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PSDR4 ProSys - Soil and climate adaptation, environmental impacts and economic value of new sustainable protein-producing cropping systems in Burgundy Franche-Comté

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Abstract

The ProSys project aimed to identify agronomically efficient protein-based cropping systems that can adapt to the context of climate change, meet environmental challenges, are economically viable and represent an acceptable alternative for farmers and the industry. The potential of production and environmental constraints encountered by legumes, under current conditions and in the context of climate change, were studied. In addition, an experiment was conducted to study the previous effect of different legume species. An innovation tracking has allowed to identify and analyze protein-producing cropping systems that have been tested by farmers in the region who are satisfied with them. The positive environmental impacts and the interest for the global production of proteins of cropping systems with legumes were evaluated through long-term experimental follow-ups. Finally, the modalities of changing farmers' practices towards plant protein producing systems were analyzed. The creation of working groups with agricultural education and professionals from the agricultural world has enabled the development of a set of tools and communication media to promote the results of the project.

Keywords: Plant proteins, Cropping systems, Sustainable production, Adaptation to changes, Educational tools.

Introduction

The intensification of agriculture that began in the 1950s has led to the current dominant model, characterised by arable and mixed crop-livestock production systems based on the use of synthetic fertilisers and the choice of crop species offering the best short-term profitability. This has led to the abandon of less productive species (such as legumes) in favour of wheat and oilseed rape (Schott *et al.*, 2010), to a loss of autonomy in terms of plant proteins and to an increase of phytosanitary uses and environmental problems. Today, climate change and the depletion of resources are calling into question the sustainability of this model (Millennium Ecosystem Assessment, 2005), and the challenge is to produce proteins that are more autonomous, efficient and sustainable in this context. These changes in practices are at the heart of the research questions. The result is: 1) in the biotechnical fields, questions about the technical feasibility and agronomic coherence of reintroducing legumes into cropping systems, 2) in the human and social sciences, an analysis of the socio-technical obstacles posed by the poor integration of legumes into crop rotations (Meynard *et al.,* 2013; European Parliament, 2011). Questions are also being raised in the field of education in relation to the development of agro-ecology, more specifically in the context of the *Teaching to Produce Differently* approach in agricultural education.

In Burgundy Franche-Comté (BFC), a French region, a large proportion of the land is used for mixed farming and livestock, divided between arable land (50.8% UAA) and permanent grassland (46.7% UAA) (2019). Grassland is mainly used for dairy and beef cattle production. The rape-wheat-barley rotation is still dominant in arable crop rotations, where very few legumes are present. Local plant proteins are therefore mainly derived from forage and arable crops. The question of developing the production of plant proteins in cropping systems in the Burgundy Franche-Comté region is therefore becoming relevant, in particular by integrating legumes into grassland or field crops to improve the sustainability of systems and increase protein autonomy at different levels. The aim of the ProSys project (PSDR4) was to produce new knowledge (on production potential and limiting factors, and their future development, nitrogen supply and the environmental impact of legume-based cropping systems), to study the agronomic, economic and environmental aspects of experimental cropping systems or those that have been tested by farmers, and to analyse the conditions that would enable them to be adopted on a wider scale. The PSDR programme (for and about regional development) aims to contribute to regional and territorial development through research and development operations carried out in partnership with local players.

1. Territories studied and methods used

1.1 Presentation of the sites

The area studied is the Burgundy Franche-Comté French region. A number of approaches have been used on this scale: maps of climatic indicators and econometric approaches have been carried out on the entire region. The search for innovation covered a variety of cropping systems including legumes in place in the area, in order to decipher the logic behind their inclusion in cropping and production systems (in arable and mixed farming). They were located in the Yonne (89), Haute-Saône (70), Saône-et-Loire (71), Doubs (25) and Territoire de Belfort (90) French departments. The farmers and industry players surveyed to identify the obstacles and levers to changes in farming practices were chosen according to the issues addressed: the role of collectives, issues linked to the industry, etc. The analysis of the surveys was then supplemented by data obtained by the ISARA-Lyon team as part of the Legitimes ANR on the plateau of southern Yonne (89) and northern Côte-d'Or (21).

At the same time, field trials and biotechnical data collected from farmers' plots were spread throughout the region. The INRAE (French National Research Institute for Agriculture, Food and Environment) experimental unit at Bretenière (21) was used for several trials, and plots from the Chambers of Agriculture farmers' network, the farms of several agricultural colleges, experimental data obtained at ISARA in Lyon in northern Isère, Ain and Jura departments, two plots monitored at Virey-le-Grand (71) and Migé (89) and plots in the Loue catchment area (25) completed the experimental set-up.

1.2 Scientific and technical approaches

The aim of the project was to identify protein-based cropping systems that are agronomically efficient, can adapt to climate change, meet environmental challenges, are economically viable and represent an acceptable alternative for farmers and the industry. This involved bringing together agronomists, ecophysiologists, geneticists, soil scientists, climatologists, economists and sociologists. All these skills were brought together in the group of researchers and stakeholders.

The network of players and researchers involved had already acquired a great deal of data relating to the issue developed. The first step was therefore to identify all the players and researchers with existing data. Several research projects, such as the PSDR-3 "Profile" project, the CASDAR (Agricultural and Rural Development Trust Account) pea-colza-wheat project and the national Legitimes project, contributed to the acquisition of data that we were able to use. The BFC Regional Directorate for Food, Agriculture and Forestry (DRAAF BFC), the Chambers of Agriculture, Terres-Inovia and the cooperatives also have data that were used in the project. In addition, several databases were used, such as the DONESOL data from the Regional Soil Reference Frameworks Burgundy and Franche-Comté, the Graphic Parcel Referential (RPG), agricultural statistics data (Regional Statistical and Economic Information Service of the DRAAF), SIM climate data (SAFRAN-Isba-Modcou from Météo-France; Quintana-Seguí *et al.,* 2008) and simulated climate data produced as part of the national project CoSAC (https://www.projet-cosac.fr/Presentation - Cavan *et al*., 2020).

Qualitative surveys were also carried out using semi-structured interviews with farmers and other players in the sector. The work was carried out in two main stages: an initial exploratory stage, carried out thanks to projects by students at ISARA Lyon and Institut Agro Dijon, followed by a second stage in which the hypotheses arising from the exploratory stage were examined in greater depth using case studies. The surveys were conducted on a sample representative of the diversity of farmer and farm profiles in BFC, and constructed using the snowball method (Mitchell *et al.*, 1997). An econometric analysis based on soil and climate data (soil type, temperature, rainfall, etc.) and agro-industrial data (location of processing plants, cooperative collection areas, livestock density, etc.) was also carried out at the start of the project.

The final approach used was modelling. Several models were used in the various tasks. These models were used to synthesise and link experimental data, and also to evaluate and make projections according to different scenarios. The Azodyn-Pea crop model (Jeuffroy *et al.*, 2012; Larmure *et al.,* 2017) was improved, in conjunction with the PIA (future investment programme) PeaMUST project, and incremented on INRAE's Record platform. Data enabling future development of the Azodyn model for faba bean were also acquired. The STICS crop model (Brisson *et al.,* 2003) was used to simulate the nitrogen flows generated by 10 legume species. The data from the surveys was processed using a multi-criteria evaluation model. Finally, climatologists used the ARW/WRF regional climate model (Skamarock *et al.*, 2008) to simulate the regional climate for the recent past and for the future.

2. Results

2.1 Climate change: risks and adaptations in winter peas

Regional climate simulations have enabled us to estimate the possible characteristics of the climate over the 21st century in Burgundy and Franche-Comté. To produce daily climate data at a spatial resolution of 8 km x 8 km, a dynamic downscaling approach based on the nesting of two domains has been used. The regional climate simulations were carried out using the ARW/WRF limited-area climate model (Skamarock *et al.*, 2008). An initial set of climate data (ERA INTERIM climate reanalysis - Dee *et al.*, 2011) was used to validate the climate downscaling experimental setup over the so-called historical period (1980-2016: Brulebois *et al*, 2017; Cavan *et al*.; 2020). From there, the model was forced with the bias corrected climate projections (Bruyère *et al.*, 2014) according to two IPCC trajectories: RCP 4.5 and 8.5 (Representative Concentration Pathway -- Taylor *et al.*, 2011), leading respectively to an increase in annual average terrestrial temperatures of around 2 and 4°C by 2100 respectively. Simulated daily temperature data (Tmin and Tmax) combined with two agronomic models were used to assess changes in winter frost stress and flowering date of pea (*Pisum sativum* L.) in Burgundy and Franche-Comté for both the near future (2017-2049) and the far future (2050-2100).

Winter frost damage (Figure 1) was estimated using the Lecomte *et al.* (2003) frost stress model adapted for peas. This model accounts for the crop's effective frost resistance temperature, which is computed daily by considering the variety (characterized by a maximum resistance threshold and an acclimation period), the sowing date, and the temperature regime to which the plants are subjected. Frost stress occurs when the daily minimum temperature falls below the crop's effective frost resistance temperature. Throughout the entire winter period, the model computes a frost stress index expressed in degree-days (°C.d), which corresponds to the cumulative daily frost stress intensity. This frost stress index has been shown to be significantly correlated with the frost damage observed on the crop (Castel *et al.,* 2017). The results depicted in Figure 1 indicate that despite rising temperatures, frost intensity does not decrease until 2050, even under the warming climate trajectory RCP 8.5. A clear decrease occurs after 2050, and it is greater for the RCP 8.5 trajectory than for RCP 4.5. This is due to greater warming under the RCP 8.5 trajectory from 2050 onwards. Damage intensity decreases, but with a high degree of inter-annual variability and a greater risk of damage for varieties with low maximum resistance. Previous work has shown that with warming, the intensity of frost damage has decreased in the past, but the number of days with damage has increased (Castel *et al.,* 2017; 2019). In other words, more days of stress, but of less intensity. To withstand frost, plants need to acclimate. Milder autumns and winters prevent this acclimation, increasing their vulnerability. Hence, when frosts occur, even if they are of low intensity, they are likely to cause damage. It is therefore advisable to offer and maintain pea varieties with good maximum frost resistance and a short acclimation period until around 2050.

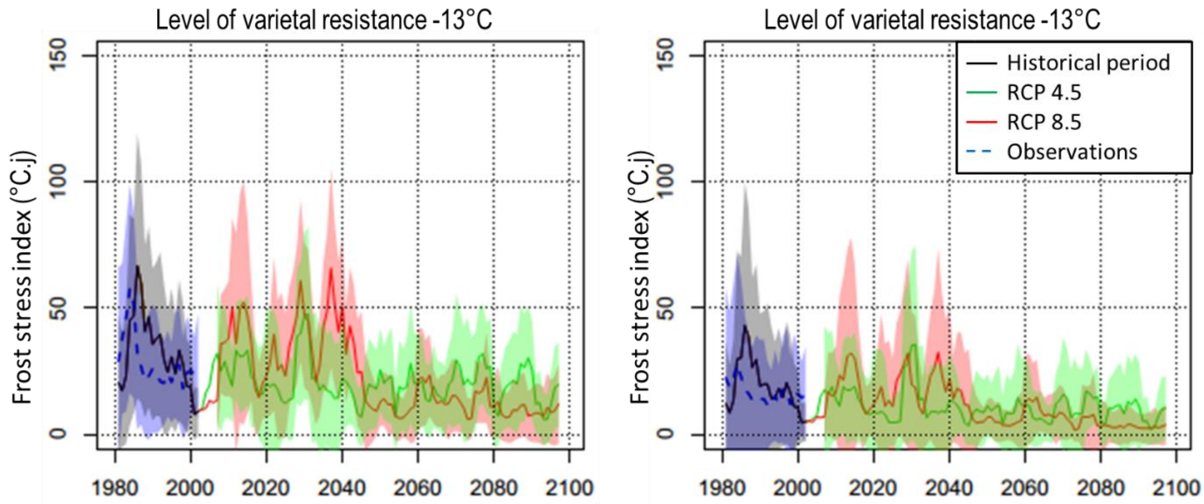

Figure 1: Changes in the intensity of winter frost damage (frost stress index), for two maximum varietal resistance temperatures (-13°C and -23°C), for several sowing dates (2, 10, 21 and 31 October) and several acclimation periods (35 to 49 days in 2-day steps). Winter frost stress is assessed for each winter by the sum of the differences between the crop's effective daily resistance temperature calculated by the model and the minimum temperature when the latter is lower than the resistance. Mean trend (solid line) and envelopes of simulations carried out using observed and simulated data: historical period (1980-2003) and future periods 2017-2049 and 2050-2100 according to the two scenarios RCP 4.5 and RCP 8.5 (Van Vuuren *et al.*, 2011).

In addition, the change in the date at which flowering starts has been simulated using an agronomic model that uses the sum of temperatures since sowing and the photoperiod (day length) (Quinio, 2015), validated using experimental data (CTPS 'Winter peas' 2007-2009, PIA PeaMUST 2012-2020). The advance in the flowering stage between the current period and the distant future (2050-2100) will be of the order of 2 weeks on average for winter peas (cv. Isard), and around 3 weeks on higher ground. As a result, it will be necessary to adapt here too, either by delaying sowing dates in autumn to avoid flower initiation stages that are too early at the end of winter, or by using varieties whose flowering date is determined by the photoperiod.

If the entire crop cycle and all the climatic variables are taken into account, the entire crop-variety-cultivation intervention system needs to be rethought. A crop model representing the overall functioning of the pea crop and the impact of climatic stresses is currently being used to test ways of adapting to climate change (Larmure *et al.,* 2017).

2.2 Input management: Benefits and risks of legumes

Legumes have the particular ability to fix atmospheric nitrogen through symbiosis with soil bacteria. Like all other species, they also have the ability to absorb inorganic nitrogen from the soil when available. Symbiosis, which is more energy-intensive and takes place within specific organs (nodules), occurs when the stock of inorganic nitrogen in the soil is depleted. However, legumes do not have the same capacity to absorb inorganic nitrogen from the soil and fix atmospheric nitrogen (Guinet *et al.*, 2018).

Experiments were carried out in 2014 and 2016 at the INRAE experimental unit in Bretenière (21) to compare the amount of nitrogen accumulated by 10 species of grain legumes and determined the origin of this nitrogen (N_2 from the air and inorganic N from the soil). 6 species were sown in March (fenugreek, lupin, fababean, pea, lentil and common vetch) and 4 in May (soybean, common bean, chickpea and Narbonne vetch). Two cereals were sown as a control: spring barley (sown in March) and sorghum (sown in May). Barley and sorghum were fertilised with nitrogen. Due to unfavourable weather conditions, no seed were harvested for chickpea and Narbonne vetch in 2014. The subsequent years (2015 and 2017) an unfertilised wheat was cultivated to study legume pre-crop effect.

The total amount of nitrogen fixed averaged 129 kg N/ha for both years and for all legume species, with values ranging from 60 kg N/ha for Narbonne vetch in 2014 to 344 kg N/ha for faba bean in 2016. The proportion of nitrogen derived from the air was around 70% for most species. The highest values were measured for faba bean and lupin (78%) while Narbonne vetch and common bean had the lowest values (60%) (Figure 2a). At harvest, seed protein content varies between species, ranging from 18% for common vetch to 42% for soybean.

The amount of nitrogen in wheat grown after legumes sown in March averaged 64.4 and 74.8 kg N/ha in 2015 and 2017, respectively. These values were higher than for wheat grown after barley. (60.3 and 54.3 kg N/ha in 2015 and 2017). The highest values were obtained after lentil and faba bean. For wheat grown after legumes sown in May, the amount of nitrogen in wheat averaged 66.9 and 65.6 kg N/ha in 2015 and 2017, respectively. These values were much higher than for wheat grown after sorghum (45.8 and 45.5 kg N/ha in 2015 and 2017) (Figure 2b). The amount of nitrogen available for wheat was a function of the amount of inorganic nitrogen remaining in the soil after the harvest of pre-crops and the amount of nitrogen mineralised from legume residues. Residue mineralisation was influenced by the C/N ratio and the biochemical composition of the residues of the different species (Guinet *et al.*, 2020).

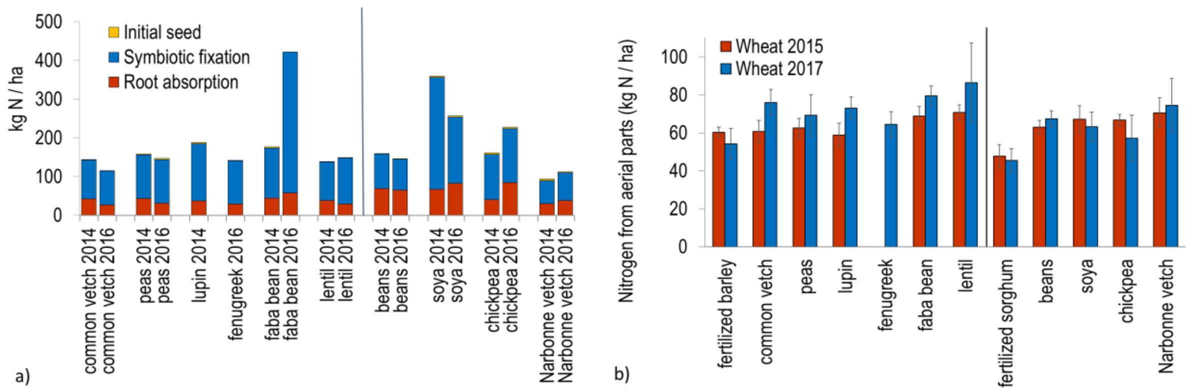

Figure 2: (a) Origin of nitrogen accumulated in different legume species in 2014 and 2016 (Guinet *et al.,* 2018). (b) Amount of nitrogen present in the above-ground parts of wheat at harvest in 2015 and 2017 as a function of

the previous crop (Guinet *et al.*, 2020). Legumes or reference cereal sown in March (on the left side of the line) or sown in May (on the right side of the line).

The various results obtained in ProSys confirm the benefits of introducing legumes into arable and mixed farming systems. However, cross-analysis of the results of four long-term experiments in which the impact of cropping systems on water quality was assessed, in contrasting soil and climate situations, shows that the sustainability of these systems can sometimes be called into question in view of their potential negative impact on water quality (Ubertosi *et al.*, 2020). The introduction of legumes into crop rotations can reduce nitrogen and plant protection inputs and, consequently, the pressure on water resources. However, in certain circumstances, such as the turning over of temporary grassland or alfalfa, or the resumption of tillage after direct sowing under cover, significant nitrate leaching has been observed, sometimes up to 18 months after ploughing (Justes *et al.*, 2001; Vertès *et al.*, 2010) (Figure 3).

With regard to the dynamics of pesticides, the results of the experiments do not allow any clear conclusions to be drawn. It would appear that the risks are mainly present in the weeks following the application of pesticides, whatever the crop (legumes or cereals) and that the reduction in use results in a reduction in the phytosanitary substances found in water (Figure 3). However, the introduction of these crops into crop rotations is often associated with the introduction of new phytosanitary molecules. The cross-effects and so-called 'cocktail' effects on environmental compartments (air, soil, water, biodiversity) of this diversification of substances used in the field are still relatively unknown.

The management of these systems and the control of their environmental impact, particularly on the water compartment, is a point of vigilance to be kept in mind, especially in the context of climate change. Rising temperatures will have an impact on the mineralisation of soil organic matter. The predicted redistribution of rainfall and longer dry periods in late spring and summer could encourage nitrate leaching by reducing the amount of water drained and increasing the nitrogen available in the soil in autumn, the period most at risk, thus leading to an increase in nitrate concentrations in draining water and then in ground water.

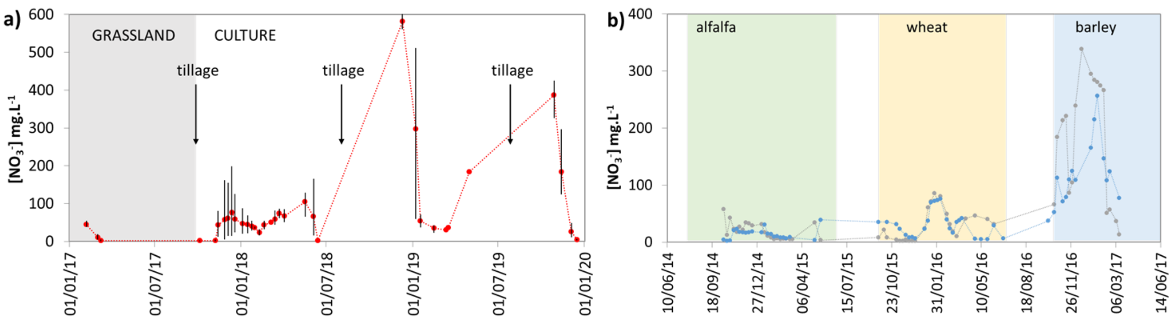

Figure 3: Dynamics of nitrogen concentration in lysimeter water: (a) deep soils in the Plaisir-Fontaine catchment (71); (b) herbicide-free plot, INRAE Bretenière experimental site (21).

2.3 Motivations for introducing legumes into cropping systems and assessment of their performances

The introduction of legumes contributes to the diversification of current cropping systems and the supply of nitrogen. These species thus represent a pillar of agro-ecological cropping systems that promote ecosystem services (Köpke and Nemecek, 2010; Tibi and Therond, 2017).

However, despite the recognised benefits of legume crops, these species are very poorly represented in current cropping systems (Magrini *et al.*, 2016), and remain minor crops on which little investment has been made throughout the sector (Meynard *et al.*, 2013). This can be explained by a number of factors, including lower yields than cereals, a lack of solutions to manage pests and a lack of technical advice and references.

However, some farmers continue to grow legumes and are satisfied with the results. Farmers are therefore a source of innovative solutions that we have sought to identify. We identified and analysed cropping systems implemented by farmers that successfully and satisfactorily integrated legumes, in order to i) identify farmers' motivations for growing legumes, ii) list the different ways of integrating legumes into crop successions according to the ecosystem services targeted, and iii) assess the performance of the cropping systems implemented. This work was carried out in successive phases with advisors and farmers in Burgundy and Franche-Comté, to identify the technical, systemic or organisational innovations designed by farmers. A specification was followed to characterize these innovations in the form of coherent practices, assess their agronomic, economic and environmental performance, and specify and formalise the conditions for success (Salembier and Meynard, 2013; Salembier *et al.*, 2016).

The results of the surveys revealed 11 different cropping systems grouping together 6 ways of introducing legumes: temporary grassland, legume-cereal mixture, grain legumes, cover crop, permanent cover crop and companion plant (Table 1). Among the cropping systems studied, 33 cases of legume insertion were identified. The services most often observed by farmers when legumes were included in their cropping systems were increasing the farm’s protein autonomy, improving soil structure, adding nitrogen to the soil, regulating weeds and adding organic matter to the soil. These results illustrate the diversity of possibilities for integrating legumes and the associated ecosystem services. In mixed crop-livestock farms, increasing the farm's protein autonomy is the primary service provided by legumes, mainly through legume-based grassland and legume-cereal mixtures. Companion plants and cover crops (temporary or permanent) are occasionally used to feed livestock. On the other hand, in mixed and arable farms, grain legumes are mainly used for sale The introduction of grain legumes makes it possible to introduce nitrogen into the system while reducing the use of synthetic N fertilisers. The inclusion of legumes in crop mixtures or cover crops helps to manage weeds (except in the case of poor establishment and development).

Table 1: Ecosystem services observed by farmers when legumes are introduced in cropping systems (green: large number, yellow: moderate number, red: small number of occurrences of the service observed per type of legume inclusion).

observed ecosystem services	temporary grassland (7)	legume-cereal mixture (8)	grain legumes(6)	cover crop (7)	permanent cover crop (3)	companion plant (2)
increase the farm's protein autonomy	7	8		2	2	
improve soil structure	4	6	1	7	3	1
nitrogen supply to the soil		2		4	2	1
weed regulation	6	7		5	3	1
add organic matter to the soil (promotes soil life)		1	1	7	1	1
decrease nitrogen fertilisation	5	1	6		1	1
feed and food production			6			
reduce erosion	2	2		3		
reduce water polution (nitrogen, pesticides)		3		1		
reduce the use of pesticides	2	3	2		2	
food traceability		1				
pest regulation						2
water resource management		5				
work time distribution		4	1			
limit soil crusting				1		
disease regulation			1	1	2	1
animal health	1	2			2	

Our analysis also showed that the treatment frequency indices (TFI) for cropping systems with legumes are lower (0.8 to 4.2) than those of reference cropping systems without legumes (4 to 6.7). The energy cost of cropping systems with legumes is lower on average (10.2 GJ/ha) compared with reference cropping systems (12.6 GJ/ha), which also vary considerably (6.1 to 14 GJ/ha). An analysis of the agronomic reasoning associated with this feedback has made it possible to identify the conditions for obtaining satisfactory performances and to extrapolate them to other situations. These examples of successful crops based on concrete cases are grouped together in a booklet and could serve as a source of inspiration for other farmers to design cropping systems including legumes (Guinet *et al.,* 2021).

2.4 The role of collectives in the agro-ecological transition

In mixed farming, fodder legumes are regularly grown and incorporated into rations. The ecosystem services provided by legumes have led to the widespread use of these crops in organic farming. In arable farming, the introduction of legumes into rotations is less widespread. In order to understand the determinants of these choices, surveys were carried out among farmers growing pulses (Garcia, 2008), in particular among farmers involved in technical groups. Since the 1950s, collectives have been at the forefront of agricultural modernisation (Gerbaux and Muller, 1984), and it has been established that the introduction of new crops requires a learning phase facilitated by exchanges between peers (Rivaud and Mathé, 2011). The collectives surveyed were chosen in consultation with local stakeholders (Chamber of Agriculture, cooperatives and DRAAF).

Analysis of the interviews highlights the cognitive and social contributions of the collectives to the diversification process. To begin with, "getting off the beaten track" by introducing new crops reveals a pioneering position, a quest for autonomy, breaking with the existing organisational system, based on technical advice that disseminates knowledge developed by experts from outside the farm. The farmers met are involved in research and learning, and participate in groups with the aim of sharing, seeking out or building *ad hoc* knowledge and know-how. They are not closed to advice, but they analyse it as one resource among other information resources, in order to develop their own assessment of what would be relevant to do on their plots (Vergote *et al.,* 2019).

Collectives are also a place for professional socialisation: they enable their members not to find themselves alone in the face of their difficulties and to progress more quickly through the aggregation of shared experiences; they provide a convivial atmosphere in a profession that is usually practised alone; they also generate legitimacy, to dare together and move away from the existing technical system.

When it comes to the agro-ecological transition, collectives are a real support, a tool for implementing innovations. However, the choice of new crops and the adoption of new farming practices are also the result of an individual path, a personal trajectory following a triggering event. Among the farmers met, this commitment may be a deliberate choice in the spirit of innovation, or it may be the result of the need to find solutions to particular difficulties, or even impasses (resistance to insecticides or herbicides, extra costs linked to over-application of treatments, falling yields). It can also be the result of serendipity (Carnoye *et al.*, 2019). Today, peer groups only involve a minority of farmers. This is not necessarily a problem if these farmers play the role of “gatekeepers” or "door unlockers" (Polge and Torre, 2015), i.e. if they are recognised by their peers as professionals whom others seek to imitate. Beyond the necessary agronomic success that will enhance their approach, socio-economic and institutional recognition of their contributions is essential. The Economic and Environmental Interest Group (GIEE) label is an example of institutional recognition. But the recognition that is also needed to encourage a growing number of farmers to take an interest and start working together, is better economic value for the produce resulting from these agro-ecological practices and approaches, which are recognised as virtuous.

3. Contribution to regional and local development

The PSDR3 programme, which focused on seed legumes, helped to develop mutual knowledge and cooperation between players in Burgundy who knew little about each other. Since then, joint work has continued (work on climate change, leading to several publications and presentations to agricultural professionals; presentations by researchers at Damier Vert and Tech'n Bio open days, etc.) on the benefits of legumes and the cultivation techniques to be adopted for these crops. This programme has helped to disseminate knowledge about protein crops and to test these crops on farmers and experimental farms. Figures on the economic and environmental benefits of protein crops have been collected and published, helping to inform public authorities on a number of measures that could be taken to promote these crops.

In 2015, helping to structure the plant and animal sectors in the Burgundy region, through innovative, sustainable and more autonomous supply and use of proteins, was at the heart of the region's concerns. Following the merger of the two original regions of Burgundy and Franche-Comté, a necessary audit of the sectors at regional level also reinforced the need to address the issues surrounding the production of plant proteins. The Regional Chamber of Agriculture was asked to set up a network bringing together the main players in the region. The Groupe Opérationnel Proteins was born.

The PSDR4 ProSys project has therefore taken place in a regional context that is favourable to the themes being addressed: soil and climate adaptation, positive environmental impacts and the economic value of new sustainable protein-producing cropping systems. The sector contracts for arable crops, pigs, standard milk cattle and beef cattle, signed in the region in November 2018, highlight the need to produce quality plant proteins in BFC. The success of these commitments depends on improving the performance of farms and the resilience of systems, securing and developing food autonomy, but also on coordinating the sector and sharing scientific and technical references.

The aim of the project was to establish a complete overview of the data and references available to all the players involved, and to provide them with objective means of assessing cropping systems with a view to increasing protein content on a crop and rotation scale, while preserving the sustainability of the systems (in economic and environmental terms). Agricultural advisers and teachers are looking for technical references and tools to help them think about adopting new cropping systems for plant protein production. The collective set up for this project is an appropriate framework for promoting this transfer of knowledge and encouraging innovation.

The task of disseminating information began at the start of the project with the creation of a group of researchers, teacher-researchers, teachers from agricultural colleges and players from the agricultural world. Work on climate change and its adaptation, and work on cropping systems incorporating legumes were disseminated and shared as they were acquired, notably through forums, seminars and working meetings. Teachers at BFC high schools have been heavily involved from the outset of the programme, playing an active part in developing the value-added approach and putting forward proposals for possible developments, such as hosting experiments on high school plots. As far as the professionals were concerned, the process was more complex to manage and the group mobilised was often 'Dijon-centric'.

Finally, the analysis of the drivers and barriers to change among farmers has provided essential information for the choice of public policies to steer production towards greater economic and environmental sustainability, and greater protein autonomy for the areas and crops covered by the project. In this context, the ProSys project has made its contribution.

4. Discussion

A comparison of the project's initial ambitions with the final results shows a high degree of consistency. A number of objectives have been achieved: regional climate modelling has made it possible to study the climatic impacts on pea crops, data on the ecosystem services provided by 10 legume species has been produced and cropping systems that meet the objectives set have been identified and studied.

However, certain objectives were only partially achieved or not achieved at all. The production potential in a future climate context was to be studied on several leguminous species. Unfortunately, it was not possible to develop ecophysiological models for species other than pea during the project. In addition, the results of field experiments already in place in the region (Artemis network of cooperatives, Chambers of Agriculture network, Dephy farms, etc.) were to be used and analysed to improve the catalogue of local references. Co-design workshops were to be held with professionals: these workshops have been tried out by the project's researchers as part of other research projects, but could not be implemented in our project. However, this aspect of "promotion to agricultural professionals", i.e. advisors, facilitators and farmers, is an objective of the Proteins Operational Group led by the Chambre Régionale d'Agriculture (CRA), in which the PSDR4 is a stakeholder. The researchers and players involved in the ProSys project will therefore continue to pass on this knowledge beyond the end of the project. The actions undertaken with the agricultural colleges and the DRAAF will also be carried out beyond 2020.

The challenges of plant and animal proteins are linked in the region: the chicken, beef and dairy cattle sectors are emblematic of the region, with products under quality labels. Ensuring greater protein self-sufficiency involves developing seed legumes and fodder legumes, optimising grassland management and developing associated industries, and finally choosing crop systems suited to possible outlets for animal and human food. The work carried out can all be linked to the issue of managing the nitrogen cycle in the context of climate change, in a 'global health' context (Duru *et al.*, 2017). In theory, nitrogen is an inexhaustible resource because it is present in large quantities in the air. But in gaseous form, it is not directly accessible to most living organisms. Only leguminous plants have the capacity to fix it, in symbiosis with soil bacteria. The industrial synthesis of nitrogen in a form that can be assimilated by other plants (ammonia and nitrate) (Haber-Bosch process) requires a great deal of non-renewable energy, and the production, transport and spreading of this nitrogen result in the emission of greenhouse gases (GHGs) in the form of CO_2 and N_2O. Poor synchronisation between nitrogen supply (whether from fertilisers or legumes) and crop requirements leads to nitrate losses to water and pollution of the associated ecosystem. Working on the flow of nitrogen and legumes, via a systemic approach, could make sense in the region: from the capture of nitrogen from the air by legumes to the GHG emissions inherent in the sector right through to the end consumers (humans or animals).

Conclusions

The PSDR ProSys project has made it possible to work on several of the major issues facing agriculture today. The characterisation of climate change on the scale of the Burgundy and Franche-Comté region and the associated impacts have produced results that can be extrapolated to other areas of France. The social, economic and environmental context is forcing agriculture to evolve and even change radically. Cropping and production systems have been re-analysed in the light of the new challenges: preserving resources, saving inputs, protein self-sufficiency, etc. The results of the project on the ecosystem services provided by legumes show the advantages and limitations of integrating them into cropping systems. One of the major achievements of ProSys has been the ability to co-construct the project from the outset with partners from education and professional farming, and to set up joint working groups on a number of topics. Pooling knowledge and expertise, sharing innovations and developing supply chains are all key to the successful development of sustainable, protein-producing cropping systems. In the current context of agro-ecological transition, the scientific results of the project, as well as the approach to promoting scientific results, partnerships and the co-construction of knowledge, are intended to be disseminated and shared. The dynamics generated by the previous PSDR3 "Profile" project has thus been strengthened and is likely to continue beyond the end of the ProSys project. One of the highlights of the project was the closing WebTV (1st April 2021), which highlighted the results obtained jointly with the second regional project (POEETE), on mixed farming (WebTV, 2020).

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 to help them with the French-to-English translation process.

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Declaration of interest
The authors declare that they do not work for, advise, 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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