio trial.

All the straw cereal samples harvested in the Rés0Pest trials were analysed by the UR MycSA of INRAE-Bordeaux, to determine their mycotoxin content (see tables 3 and 4 below). In France, among the mycotoxins regulated by the EU, the one most frequently found on wheat is deoxynivalenol, followed by zearalenone. Nivalenol is found more occasionally. Acetylated forms are present at very low levels and are essentially 15-Acetyldeoxynivalenol (ADON). T-2 and HT-2 toxins were quantified much less frequently, with a higher occurrence in barley .[3]

[3] Source Florence FORGET, UR MycSA - INRAE

Table 3 Mycotoxin analysis results for deoxynivalenol, ADON and nivalenol

	Deoxynivalenol	ADON*	Nivalenol
2013 and 2014 campaigns, quantification threshold = 500 ng.g-1 (HPLC-DAD)			
Number of analyses	58	58	34
<=500 ng.g-1	54 (93%)	58 (100%)	34 (100%)
>500 ng.g-1	4 (7%)	0	0
Maximum content	1271 ng.g-1	<500 ng.g-1	<500 ng.g-1
Campaigns 2015 to 2023, quantification threshold = 50 ng.g-1 (HPLC-MS)			
Number of analyses	318	318	318
<=50 ng.g-1	235 (74%)	317 (99,7%)	310 (97%)
>50 and <=500 ng.g-1	59 (19%)	1 (0,3%)	8 (3%)
>500 and <= 1000 ng.g-1	17 (5%)	0	0
>1000 and <= 2000 ng.g-1	5 (2%)	0	0
> 2000 ng.g-1	2 (1%)	0	0
Maximum content observed	2629 ng.g-1	58 ng.g-1	158 ng.g-1

* acetyldeoxynivalenol, sum of forms 3 and 15

Table 4 Results of mycotoxin analyses for Zearalenone Fusarenone X, and T2 and HT2 toxins, 2015 to 2023 campaigns, quantification threshold = 10 ng.g-1 (HPLC-MS)

	Zearalenone	Fusarenone X **	HT-2 toxin	T2 toxin ***
Number of analyses	318	290	156	120
<=10 ng.g-1	316 (99%)	282 (97%)	156 (100%)	120 (100%)
10-100 ng.g-1	2 (1%)	8 (3%)	0	0
Maximum content	17 ng.g-1	22 ng.g-1	<10 ng.g-1	<10 ng.g-1

** acetylated form of nivalenol *** acetylated form of HT-2 toxin

The results attest to the good sanitary quality of the harvests, since over the period 2013-2022, very few samples exceeded a level of 50 ng.g-1 for Deoxynivalenol, ADON and Nivalenol (table 3). For the mycotoxin deoxynivalenol (see appendix 4), only one sample exceeded the standard for human consumption, which has been stricter since April 2024: (1000 ng.g-1 for common wheat and malting barley and 1500 ng.g-1 for durum wheat[4] . For zearalenone and toxins T2 and HT2, no sample exceeds the standard for human food[5] . For animal feed, no sample exceeds the recommendation (8000 ng.g-1 for winter barley and triticale). **This shows that it is generally possible to use cereals produced without fungicide treatment in the food and feed sectors.**

2.2.2 *Profitability of cropping systems*

In MASC 2.0, profitability is estimated by the semi-net margin of the cropping system:

Semi-net margin = (Gross product + Subsidies[6]) - (Operating costs + Mechanisation costs)

The MASC 2.0 rating is awarded using the RMT SdCi method, based on the number of SMICs[7] generated by the cropping system for one Human Labour Unit (HLU):

[4] Commission Regulation (EU) 2024/1022 of 8 April 2024 amending Regulation (EU) 2023/915 as regards the maximum levels for deoxynivalenol in foodstuffs

[5] COMMISSION REGULATION (EU) 2024/1038 of 9 April 2024 amending Regulation (EU) 2023/915 as regards the maximum levels of T-2 and HT-2 toxins in foodstuffs.

[6] The aids taken into account here are those in force at the start of the Rés0Pest trial, i.e. before the implementation of the 2023 reform.

[7] SMIC correspond to annual minimum wage

$$Threshold_{Nb} = \frac{Nb * Gross\ annual\ SMIC\ by\ HLU}{Agricultural\ area\ by\ HLU} + \frac{Cost\ of\ renting\ land}{ha} + Overheads/ha$$

The semi-net margin will be:

1. **"Very low"** if it is below the threshold1 (less than one SMIC/HLU);
2. **"Low to medium"** if it is between threshold1 and threshold2 (between one and two SMIC/HLU);
3. **"Medium to high"** if it is between threshold2 and threshold3 (between two and three SMIC/HLU);
4. **"Very high"** if it exceeds the threshold3 (more than three SMIC/HLU).

The thresholds are therefore specific to each system and the semi-net margin is calculated according to different price scenarios, common to all systems (Table 5).

Compared to the method used in Cellier et al (2018), with the price scenarios developed by the Innovative Cropping Systems RMT, **we chose to use the IPPAP and IPAMPA price indices published by FranceAgriMer** to analyse how the profitability of cropping systems changed in line with price trends over the period 2013-2022. The value of the annual minimum wage used was taken from INSEE data[8] . The value of farm rent provided by the experimenters at the start of the Rés0Pest project (2013) and the overheads were set at €100.ha^{-1} (source Arvalis).
The data used are shown in Appendices 2 and 3.

For this we have :

1. Calculated the technical results of the cropping system (yield, inputs, mechanisation costs, etc.) based on **the average of all the cropping system's operations (**the experimental period is specified in the name of the cropping system);
2. Calculated the economic results of a campaign from the technical results of the SdC (calculated in 1-), taking **into account the economic data for the campaign in question** (e.g. Semi-net margin of the SdC Breteniѐre 2013-2022 evaluated with the prices (inputs and crop sales) of the 2022 campaign = 610 €.ha^{-1}).

Table 5 shows the semi-net margin of the cropping systems according to the price scenarios, with an indication of the associated level of income/HLU using a colour code. The average profitability of Rés0pest systems varies widely from one system to another: from €59.ha^{-1} .an^{-1} at Le Rheu to €885.ha^{-1} .an^{-1} at Estrées-Mons. It is possible to obtain good profitability for pesticide-free cropping systems, at least in some production situations (Estrées-Mons, Auzeville, Grignon, and to a lesser extent Breteniѐre), without any economic compensation in the selling price of the harvested produce.

Table 5 Changes in semi-net margin per hectare according to price scenarios.

Department, site and trial period	Pricing scenarios										Mean of scenarios
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	
31 Auzeville 2013-2017	914	714	663	725	614	572	630	660	690	945	**713**
21 Breteniѐre 2013-2022	688	525	430	466	417	394	491	464	482	610	**497**
34 Mauguio 2013-2022	267	187	271	319	174	157	159	217	232	388	**237**
78 Grignon 2013-2020	849	669	570	609	556	544	656	631	663	784	**653**
80 Estrées-Mons 2013-2022	1106	839	772	868	786	724	808	830	883	1148	**876**
37 Nouzilly 2013-2022	543	413	350	385	355	325	401	386	402	516	**408**
35 Le Rheu 2013-2022	199	92	40	75	32	17	92	89	76	115	**83**
86 Lusignan 2013-2022	438	373	351	378	365	342	371	386	367	400	**377**

Colour code income/HLU : [red] < 1 Smic [orange] 1 à 2 Smic [green] 2 à 3 Smic [blue] > 3 Smic

Mixed crop-livestock systems are finding it harder to achieve good profitability, even though, compared with the first assessment carried out in 2018, a higher arable area.HLU^{-1} has been chosen (increase from

[8] https://www.insee.fr/fr/statistiques/1375188

70 to 100 ha.HLU^{-1} , solely for the management of the cropping system), but this needs to be seen in the context of the livestock system to which it provides part of the feed resources and which also generates income for the farmer. The Le Rheu site is performing particularly poorly, but this is mainly due to the testing of a method of planting fodder beet in mini clumps, which ensures that the crop gets off to a good start and limits manual weeding operations, but which is not economically viable: €3,000.ha^{-1} of seedlings and 90 h.ha^{-1} of labour (€1,500.ha^{-1}). In the previous evaluation (2013-2017, i.e. before the adoption of this fodder beet planting method), the semi-net margin for the Le Rheu site (€469.ha^{-1}) was higher than for Lusignan (€410.ha^{-1}) and Nouzilly (€434.ha^{-1}).

As far as field crop systems are concerned, the poor performance of the Mauguio site is due to failures in the cultivation of chickpea, which was a new crop on the site, to problems of bird damage to sunflowers (the site is located in a peri-urban area favourable to this type of damage, the economic loss of which is estimated at around €200.ha^{-1}), as well as to water deficits in certain years, which were not compensated for by irrigation, which is not authorised on this system because it is unrealistic (except in the case of seed bearing crops).

In these calculations, **no specific economic valuation has been applied to crops produced without pesticides**, although it would be normal for these crops to be better valued. Recognition of the services provided to preserve biodiversity and protect human health, through economic compensation in the selling price, would improve the profitability of these cropping systems. On the basis of these results, we can estimate that, with the exception of the mixed crop-livestock sites and the Mauguio site where profitability is very low, a 20-30% improvement in the value of production would enable satisfactory profitability to be achieved. This "extra cost" should be seen in the context of the hidden costs of using plant protection products (impacts on biodiversity and various ecosystem services, impacts on human health, cost of water decontamination in particular; Bourguet and Guillemaud, 2016).

As far as the variability of economic performance is concerned, it is difficult to pinpoint since, with the exception of the Auzeville site, not all the terms in the succession are present every year. Nevertheless, we can assume that diversified systems can be fairly robust in the event of unfavourable conditions. For example, at the Bretenière site in 2016 (a year that was highly unfavourable for straw cereals), the poor performance of cereals (spring barley (25 q/ha) and, to a lesser extent, the wheat-pea combination (38.7 q/ha)) was offset by the good performance of spring crops (industrial hemp and soya).

2.3 The social sustainability

Social sustainability varies greatly from one site to another, ranging from "low" to "very high" (Figure 5). Overall, farmers' expectations are fairly well taken into account, with a "Medium to high" to "Very high" level, with few health risks (no dangerous products used) but more complex interventions and extra workloads.

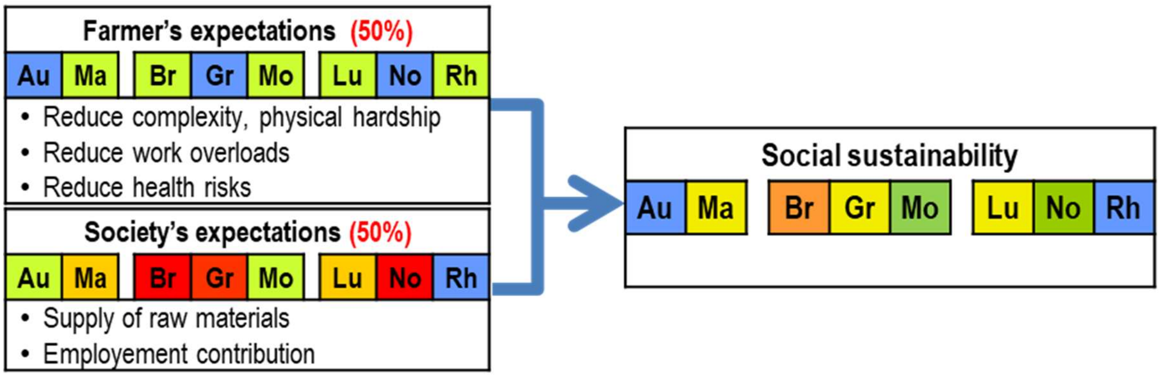

Figure 5 Contribution to the social sustainability of eight Rés0Pest cropping systems (2013-2022).

The Society's expectations are less well taken into account, both in terms of the supply of raw materials, which is quantitatively lower than the production potential for intensive cultivation, and in terms of the contribution to employment. This evaluation criterion is favourable for social sustainability, but penalizes the economic results, since the workforce is included in the expenses. It should also be emphasised that this criterion does not correspond to the objectives set at the design stage, as arable farming systems generally generate few jobs. In addition, the question arises as to whether this very occasional need for workforce, which may even be random depending on possible "crop accidents", can be easily met and whether it is of any real interest to the Society's given its very precarious nature.

2.4 Environmental sustainability

Environmental sustainability was "very high" for all cropping systems (Figure 6).
The situation is more nuanced as far as soil quality is concerned, due to "poor" or "poor to average" control of organic status on some sites with intensive use of tillage.
This effect of tillage is also found in biodiversity conservation, in particular because of its negative effect on the conservation of soil macrofauna, where six sites have a "Low to medium" rating for this criterion.
The non-use of pesticides has had a positive effect on environmental quality indicators (water and air), as well as on the conservation of biodiversity.
Due to the reduced use of mineral fertilisers, the corresponding indicators (control of P and NO3 losses to water, control of NH3 and N2O emissions to air) are "medium to high" or "very high", except for the control of NH3 emissions to air at the Nouzilly site, which uses a lot of organic fertilisers. At the Estrées-Mons site, energy consumption is high because of the numerous soil-working operations such as mechanical weeding.

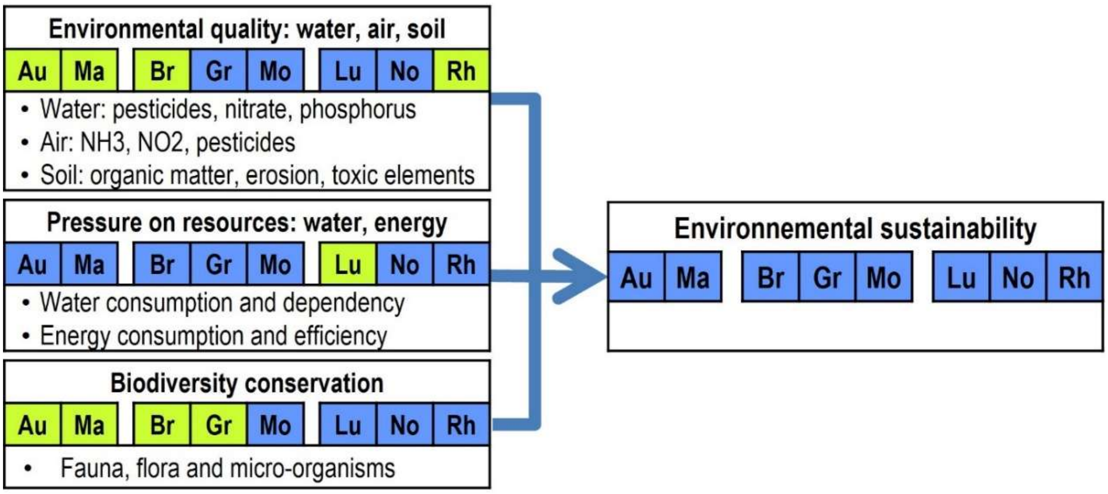

Figure 6: Contribution to the environmental sustainability of eight Rés0Pest cropping systems (2013-2022).

3 Learning and network dynamics

Within the network, training and the sharing of experience have enabled progress to be made together in mastering pesticide-free cropping systems. At the beginning of 2022, an assessment of what has been learnt was carried out at a seminar for experimenters.
The experimenters were asked to give three examples of successes, learning or difficulties they had encountered in running their systems. The main points mentioned are presented in Table 6 below.

Table 6 Successes, learning and difficulties mentioned by Rés0Pest experimenters.

LEVEL OF WEED CONTROL	- "The importance of mechanical weeding in weed management - "There's a lot to learn from these mechanical weeding techniques, so don't hesitate to attack early! - "Control is difficult on the row - "Importance of alternating sowing periods". - "Controlling perennials is tricky but possible, perhaps also learning to live with them".
LEVEL OF PEST CONTROL	- "Problems on oilseed rape, chickpeas, beetroot...". - "Few slug problems
DISEASE CONTROL	- "Few disease problems in the network".
CHOICE OF CROPS AND SUCCESSION	- "A key element in successions - "Hemp is known for its choking effect" (2 sites)
CHOICE OF VARIETY	- "Difficulties in finding suitable **AND** untreated varieties".
GROUND COVER	- "Essential for weed control". - "But it's difficult to succeed with intercropping cover crops in dry conditions". - "Significant cost of seeds
CROP ESTABLISHMENT PHASE	- "Essential for good soil cover and early mechanical weeding". - "We've learned a lot about choosing the right sowing date, especially for spring crops.
NITROGEN FERTILISATION	- "Difficult to manage, especially on cereals". - "You have to adapt the dose to the yield potential during the campaign". - "Take care not to encourage weeds".
WORKING HOURS	- "Work overload not mentioned in feedback - "Lack of weeding slots in the autumn".
WORKING THE SOIL	- "Res0Pest cropping systems are dependent on tillage".

4 Weed management in Rés0Pest

Weed management is an example of the evolution of technical control of pesticide-free cropping systems, particularly in view of the consequences that occasional poor weed management can have in the long term, by contributing to the enrichment of the seed stock of plots. In the 2018 publication, we find a classification made by the experimenters of the relative importance of the levers within the weed management strategy implemented in their cropping system (Innovations Agronomiques 70, 273-289).

4.1 Experimenters' perception of weed control

The weed control rating used in the multi-criteria evaluation of Rés0Pest cropping systems is given "by expert opinion" by the experimenters on the basis of the results they obtain and the difficulties they encounter. After a period of fine-tuning at the start of the project (2013-2015), the experimenters consider that they have better control of weeds (2017) and that they do not impact production potential (see table 7 below). For the two sites where production potential is still slightly down, it is mainly due to dock management problems in temporary grassland. In 2022, this perception is confirmed, except for the Estrées-Mons site.

	2015	2017	2022
Auzeville	(orange)	(green)	(green)
Mauguio	(orange)	(green)	(green)
Bretenière	(green)	(green)	(green)
Grignon	(orange)	(green)	(green)
Estrées-Mons	(orange)	(green)	(orange)
Lusignan	(orange)	(green)	(green)
Nouzilly	(orange)	(orange)	(orange)
Le Rheu	(orange)	(orange)	(orange)
Purpan	--	--	(green)

Table 7 Evolution of the weed control rating given by the experimenters to the Rés0Pest systems between 2015 (2018 for Purpan) and 2022. The colour indicates whether production potential has deteriorated slightly due to the presence of weeds (orange) or whether it has been maintained (green).

4.2 Changes in the weed biomass/total biomass ratio

The data collected in the Rés0Pest trials, in particular the crop and weed biomass measurements, provide a more objective assessment of the evolution of the weed flora in these pesticide-free cropping systems (the Mauguio site is not represented due to a lack of quantitative data).

In the Rés0Pest experiments, samples of crop and weed biomass were taken in the plots at row closure (which corresponds roughly to flowering for cereals). These samples were taken from 4 to 8 places/plot and were dried and weighed to calculate the following ratio:

$$R_{adv} = \frac{\text{Weed biomass}}{\text{Weed biomass} + \text{Crop biomass}}$$

By construction, this ratio varies between 0 (no weeds) and 1 (the biomass harvested corresponds solely to weeds). This indicator is considered to be a yield loss indicator.[9]

In the absence of sampling, the data is indicated as missing, but in a few rare cases where the experimenter clearly noted that the weeds were virtually absent and that no sampling had therefore been carried out, it was set to zero.

The graphs below show the evolution over time of these ratios and therefore of the capacity of cropping systems to control weeds. Since the weed population is dependent on the history of the plot, **it is important to consider the evolution of the ratio on the same plot.** In the graphs, in the event of missing data, the line linking the points on the same plot is interrupted.

The graphs in Figure 7 show (i) that there is no obvious change in weed populations (neither positive nor negative), (ii) that weed control can be poor in some years but that weed populations can be controlled in the following farming seasons, thus demonstrating the resilience of these cropping systems.

[9] Nicolas Munier-Jolain, Maïwen Abgrall, Guillaume Adeux, Lionel Alletto, Catherine Bonnet, et al, Projet SYSTEM-ECO4 : Évaluation de systèmes de grandes cultures à faible usage de pesticides. Innovations Agronomiques, INRA, 2018, 70, pp.257-271. hal-02105004

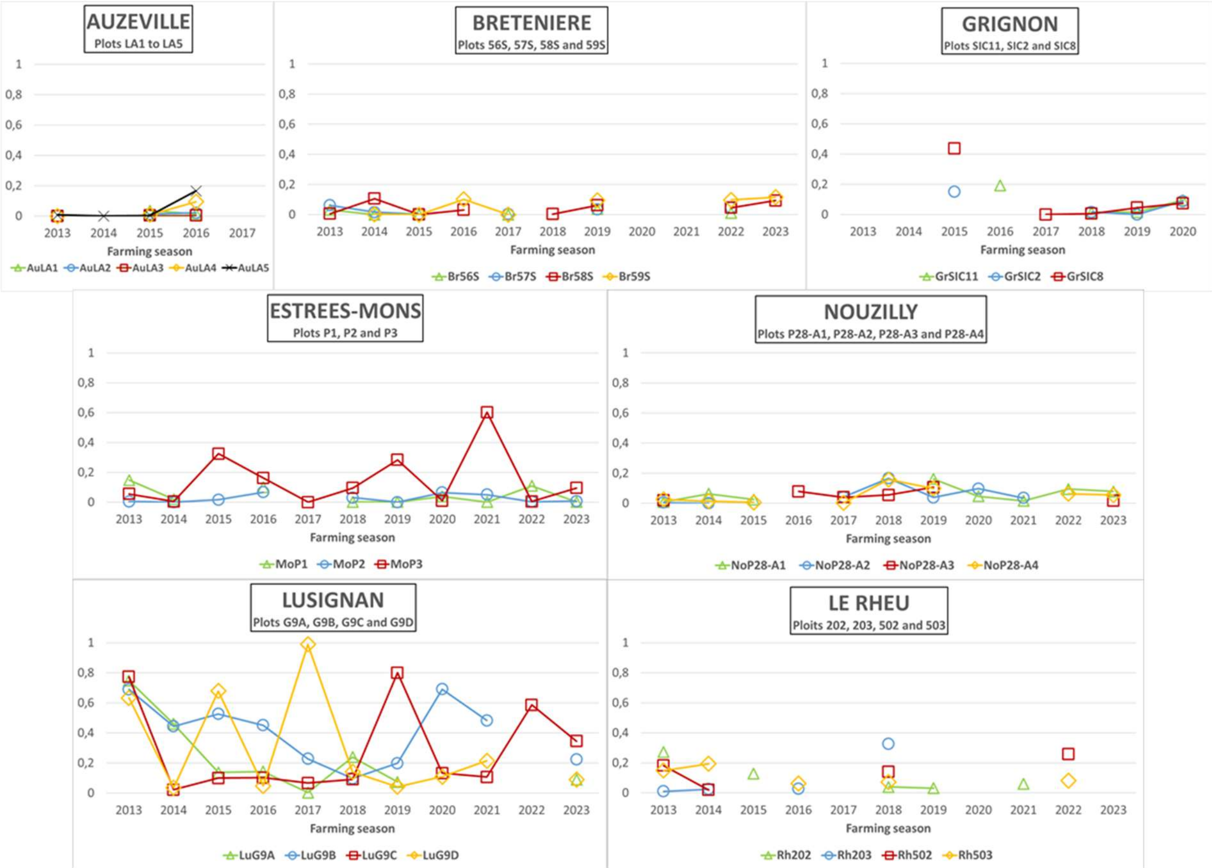

Figure 7 Trends in weed biomass/total biomass ratios in Rés0Pest plots between 2013 and 2023.

4.3 Original management of weed infestations in mixed crop-livestock systems: example of the Lusignan site

The Lusignan site was the one where there were the most fluctuations in the ratio of weed biomass to total biomass. In the context of a cropping system trial, there is a strong interest in going beyond the results obtained alone in order to: (i) understand precisely the reasons for a failure or success; (ii) determine whether or not the cause depends on the cropping system as designed; and (iii) if so, to consider adaptations to the system.

Lusignan is a mixed crop-livestock site and, as such, it has additional levers for managing weeds, since it is possible to harvest certain crops as fodder in the event of very heavy weed development. The example of oilseed rape in the 2019 season is an interesting one to consider.

- The poor emergence of rapeseed was general in the small farming region and is therefore not specific to the Rés0Pest system;
- In the Rés0Pest system at Lusignan, instead of replanting a crop, the crop was harvested as silage with a yield of 63 q.ha^{-1} (DM), fairly close to the target yield for grassland;
- This option has made it possible to manage weeds and prevent them from multiplying, as shown by the change in the ratio of weed biomass to total biomass, which fell from 0.8 (rapeseed 2019) to 0.13 (sorghum 2020);
- In economic terms, there were no costs involved in planting a replacement crop.

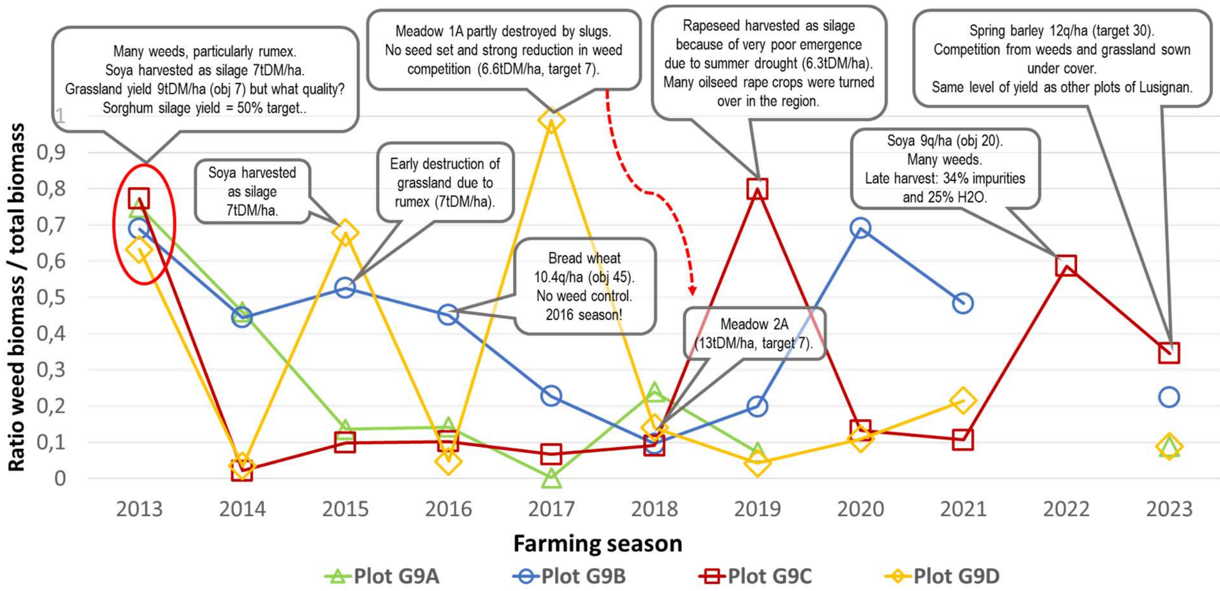

Figure 8 Trends in the weed biomass/total biomass ratio on plots at the Lusignan site (plots G9A to G9D), with the experimenter's comments.

5 Conclusions and outlook

Although some of the failures encountered by these cropping systems should not be overlooked, the levels of production achieved (quantity and quality), the maintenance of long-term productive capacity (physico-chemical fertility and control of bio-aggressors), and to a lesser extent the economic results obtained, are very encouraging for cropping systems **with such a reduction with regard to the use of pesticides**. These results are original and constitute important benchmarks, especially as they benefit from ten years' experience of experimentation. The systems were improved as they went along, and the experimenters were able to make progress in learning how to conduct cropping system trials.

One of the keys to the profitability of these cropping systems undoubtedly lies in the possibility of being able to sell untreated crops at a higher price, as they have less impact on the environment and health. The study of specifications leading to a particular label goes well beyond the scope of this study and requires other resources and skills. It is also possible that in the future we will have varieties that are better suited to this type of growing system (hardiness, covering power, etc.).

The Rés0Pest experiment will come to an end at certain sites (Grignon, since 2020; Mauguio and Bretenière - but the CA-SYS platform has a cropping system very similar to that of Rés0Pest - the Purpan site is already involved in a project in the Occitanie region. A project called "0Phyto" will be submitted to the DEPHY EXPE 3 call for projects, based on the results obtained by Rés0Pest, in order to continue to develop these original systems and acquire benchmarks. This continuation of experimentation will be an opportunity to move closer to Organic Farming.
It is important to emphasise the strength of an experimental network of nine sites for analysing the results of different cropping systems, all designed according to the principles of integrated crop protection with common specifications. The lessons that can be drawn from these experiments will be more robust if they prove to be common to all the sites, or can be nuanced according to their adaptation to certain production situations.

One of the important results of Rés0Pest is that it has built up a community of cropping system experimenters in the participating experimental units.

Ethics
The authors declare that the experiments were carried out in compliance with the applicable national regulations.

Declaration on the availability of data and models

The data supporting the results presented in this article are available on request from the author of the article.

Declaration on Generative Artificial Intelligence and Artificial Intelligence Assisted Technologies in the Drafting Process.

The authors used artificial intelligence in the translation process from French to English

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Declaration of interest

The authors declare that they do not work for, advise or own shares in, or receive funds from any organisation that could benefit from this article, and declare no affiliation other than those listed at the beginning of the article.

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Voir aussi les références bibliographiques figurant dans Innovations Agronomiques 70, 273-289.

APPENDICES

Appendix 1: Main characteristics of the Domaine de Lamothe experimental site (EI Purpan), which joined the Rés0Pest network in 2018.

CLIMATE (SOURCE: METEO FRANCE)	Degraded oceanic with Mediterranean influence (650 mm/year) : - Temperature: minimum = 9.4°C, average = 13.9°C, maximum = 18.5°C - Average precipitation: 625.6 mm.yr-1 (average 1981-2010)
TYPE OF SOIL	Clayey-sandy loam with pebbles (boulbène soil), texture varies widely across the site Soil depth: approx. 30 cm, useful reserve: approx. 60 mm Frequent winter hydromorphy and summer drought limit crop potential
PLOTS	4 plots of 0.4 ha.
AGRO-ECOLOGICAL INFRASTRUCTURE	Various types of landscape features are present around the plot: tree-lined lake, hedges, wetland and soft bank (since 2020), grassed and flowered strips and ditch.
REPRESENTATIVE CROPS	Fodder crops, soft wheat and barley
ENVIRONMENTAL ISSUES	The experimental site is located in a nitrate vulnerable zone, less than 2 km from a tributary of the Garonne and 7 km from the Garonne itself (very shallow water table). There are also residential areas less than one kilometre from the site.

Appendix 2: Site-specific data used in multi-criteria assessment calculations

DEPARTMENT, SITE AND PERIOD	HA/HLU	OVERHEADS (€.HA)$^{-1}$	RENTING LAND (€.HA)$^{-1}$	SUBSIDIES (€.HA)$^{-1}$
31 AUZEVILLE 2013-2017	120	100	200	307
21 BRETENIERE 2013-2022	150	100	157	274
34 MAUGUIO 2013-2022	120	100	170	129
78 GRIGNON 2013-2020	110	100	108	325
80 ESTREES-MONS 2013-2022	110	100	150	413
37 NOUZILLY 2013-2022	100	100	110	294
35 LE RHEU 2013-2022	100	100	155	388
86 LUSIGNAN 2013-2022	100	100	200	297

Appendix 3: Price of fertiliser units, fuel (GNR) and value of the annual minimum wage taken into account in the economic evaluation of cropping systems

		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
PRICE OF FERTILISER UNITS (€/KG)	N Ammonitrate	1,04	1,02	1,03	0,86	0,85	0,90	0,92	0,84	1,23	2,40
	N Liquid	0,80	0,79	0,80	0,66	0,66	0,69	0,71	0,65	0,95	1,86
	N Urea	0,91	0,86	0,84	0,67	0,70	0,74	0,77	0,71	1,13	1,99
	Phosphorus	0,95	0,88	0,96	0,87	0,82	0,87	0,90	0,80	1,07	1,85
	KCL60	0,68	0,62	0,65	0,62	0,58	0,60	0,63	0,59	0,71	1,26
	KCL40	0,69	0,62	0,65	0,63	0,59	0,61	0,63	0,60	0,72	1,27
	Sulphur	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
FUEL ($€.L^{-1}$)		0,76	0,71	0,54	0,47	0,55	0,67	0,65	0,49	0,66	1,09
ANNUAL SMIC* ($€.HLU^{-1}$ **)		17163	17345	17490	17599	17763	17982	18255	18473	19074	19237

* Annual minimum wage **HLU = Human Labour Unit

Appendix 4: Maximum deoxynivalenol content in harvest samples (average of two measurements).

YEAR	MAX DON ($NG.G^{-1}$)	CROP AND SITE CONCERNED, COMMENTS
2013	1251	Triticale, Grignon
2014	<500	Quantification threshold
2015	94	Durum wheat Auzeville
2016	1204	Soft winter wheat, Grignon
2017	682	Triticale, Nouzilly
2018	659	Soft winter wheat, Nouzilly
2019	2550	Triticale, Nouzilly
2019	721	Soft winter wheat, Nouzilly
2020	669	Durum wheat Auzeville
2021	15	Soft winter wheat, Nouzilly
2022	0	No detection

Appendix 5: MASC tree for the Rés0Pest multi-criteria assessment over the period 2013-2022. The weightings assigned to each sustainability attribute are shown in red and the number of levels of the scale used is shown to the right of the wording. The filling of the boxes corresponds to the colour of the MASC 2.0 generic ordinal sustainability rating scales. Site names are abbreviated as follows: Auzeville (Au), Mauguio (Ma), Bretenière (Br), Grignon (Gr), Estrées-Mons (Mo), Lusignan (Lu), Nouzilly (No), Le Rheu (Rh)