HAL open science

Adapting agricultural production systems to changes in the environmental, agricultural and social context, and the role of legumes in the agro-ecological transition

Marjorie Ubertosi, Gilles Brunschwig, Thierry Castel, Denis Chapuis, Jean-Philippe Goron, Maé Guinet, Anne Jarousse, Annabelle Larmure, Christophe Lecomte, Jean- Pierre Manteaux, et al.

▶ To cite this version:

Marjorie Ubertosi, Gilles Brunschwig, Thierry Castel, Denis Chapuis, Jean-Philippe Goron, et al.. Adapting agricultural production systems to changes in the environmental, agricultural and social context, and the role of legumes in the agro-ecological transition. Innovations Agronomiques, 2024, 86, pp.5-23. 10.17180/ciag-2024-vol86-art02-GB . hal-04700850

HAL Id: hal-04700850
https://hal.inrae.fr/hal-04700850v1

Submitted on 18 Sep 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

Adapting agricultural production systems to changes in the environmental, agricultural and social context, and the role of legumes in the agro-ecological transition

Marjorie UBERTOSI [1], Gilles BRUNSCHWIG[2], Thierry CASTEL[3], Denis CHAPUIS[4], Jean-Philippe GORON[5], Maé GUINET[1], Anne Jarousse[2], Annabelle LARMURE[1], Christophe LECOMTE[1], Jean-Pierre MANTEAUX[6], Aymeric MONDIERE[2], Claire MOSNIER[2], Bernard NICOLARDOT[1], Marie-Sophie PETIT[7], Wilfried QUEYREL[1], Corinne TANGUY[8], Eglantine THIERY[2], Marie-Hélène VERGOTE[8], Patrick VEYSSET[2], Anne-Sophie VOISIN[1], Candice LAROCHE[1]

[1] UMR Agroécologie, Institut Agro Dijon, INRAE Dijon, Univ. Bourgogne, Univ. Bourgogne- Franche-Comté, 17 rue Sully, BP 86510, F-21034 Dijon Cedex, France

[2] UMR Herbivores, VetAgro Sup, INRAE Clermont-Ferrand, 89 avenue de l'Europe, F-63370 Lempdes, France

[3] UMR Biogéosciences, CNRS/UB/EPHE, Univ. De Bourgogne, 6 Bd Gabriel, 21000 Dijon

[4] Chambre d'Agriculture de Saône-et-Loire, BP 522, 71010 Macon Cedex, France

[5] PEP bovins lait Chambre d'Agriculture, 40 avenue Marcelin Berthelot, 38100 Grenoble, France

[6] Chambre d'Agriculture de la Drôme, 145 avenue Georges Brassens, CS30418, 26500 Bourg-lès-Valence, France

[7] Chambre Régionale d'Agriculture de Bourgogne Franche-Comté, 1 rue des Coulots, 21110 Bretenière, France

[8] CESAER, INRAE Dijon, Institut Agro Dijon, 26 Boulevard Dr Petitjean, 21000 Dijon, France

Correspondence: marjorie.ubertosi@institut-agro.fr

Abstract

In the Burgundy Franche-Comté and Auvergne-Rhône-Alpes French regions, the regional projects POEETE and ProSys dealt with the adaptation of agricultural production systems to changes in the environmental, agricultural and social context, focusing on different scales and taking into account the context of reduced inputs and the search for autonomy by introducing legume crops. The processed data come from various approaches: surveys, experimental monitoring, modelling approach... The impact of climate change on the ecophysiology of legume crops was addressed through a model plant, the pea, and two criteria: flowering date and frost stress. To ensure the sustainability of mixed farming operations, new forage mixtures have been tested. Then the ecosystemic services provided by legume crops were studied: precedent effect, nitrogen content and interest in improving the protein autonomy of farms. The prioritization of ecosystem services in the adoption of these crops was studied via surveys of pioneer farmers in the region. Finally, the agroecological transition was studied via questions about the complementarity of mixed farming and livestock production, the performance of cropping systems including legume crops, farmers' motivations to develop more agro-ecological practices and the study of model farm trajectories.

Keywords: Legume crops, Cropping system, Mixed crop-livestock farming, Global change, Transition

Introduction

The global changes brought about by human activity since the industrial revolution of the 19th century (industry, transport, energy consumption) have led to major changes in the consumption of natural resources, climate change and the development and feeding of human populations, with significant negative impacts on the environment. Since the 1950s, mechanisation and the use of synthetic inputs (nitrogen fertilisers and pesticides) have led to the simplification and specialisation of European agricultural production systems and associated structures. At the same time, as a result of international trade agreements, imports of soya meal have become the major source of plant proteins for livestock feed in Europe (Solanet *et al.,* 2011). All these developments have led to a drastic reduction in the agricultural land devoted to growing legumes in Europe (Voisin *et al.*, 2014). Currently in France, agricultural policy includes the development of agriculture based on the principles of agroecology (Fosse *et al*., 2019), i.e. making the most of the functionalities of agroecosystems to replace synthetic inputs with the services provided by biodiversity (Isbell *et al.,* 2011). This form of agriculture requires production systems to be diversified. To achieve this, cropping systems and technical itineraries need to be redesigned, and the complementary nature of mixed farming and livestock farming needs to be better exploited (Power, 2010; Tibi and Therond, 2017). These transformations involve adaptations and the acquisition of local references to optimise the supply of common goods: production of plant and animal raw materials, water and air quality, protein production, reduction of greenhouse gas emissions. The diversity of agricultural production systems requires a better characterisation of their relative strengths and weaknesses, particularly in terms of their ability to achieve several environmental objectives simultaneously, but it also requires a social approach to identify the obstacles and levers to the development of agro-ecological agriculture based on the development and enhancement of biodiversity at different scales of time and space.

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. The PSDR4 projects POEETE and ProSys dealt with the adaptation of agricultural production systems (animal and plant) to changes in the environmental, agricultural and social context (climate, reduction in inputs, quest for autonomy), in the Burgundy-Franche-Comté and Auvergne-Rhône-Alpes French regions, looking at different scales (cropping system, livestock system, farm, sectors and territory).

Adapting agricultural production systems to changing conditions requires a multidisciplinary approach. The POEETE and ProSys projects brought together animal and plant production agronomists, modellers, ecophysiologists, geneticists, soil scientists, climatologists, economists and sociologists. This group had already acquired a great deal of data relating to the issues developed, at farm and regional levels. In addition, surveys of a sample of farmers representative of the diversity of profiles encountered in Burgundy-Franche-Comté and Auvergne-Rhône-Alpes, and surveys of other players in the sectors were carried out. Furthermore, field trials were carried out on farms belonging to networks (Dephy network, Economic and Environmental Interest Group, etc.), plots on an INRAE (French National Research Institute for Agriculture, Food and Environment) experimental estate and farms on agricultural colleges in the regions concerned. The final approach used is modelling: a number of climate, agronomic and farm management models have been used, or even developed. These models are global (agronomic and climatic models), regionalised (climatic models), or integrate the dimension of proximity between players (econometric models, bioeconomic modelling of exchanges between farms). They can be used to enhance the value of data from experiments or databases. They can also be used to evaluate and make projections based on different scenarios in the form of *in silico* experiments.

1. Impact of climate change on legume crops and adaptation options

Production systems are having to adapt to a number of major changes in the agricultural context, known as global changes. Among these, climate change on a global scale is having a differentiated impact, depending on the region, on arable crop production and mixed crop-livestock systems, as well as on the operation of livestock farms themselves. This climate change is already affecting all animal and plant production, its first effects are already being felt, and it is being studied on different scales: the world, Europe, France and the regions. Our projections have been scaled down to the regional level, because it is necessary to assess these effects in order to project and anticipate future developments and adapt production systems. This question can be addressed using two approaches: a modelling approach, based on the coupling of climate models and agronomic models, and an experimental approach based on experimental field monitoring and surveys.

1.1 Simulation of climate change on an agricultural scale

In order to assess the current and future impacts of climate change on the cultivation and production of legumes, on a local scale compatible with that of agricultural decision-making/advisory, it is necessary to estimate the possible characteristics of the regional climate. This has been done in Burgundy Franche-Comté for the 21st century using climate simulations.

To produce daily climate data at a spatial resolution of 8 x 8 km, a dynamic downscaling approach based on the nesting of two domains has been used. The regional climate simulation were carried out using the ARW/WRF limited-area climate model (Skamarock *et al.*, 2008). An initial large-scale forcing climate dataset (ERA INTERIM climate reanalysis; Dee *et al.*, 2011) was used the climate downscaling experimental setup over the so-called historical period (1980-2016) to simulate regional-scale climate at a target resolution of 8 km and daily time step. The data produced were then compared with SIM (Safran-Isba-Modcou) data from Météo-France for validation. The characteristics of the protocol and the validation of the simulations are presented in Brulebois *et al*. (2017) and Cavan *et al.* (2020).

The WRF model was then forced, using the same protocol, by climate projections produced by the CCSM4 model (Bruyère *et al.*, 2014) as part of the international CMIP5 programme (Taylor *et al.*, 2011). Two climate scenarios were selected from those described by the IPCC: RCP 4.5 and RCP 8.5 (Representative Concentration Pathway), leading respectively to an increase in annual average terrestrial temperatures of 2 and 4°C by 2100.

The daily values of 5 variables, minimum (Tmin) and maximum (Tmax) temperatures, precipitation (PP), potential evapotranspiration (ETP) and global radiation (Rg) were extracted in order to feed the agronomic models.

1.2 Examples of the impact of temperature changes on winter peas

Simulated daily temperature data (Tmin and Tmax) combined with two agronomic models were used to assess changes in winter frost stress and flowering date in pea (*Pisum sativum L.*) in Burgundy-Franche-Comté for the historical period (1980-2003), the near future (2017-2049) and the distant future (2050-2100).

Winter frost damage (Figure 1) was estimated using the Lecomte *et al.* (2003) model adapted for peas, in which frost resistance is calculated for each day, considering the variety (characterised by a resistance threshold and an acclimation period), the sowing date and the temperature regime to which the plants are subjected. Frost damage is described by the number of days on which the minimum daily temperature falls below the calculated resistance. The cumulative difference between these two values (frost stress index) has been shown to be significantly correlated with the damage observed (Castel *et al.*, 2017).

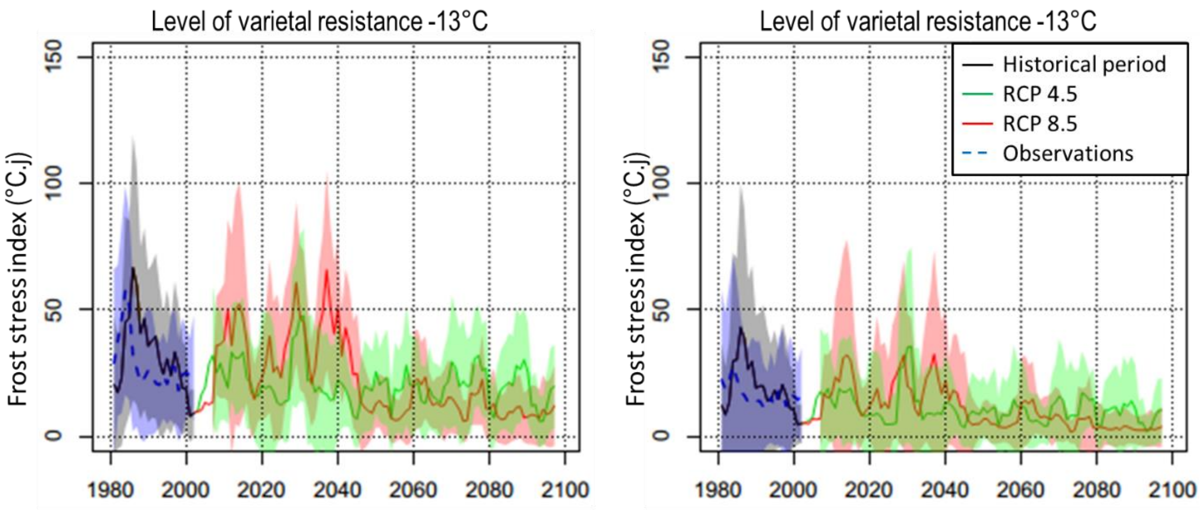

Figure 1: Trends in the intensity of winter frost damage, for two levels of varietal resistance (-13°C and -23°C), for several sowing dates (2, 10, 21 and 31 October) and several acclimation periods (35 to 49 days in 2-day steps). Winter frost stress is assessed for each winter by the sum of the differences between the resistance calculated by the model and the minimum temperature when it is lower than the resistance temperature. Mean change (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).

For the historical period (1980-2003), the frost stress calculated from observed climate data is of the same order of magnitude as that calculated from simulated climate data. In some years, however, the frost stress calculated from simulated climate data is overestimated (Figure 1).

For the projections, the intensity of frost stress does not decrease until 2040/2050, whatever the warming scenario (Figure 1). A decrease appears after 2050, and it is greater for the most rapid warming scenario RCP 8.5. The intensity of damage decreases, but with a high degree of inter-annual variability and a greater risk of damage for varieties with a low level of resistance. It is therefore advisable to offer varieties with a good level of frost resistance and a short acclimation period, so that they can adapt more quickly to the jolts in temperature between periods of frost and periods of thaw. These varietal characteristics are two important levers for adapting to sudden cold spells that can occur in the middle of a mild winter, such as the winter of 2011/2012 when severe frost damage to winter peas was observed.

Based on historical data, a parallel study (Castel *et al.*, 2017; 2019) has shown a subtle change in the risk: the intensity of frost damage has decreased while the number of days with damage has increased. This paradox, as well as the fact that the level of damage in our simulations remains unchanged until 2050, can be explained by the fact that plants need to acclimate in order to withstand frost. Milder autumns and winters prevent this acclimation, and when frosts do occur, even if they are of low intensity, they are likely to cause damage.

A second agronomic model was used to study the pea flowering date (Figure 2). This model uses the sum of temperatures since sowing and photoperiod (day length) (Quinio, 2015). It has been validated for a spring pea variety (Lumina) and a winter pea variety (Isard) on experimental data from several research programmes (CTPS 'Pois d'hiver' 2007-2009, PIA PeaMUST 2012-2020).

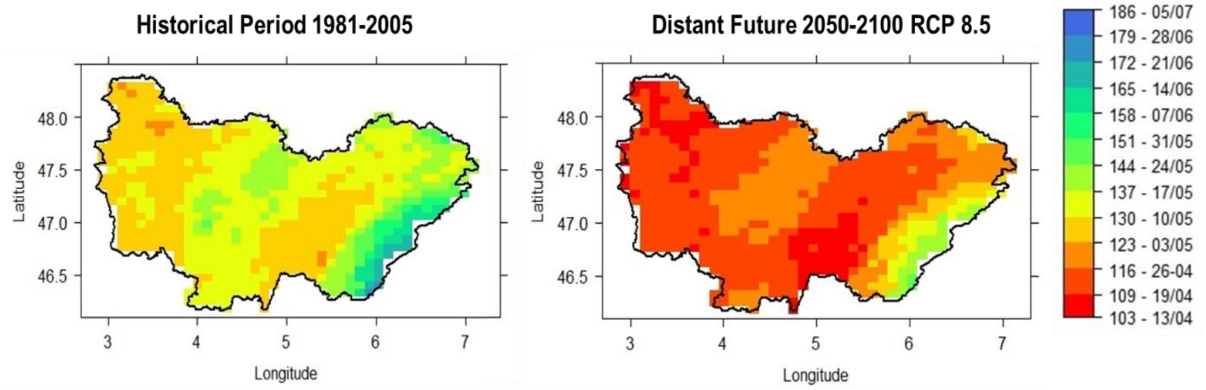

Figure 2: Changes in the date of the early flowering stage between the historical period (1981-2005) and the distant future (2050-2100) in Burgundy-Franche-Comté (8 x 8 km grid) for a winter pea variety (Isard), according to the most marked warming scenario (RCP 8.5).

The evolution of the date at which flowering begins was simulated for a variety of winter pea sown on 1er November, in the Burgundy-Franche-Comté region (on an 8 x 8 km grid) between the historical period and the distant future, for the most rapid warming scenario we are currently heading towards. The advance in the flowering stage between these two periods will be around 2 weeks on average, and around 3 weeks on the higher ground. As a result, it will be essential to adapt the positioning of the pea crop cycle, either by delaying autumn sowing dates so that the frost-sensitive flower initiation stage does not appear too early in the winter, or by using photoperiod-sensitive varieties that wait for sufficient daylight to initiate their reproductive phase.

1.3 Choosing new forage mixtures for mixed crop-livestock farming

Climate change is having an impact on fodder production, drastically reducing summer production (maize, 3ème alfalfa, etc.) and grazing. It is therefore necessary to identify grassland compositions that are resilient to water stress and high temperatures. For this reason, experiments with several grazed or mown compositions have been carried out at the agricultural high school of Le Valentin mixed crop-livestock (dairy cattle) experimental farm in Drôme French department. Mixtures incorporating Mediterranean species and including legumes to improve the protein autonomy of the farm were sown.

Since 2011, the farm has been growing a multi-species grazed meadow comprising a range of species including 3 grasses (tall fescue, orchardgrass, ryegrass), 5 legumes (alfalfa, sainfoin, red clover, white clover, trefoil) and various species such as chicory. This temporary grassland is kept for 4 years, followed by 4 years of crops (maize, grain meslin, etc.). The meadow is farmed organically and irrigated if necessary (e.g. 3 irrigations in 2019). In 3 years of operation, the mix has remained balanced: 41% of the species present are grasses and 35% are legumes. The species most favoured were orchardgrass (23% of the mix), alfalfa (13% of the mix) and chicory (21% of the mix) (Figure 3). The average yield over 10 years (2011-2020) is 13 t dry matter (DM)/ha.

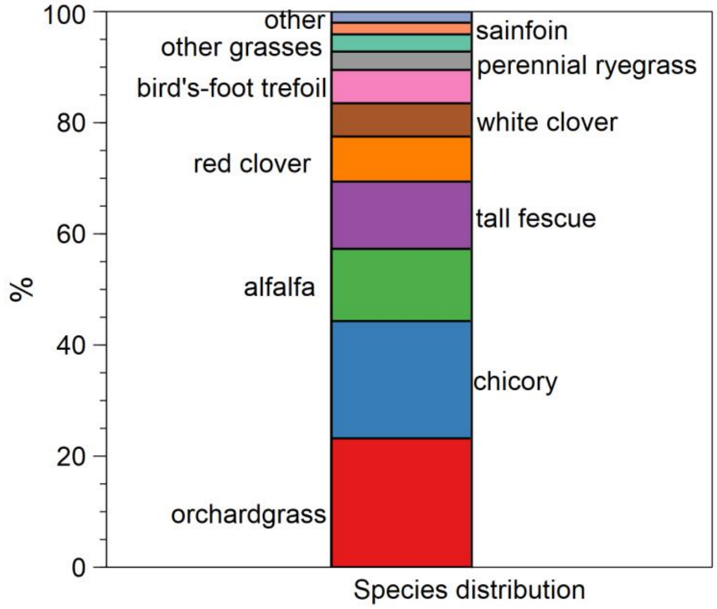

Figure 3: Distribution of species present in 2017 in the grazed multi-species permanent grassland on the farm of the agricultural high school of Le Valentin (Drôme).

Since 2016, trials have also been carried out on mown multi-species temporary grasslands in order to validate the hypothesis that mixtures would make them more resistant to climatic hazards. On these grasslands, 3 successive cuts are made each year. Several methods were tested: grasslands with the introduction of annual legumes (Persian clover, pink serradella, blistered clover, Jamin clover, rough clover) or with the introduction of perennial legumes (Caucasian clover, strawberry clover, subterranean clover) and a comparison of alfalfa varieties grown pure or in mixtures, with Mediterranean varieties in particular. These alfalfa-based mixtures could be used to build up stocks in early spring (on the 1st and 2nd cuts), then in autumn if the regrowth allows, in order to stagger the harvesting period. Two annual legumes (Persian clover and shaggy clover) are of interest because of their ability to cover the ground and develop rapidly from the first year, and one perennial legume (strawberry clover) covers the ground well and is drought resistant. Their production, around 9 t DM/ha for the 3 cumulative cuts in 2017, is lower than the average for alfalfa (12.5 t DM/ha) or multi-species grassland (11.5 t DM/ha), but remains interesting for its drought resistance (Figure 4).

In mown mixed grassland, the composition is fairly quickly dominated by 3 or 4 species, including alfalfa, which accounts for up to 70% of the ground cover, and orchardgrass (10 to 20%). The presence of alfalfa in the mix increases production by around 4 t DM/ha compared with a multi-species meadow without alfalfa. This species therefore appears to be well adapted to the climatic constraints prevailing in the Valence area. The 'Pradel' mixture, with a higher proportion of drought-resistant species (tall fescue, orchardgrass, sainfoin and chicory) outperformed all the other mixtures and alfalfa alone (Figure 4).

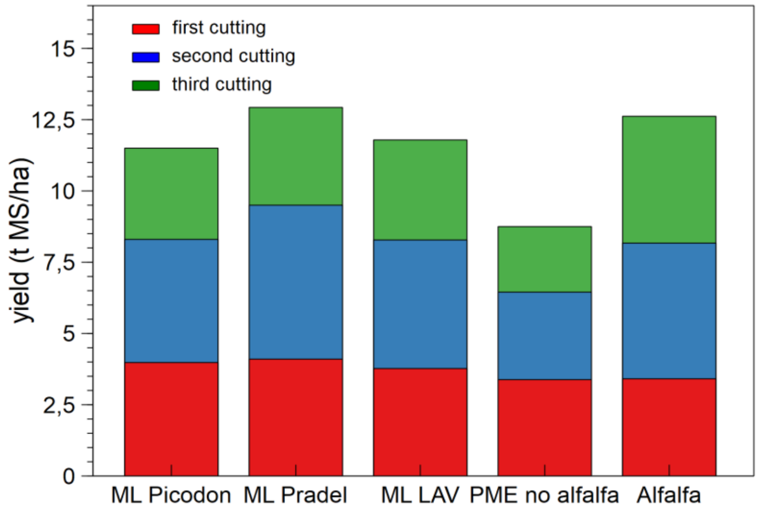

Figure 4: Average production over 2 years (2017 and 2018) of 5 mown meadows (3 cuts). 3 multi-species mixtures including alfalfa (ML Picodon, ML Pradel and MLLAV: Lycée Agricole Valentin), a multi-species meadow without alfalfa (PME without alfalfa) and a meadow consisting solely of alfalfa (100% alfalfa).

These trials show the value of adapting the composition of grasslands in the context of global warming by choosing new forage mixtures. Carried out today in the Rhone Valley, they could be used in the future to adapt forage supply in Burgundy-Franche-Comté.

2. The services provided by legumes in cropping systems

The introduction of legumes is a diversification strategy based on the complementary nature of the ecosystem services they provide and the functions they perform (Köpke and Nemecek, 2010; Tibi and Therond, 2017). They provide a supply service, linked to the production of protein-rich seeds and fodder for human and animal consumption. They save on nitrogen inputs in the year they are planted, thanks to symbiotic fixation, and in the following year, thanks to the mineralisation of their residues (Guinet *et al.*, 2020a). What's more, since legumes account for around 3% of cultivated land in France, reintroducing them would diversify crop rotation, helping to break pest and disease cycles and encourage the presence of beneficial insects.

2.1 Motivations for introducing legumes into cropping systems

A survey and analysis of the systems implemented by farmers integrating legumes successfully and satisfactorily was carried out. The aim was to identify a variety of methods of integration based on the services observed. The services most often observed are increasing the protein autonomy of farms, improving soil structure, regulating weeds and adding organic matter to the soil. In mixed crop-livestock farming, the primary service provided by legumes is to increase the farm's protein self-sufficiency, mainly through legume-based grassland and meslin. Companion plants and temporary or permanent cover crops are occasionally used to feed livestock. On the other hand, grain legumes are mainly used for sale in mixed farming and arable farming. The inclusion of forage or seed legumes contributes to grass management (Guinet *et al.*, 2021).

2.2 Origin of nitrogen accumulated by different legume species

Experiments carried out in 2014 and 2016 at the INRAE experimental unit in Bretenière (Côte d'Or French Department) compared the amount of nitrogen accumulated by 10 species of seed legumes and determined the origin of this nitrogen (atmospheric nitrogen and soil mineral nitrogen). Fenugreek, lupin, broad bean, pea, lentil and common vetch were sown in March, while soybean, bean, chickpea and Narbonne vetch were sown in May. No mineral nitrogen was applied. Seed yields, which varied between legume species, were largely influenced by the year's weather conditions. Chickpea and Narbonne vetch seeds were not harvested in 2014.

The amount of nitrogen fixed varied from 87 kg N/ha (common vetch) to 365 kg N/ha (faba bean) for species sown in March, and from 60 kg N/ha (Narbonne vetch) to 290 kg N/ha (soya) for species sown in May. The proportion of nitrogen from symbiotic fixation was around 70% for most species, but there were species with high fixation rates (faba bean, lupin: 78%) and others with low fixation rates (bean and Narbonne vetch: 60%) (Figure 5). At harvest, seed protein content varies between species, ranging from 18% for common vetch to 42% for soya.

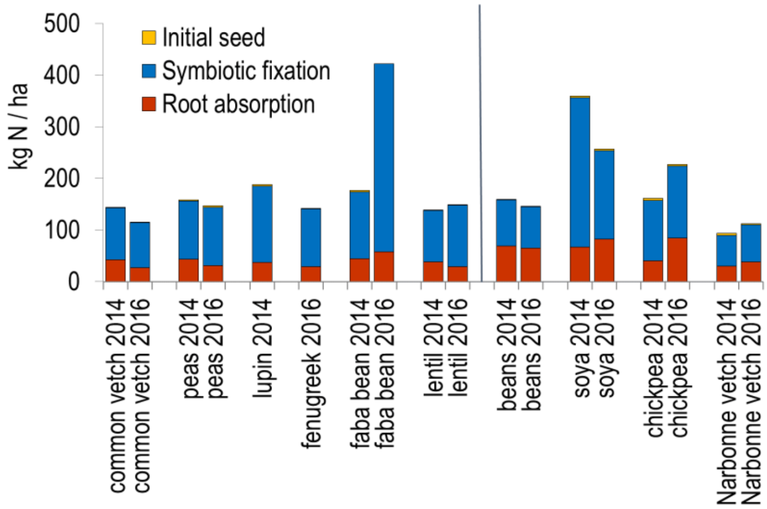

Figure 5: Origin of nitrogen accumulated by different species in 2014 and 2016; left species sown in March, right species sown in May (Guinet *et al.,* 2018).

Variations in the quantities of nitrogen fixed between species depend both on the specific characteristics of each species and on climatic conditions. Further studies have shown that in the presence of mineral nitrogen in the soil, legumes preferentially take up this mineral nitrogen. Symbiotic fixation is triggered when the level of available mineral nitrogen becomes insufficient to meet the plant's growth needs. In addition, the efficiency of mineral nitrogen uptake from the soil of the species studied is correlated with the speed of horizontal root exploration (Guinet, 2019).

2.3 Previous crop effect of legumes

There are differences between legume species in terms of residue quantities and nitrogen content, which leads to different 'precedent' effects. In our experiments at the Bretenière site, following the cultivation of each seed legume, the crop residues were buried and an unfertilised wheat crop was planted in 2015 and 2017. The quantities of nitrogen present in the above-ground parts of the wheat were measured (Figure 6). Two control plots were planted with a spring barley preceding the legume species sown in March and with a sorghum preceding the species sown in May. The barley and sorghum were fertilised in a controlled manner.

The yields of wheat grown after legumes sown in March were on average 7.7 q/ha higher in 2015 and 9.4 q/ha higher in 2017 than wheat grown after barley. The highest yields were measured after faba bean and lentil. Yields of wheat grown after legumes sown in May were on average 19.4 q/ha higher in 2015 and 17.3 q/ha higher in 2017 than wheat grown after sorghum. The highest yields were measured for wheat preceded by whole-plant Narbonne vetch.

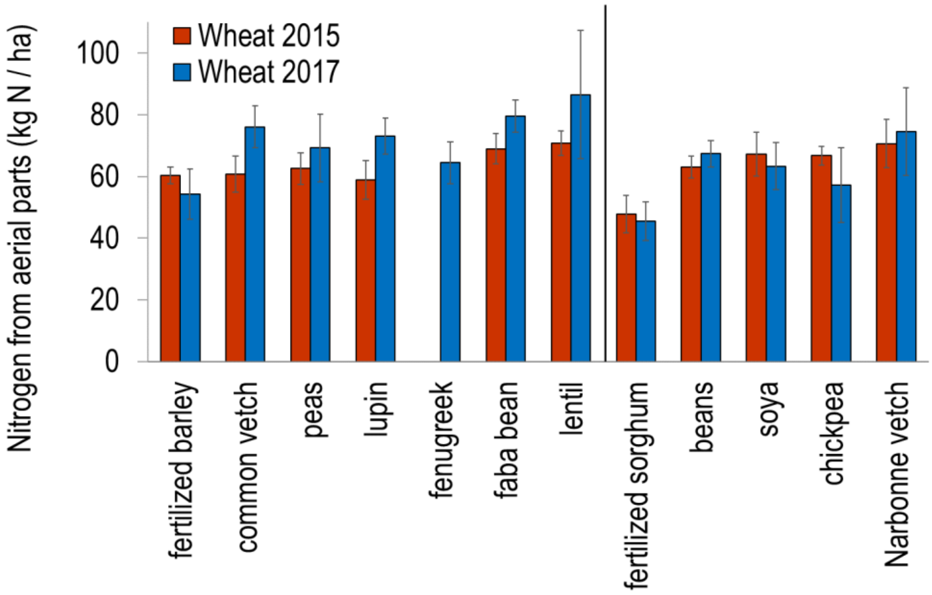

Figure 6: Amounts of nitrogen present in the above-ground parts of wheat at harvest in 2015 and 2017 depending on whether the previous crop (legume or reference cereal) was sown in March (left of line) or May (right of line) (Guinet *et al.*, 2020b).

For wheat grown after legumes sown in March, the amounts of nitrogen found in the wheat averaged 64.4 and 74.8 kg N/ha respectively in 2015 and 2017. For wheat after barley, the amounts of nitrogen were 60.3 and 54.3 kg N/ha. The highest values were obtained after lentil and faba bean (Figure 6). For wheat grown after legumes sown in May, the amounts of nitrogen found in the wheat averaged 66.9 and 65.6 kg N/ha respectively in 2015 and 2017. For wheat after sorghum, the amounts of nitrogen were 45.8 and 45.5 kg N/ha. The amounts of nitrogen available for wheat were a function of the quantities of mineral nitrogen present in the soil, plus the amounts of nitrogen mineralised from legume residues. This mineralisation capacity is influenced by the C/N ratio and the biochemical composition of the residues of the different species. Narbonne vetch, faba bean, fenugreek, lentil and common vetch have been identified as good predecessors.

2.4 Example of protein self-sufficiency in a dairy herd

A trial was conducted at the Lycée agricole de Fontaines (Saône et Loire French Department) to assess the impact of replacing maize silage in the ration on the performance of the dairy herd (Bertholon *et al.*, 2020). Maize was phased out gradually: firstly, maize was replaced to a large extent by a protein-rich summer catch crop, then maize silage was completely replaced by 'protein' meslin silage containing less than 20% cereals. Milk production was maintained overall (loss of ~1 kg of milk/cow/day), with milk quality criteria remaining unchanged. From an economic point of view, the substituted ration enabled significant savings to be made on nitrogen corrector (soya/rapeseed cake), provided that a minimum protein content of 15% was achieved in the forage. However, the results need to be qualified according to the ratio of maize yields *to* catch crops. In addition, cereal requirements are higher to correct the energy ration. From an agronomic point of view, catch crops and meslin make it possible to diversify the crop rotation and benefit from the ecosystem services provided by legumes. However, growing meslin requires more land and more labour than silage maize for the same performance. The quest for protein autonomy must therefore be considered from a global perspective, taking into account all the pillars of sustainability.

3. Agro-ecological transition to redesign cropping systems that include legumes

The agro-ecological transition involves rethinking production systems. By analysing the trajectories of farms and farmers, we can understand the aims that farmers are pursuing. The complementary nature of crops and livestock enables mixed crop-livestock farms to increase their sustainability by maximising interactions and the completion of biological cycles between the two activities. In this way, the MCL represents a favourable system for initiating or reinforcing the agro-ecological transition of farms. Complementarity between mixed crop and livestock farming can also be tackled on a regional scale through transactions or exchanges between farms. In arable farming, progress in the agro-ecological transition involves redesigning cropping systems to maximise the ecosystem services provided by selected varieties while maintaining the productivity of these systems. Identifying pioneering farmers who have implemented innovative cropping systems will enable us to characterise the technical and socio-economic obstacles and levers to the adoption and dissemination of these systems.

3.1 Evaluation of manure exchange prices using the Orfee model

The Orfee bioeconomic model (Optimization of Ruminant Farm for Economic and Environmental assessment; Mosnier et al., 2017) was used to simulate the operation of a farm with one or more ruminant livestock units, cereal and oilseed crop units as well as forage crops and grasslands. It optimises production choices, in particular herd size and production, animal rations, crop rotation and crop production, labour and equipment used to maximise an objective function (current income) under a set of strategic constraints (minimum feed self-sufficiency, production specifications, etc.), structural constraints (available land, labour and buildings), technical constraints (rotations, cropping operations, herd feed requirements, etc.) and regulatory constraints.

This model uses a crop module, which calculates mineral element requirements as a function of crop yields and takes into account previous crop effects in modulating requirements and yields. To model mixed crop-livestock farms, the crop and fertilisation modules have been modified. The fertilisation module uses the nitrogen balance equation taken from the Comifer methodological guide to calculating nitrogen fertilisation (Comifer, 2013). Organic fertilisation and the use of crop residues, in this case straw, have an impact on the mineralisation of stable soil organic matter (humus).

The application of manure is beneficial for the storage of organic matter in the soil if the frequency of application is regular and the quantity applied is significant. Ziegler and Héduit (1991) estimate that beyond an interval of 4 years between two applications of manure, the expected effect is negligible. As for the quantity to be applied, the proposed references vary from 7 to 45 t/ha over a longer period (Sleutel et al., 2006). With the help of experts, the amount of manure to be applied was set at 24 t/ha every two years to maintain or increase organic matter in the cultivated plots. The hypothesis is that the regular application of manure on the farm's plots, with straw export, increases the rate of nitrogen mineralisation and the nitrogen stocks in the soil. Consequently, after ten years of regular application of manure, soil nitrogen availability increases and the amount of nitrogen to be applied decreases. Two humus mineralisation values have been defined: the first corresponds to irregular or regular organic fertiliser applications over a short period (less than three years of application) with regular straw burial (33 kg N/ha/yr), the second to regular long-term manure applications and partial straw export (50 kg N/ha/yr).

The results obtained enable us to calculate a range of exchange prices for manure between a livestock farm and a crop farm. In the short term, a price of no more than 11 €/t for manure and the sale of straw at a minimum of 60 €/t (from the farm) would mean that the cereal farmer would not lose out on income from spreading mineral fertiliser and burying straw. Regular application over the long term would enable higher exchange prices, with the cereal farmer finding it economically worthwhile to buy manure at a price of up to 17 €/t (excluding transport costs), which seems realistic from the point of view of a long-term investment to improve soil quality. The results underline the value of this transaction for both farms, and the importance of considering the long-term application of manure.

3.2 Assessing the performance of legume-based cropping systems on the farm

Farmers are a source of innovative solutions that are often difficult to identify. Innovation tracking is a methodology that enables us to identify these technical, systemic or organisational innovations designed by farmers on the basis of a specification of what we are looking for, to characterise them in the form of coherent practices, to assess their agronomic, economic and environmental performance, to specify the conditions for success and to formalise them (Salembier and Meynard, 2013; Salembier et al., 2016).

A series of successive phases of research with advisors and farmers in Burgundy-Franche-Comté enabled us to identify cropping systems that included legumes successfully and to the satisfaction of farmers. Based on the survey data, it was possible to carry out a decision analysis of these systems. The results of these surveys revealed 11 different cropping systems grouping together 6 ways of including legumes: temporary grassland, meslin, seed legumes, intercropping cover, permanent cover and companion plant. Among the systems surveyed, 33 instances of legume insertion were identified.

The treatment frequency indices (TFI) of the legume systems studied are lower (0, 8 to 4.2) than the reference systems (4 to 6.7). The energy cost of systems with legumes is lower on average (10.2 GJ/ha) compared with reference systems (12.6 GJ/ha), with significant variability (6.1 to 14 GJ/ha).

An analysis of the agronomic reasoning associated with this feedback has enabled the conditions for obtaining satisfactory services to be identified, extrapolated to other situations and presented in a booklet for farmers (Guinet et al., 2021).

3.3 Appropriateness of applying agroecology principles to agricultural college farms

The farms run by agricultural schools are teaching aids that should, among other things, enable future farmers to design or redesign their own farms. The managers of these farms and the teaching teams are asking themselves how their production system fits in with the principles of agro-ecology taught at the same time. Various development scenarios have been developed jointly with the farm managers of the four agricultural colleges involved in the projects, in order to test how modelling can be used as a tool to assist the agro-ecological transition. The agricultural high school of “Les Terres de l’Yonne” of La Brosse (Yonne French Department) has a herd of dairy cows and field crops; the agricultural high school of Fontaines (Saône et Loire) has a herd of dairy cows, suckler cows, poultry and field crops; the one of la Côte Saint André (Isère French Department) has beef sheep, dairy cows, a beekeeping workshop and field crops and the one of Valentin (Drôme) produces organically and has dairy cows, fruit trees and field crops.

The Orfee simulation model (Mosnier et al., 2017) was used to simulate the operation of the farms of the 4 high schools. Two improvements to the model had to be made to carry out these simulations: the introduction of intercropping and dynamic rotational grazing. Various interactions between crops and livestock were taken into account: 1) The introduction of fodder crops and temporary grassland in longer rotations with crops reduces the use of synthetic inputs. 2) Livestock manure can replace mineral fertilisers and reduce inputs. 3) In the long term, manure increases the mineralisation of organic matter into plant-available nitrogen. 4) Harvesting straw used for animal bedding rather than burying it reduces crop nitrogen requirements by 10 kg N/ha/year.

Most farm managers wanted to change their farming systems to adopt more agro-ecological practices. This led to the aim of increasing the herd's self-sufficiency in feed, with grass playing a greater role in some cases. Conventional farms also wanted to test the transition to organic farming. Other strategies were more specific to some secondary schools, such as changing dairy breeds or eliminating a suckler enterprise. The strategies were tested according to an increasingly agro-ecological logic: the farm's reference situation, economic optimisation with the minimum of agro-ecological constraints, and food self-sufficiency in grassland systems and organic farming.

The initial results show that the simulated strategies use crops such as meslin (cereal-protein crop mixtures), temporary grassland and intercropping, as well as dynamic rotational grazing techniques in almost all the simulated scenarios. These crops make it possible to reduce the amount of inputs used and increase the amount of grassland, with a favourable impact on the environment. Dairy production is often favoured over suckler cow or ewe production because of its economic profitability. Overall, the simulations enable economic results to be maintained or improved, but the results are more mixed when it comes to the environmental performance of the farms. Because it takes time to set up, modelling seems to be a tool for reflection rather than for decision-making, but it is proving very useful in agricultural training to study the links between the various enterprises and the impact of internal or external changes to the systems, as well as for co-designing innovative systems.

3.4 Thinking about how mixed farming and livestock complement each other at regional level

In addition to a farm-level approach to the agro-ecological transition, this issue can also be considered on a regional scale, through exchanges between different farms.

The Orfee model (Mosnier et al., 2017) was used to calculate the interest price of alfalfa hay, i.e. the price at which the farmer produces or buys alfalfa without losing income compared with his situation without alfalfa, in a local exchange or purchase approach. Three typical farms in Auvergne-Rhône-Alpes were considered: one specialising in arable farming on the plains and two dairy cattle farms. The first is a piedmont grazing system with standard milk production. The second is a system with cheese production and processing under the Tomme and Emmental PGI (Protected Geographical Indication). These three production systems were optimised according to three scenarios: 1) no alfalfa hay (control), 2) the possibility of producing or buying alfalfa hay, with no commitment to quantity but with prices fluctuating according to fodder prices, 3) the possibility of producing or buying alfalfa hay, with a commitment to quantity over 3 years and a guaranteed price. The interest prices for alfalfa hay have been estimated and correspond to the price at which each farmer derives at least as much 'utility' from producing or buying alfalfa as from not doing so.

Several agronomic effects of alfalfa have been taken into account in the model: nitrogen requirements calculated for alfalfa are zero, as they are supplied by symbiotic nitrogen fixation. The nitrogen requirements of the following crop are reduced by 60 kg N/ha and yields are increased by 5% to take account of the preceding effect in the model (Comifer, 2013).

For alfalfa hay, a selling price range was established of between 145 and 151 €/t for the cereal farmer and a purchase price range of 179 to 181 €/t for the standard milk farmer and 201 to 206 €/t for the PGI farmer (Figure 7). These initial results seem realistic and show that farmers (breeders and cereal growers) can find an economic interest in this exchange, even if it remains moderate. This study also showed a significant difference in the price of interest for the two livestock farms, highlighting a greater propensity to pay for livestock farming with PGI cheese production. In addition to this first economic criterion, there is a real interest in the traceability of the fodder purchased, as well as in the image of local production (Thiery et al., 2020).

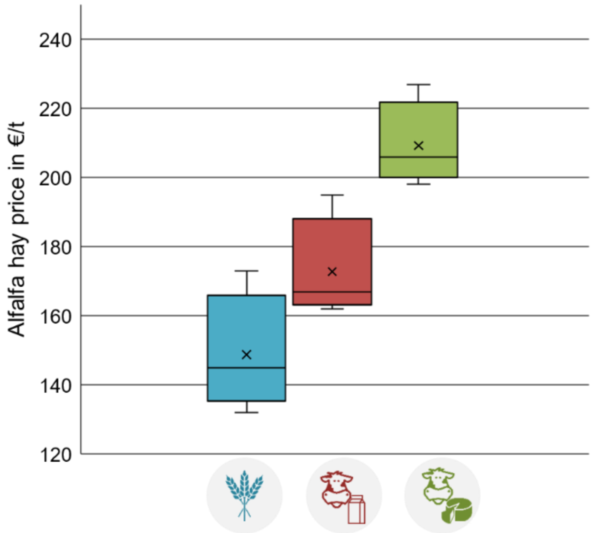

Figure 7: Price of alfalfa hay for the two livestock farms and the arable farm (blue: arable, red: standard milk, green: PGI milk).

What's more, the introduction of contract alfalfa over a number of years has enabled the farm's current income from arable crops to stabilise, due to the diversification of sales but also to the agronomic effects of alfalfa. These initial results could be used to initiate a more global debate on a regional scale to ensure greater resilience in production systems.

3.5 Analysis of the trajectories of farms involved in the agro-ecological transition

The hypothesis being tested is that mixed crop-livestock farming (MCL) represents a favourable system for initiating or strengthening the agro-ecological transition on farms. The study looked at the views of farmers who were on MCL or who had stopped MCL, on the basis of semi-directive on-farm surveys, in order to explore their motivations for choosing their system and the link they made or did not make with the transition that agriculture is undergoing. The technical implementation of these motivations was also studied through the intensity of workshop coupling. In order to capture a wide diversity of systems, and therefore potentially different organisations and points of view, the farmers surveyed were selected using the snowball method (Mitchell et al., 1997).

The discourses were studied using three complementary analyses. A first 'biotechnical' analysis quantified the references to the three pillars of sustainability (economic, social and environmental) in the farmers' discourse and in the description of their system. The aim was to see whether the choice of a MCL system stemmed from concerns linked to one or more pillars of sustainability, and which pillars were favoured by the farmer. A second, sociological, analysis was based on the notion of 'Modernity' in the sociological sense of the term (Latour, 1991), which can be likened to a focus on the market economy, productivism and the domination of nature... The aim was to identify the fundamental values on which each farmer had built his system. A third, more technical and organisational, analysis schematised and quantified the intensity of interactions between the crop, livestock and grassland units, via couplings assessed with the NICC'EL tool (Martel et al., 2020) as a concrete implementation of the ideas developed in the speeches and the farmers' positioning in the agro-ecological transition. A graphical approach was used to summarise all the results in a diagram that could also be used to plot the trajectories of the farms.

The biotechnical analysis enabled us to position the farmers on a scale ranging from level 1, where the economic pillar is largely predominant in the discourse, to level 6, where references to the economic, social and environmental pillars are also very present. Similarly, the sociological analysis enabled us to position these same farmers on a scale ranging from a deep-rooted attachment to modern values, relating to the productivist, economic and commercial world, to a strong questioning leading to the liberation of these values. By projecting these scales onto two axes, we obtained the position of each farmer on a modernity-sustainability graph (Figure 8).

This approach reveals a wide range of positions, with 14 distinct positions for the 26 farmers surveyed. These positions reveal a linear relationship between sustainability concerns and farmers' social reference values (modernity). The more farmers talk jointly about the three pillars of sustainability, the more this is accompanied by a change in the way they look at nature and a questioning of the traditional productivist system. On the farm, this translates into an intensification of the interactions, or linkages, between livestock and crop production, and therefore an increase in the system's autonomy. The most autonomous farms and those most committed to the agro-ecological transition have almost all opted for organic farming. Organic farming appears to be a way for farmers to make the most of the intensification of coupling that they have gradually put in place. Organic farming seems to be a logical next step, consistent with the redesign of their systems.

By estimating their position on this same graph 10 years ago and in 10 years' time (Figure 8), farmers were able to identify evolutionary trajectories. On the whole, farmers are all moving towards more sustainable profiles (towards the top of the scale), either by freeing themselves from modernity (trajectories to the right) or by remaining anchored in modernity (trajectories to the left). Because of the snowball sampling method, this approach makes it possible to capture the diversity of situations, but does not make it possible to assess the representativeness of the various trajectories.

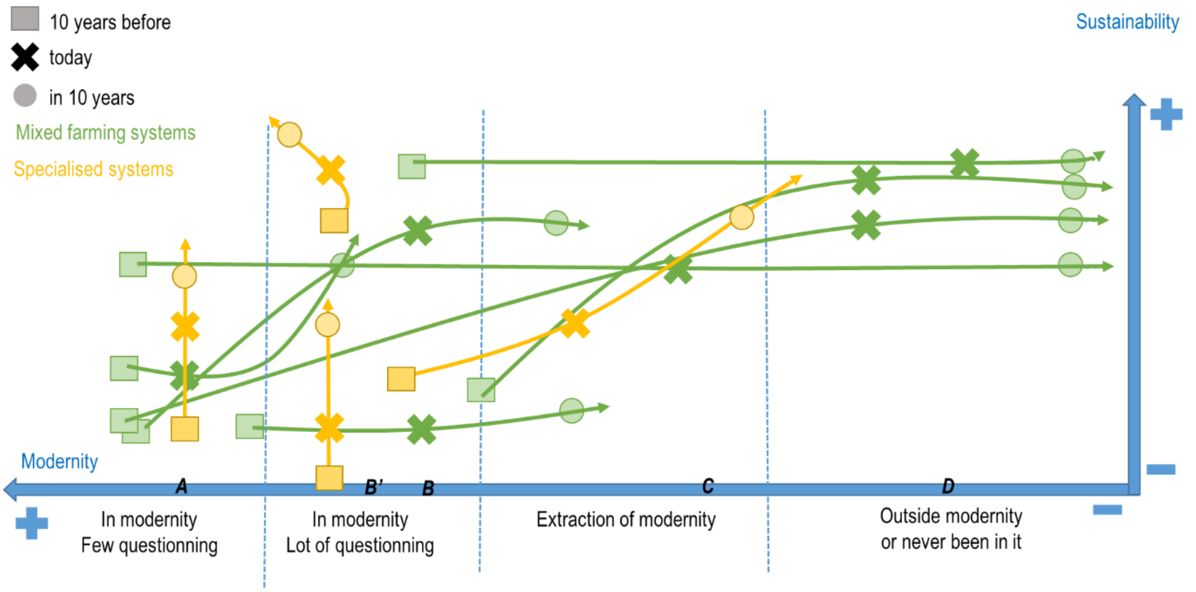

Figure 8: Typical trajectories of farms surveyed on the 2 sustainability and modernity scales. Mixed farming systems (MCL: green) and specialised systems (S: yellow).

MCL therefore appears to be a factor favourable to the agro-ecological transition since, by relying on the complementarity of crops and livestock, it increases the autonomy and sustainability of farms and facilitates their evolution and the re-design of systems. Although a specialised farm is the best way to achieve this transition, it can also increase its sustainability by encouraging natural agronomic processes and drawing on the resources at its disposal.

3.6 The role of collectives in the agro-ecological transition

In mixed farming, fodder legumes are regularly grown and included in animal feed 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, farmers growing legumes were interviewed (Garcia, 2018; Vergote *et al.*, 2019). It has been established that the introduction of new crops requires a learning phase facilitated by exchanges between peers (Rivaud and Mathé, 2011), so technical farmer groups were targeted. From the 1950s onwards, collectives spearheaded agricultural modernisation (Gerbaux and Muller, 1984). The collectives surveyed were chosen after consultation with local stakeholders (Chambers of Agriculture, cooperatives and DRAAF) using the snowball method (Mitchell *et al.*, 1997).

Analysis of the interviews highlights the cognitive and social contributions of the collectives to the diversification process. To begin with, 'thinking outside the box' by introducing new crops reveals a pioneering stance, a quest for autonomy, breaking with the existing organisational system, in which technical advice disseminates knowledge developed by experts from outside the farm. The farmers we met were involved in a research and learning process, and consciously participated in groups to share, seek out or build *ad hoc* knowledge and know-how. The farmers we met were not closed to advice. However, they analyse it as one of several information resources, in order to develop their own assessment of what would be appropriate to do on their farm.

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, so that together they dare to depart from the existing technical regime.

When it comes to the agro-ecological transition, collectives are a real support, an implementation tool. However, the choice of new crops and the adoption of new farming practices are the result of an individual path, a personal trajectory following a triggering event. Among the farmers we met, this commitment may be a deliberate choice in a spirit of innovation, or it may be the result of a need to find solutions to particular difficulties, or even impasses (resistance to insecticides, extra costs associated with 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 (around 10% in the regions studied). This is not necessarily a problem if these farmers act as gatekeepers (Polge and Torre, 2015), i.e. if they are recognised by their peers as professionals who can be followed. Beyond the necessary agronomic success that will enhance their approach, socio-economic and institutional recognition of their contributions is essential. The Groupement d'Intérêt Economique et Environnemental (GIEE) label provides institutional recognition. The challenge now is to ensure that this transition approach is recognised by the socio-economic fabric.

3.7 Limits to the introduction of legumes into cropping systems

A cross-referenced approach to the various results of the two research projects, ProSys and POEETE, highlights the benefits of introducing legumes into arable and mixed farming. The issue of protein autonomy at farm level, and also at the level of larger territories, involves the questions raised above. By reducing the use of synthetic fertilisers, improving soil fertility, 'breaking' weed and disease cycles, increasing the protein balance per hectare and improving the protein self-sufficiency of farms, these crops are fairly systematically considered when we think about a sustainable cropping system. However, a 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 the light of their potential negative impact on water quality (Ubertosi *et al.*, 2020). As previously mentioned, the introduction of legumes into crop rotations can help reduce nitrogen and plant protection inputs and, consequently, the pressure on water bodies. 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. To minimise the risk of leaching, it is possible to introduce intermediate crops or choose subsequent crops that require a lot of nitrogen.

With regard to the dynamics of plant protection products, the results of the experiments do not allow any clear conclusions to be drawn. However, it would appear that the risks are mainly present in the weeks following application of the products, whatever the crop, and that the reduction in use results in a reduction in the phytosanitary substances found in the water.

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 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.

Conclusion

The PSDR4 projects POEETE and ProSys dealt with the adaptation of agricultural production systems (animal and plant) to changes in the environmental, agricultural and social context (climate, reduction in inputs, quest for self-sufficiency), in particular through the introduction of legumes, by looking at the different scales (cropping system, farm, sectors and territory), taking into account the objectives of reducing synthetic nitrogen inputs and the quest for protein self-sufficiency. These projects have made it possible to acquire local references for optimising the supply of common goods: production of plant and animal raw materials, water and air quality, protein production, reduction of greenhouse gas emissions. Rather than presenting ready-made recipes, the studies and experiments carried out are designed to raise questions and encourage the co-design of innovative solutions that are adapted to local social, economic and environmental contexts. The results presented highlight the benefits of rethinking production systems, with more links between mixed farming and livestock rearing, and the benefits of increasing the proportion of legumes in regional soils to improve protein self-sufficiency while enhancing the functionality and sustainability of agro-ecosystems. The success of these moves towards more agro-ecological systems will depend not only on the ability to disseminate the results produced, but also on the ability to convince all levels of the agricultural sector and the regions of the benefits of these changes.

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.

Author ORCIDs
Marjorie Ubertosi - id ORCIDs: 0000-0001-8761-3544
Brunschwig Gilles - id ORCIDs: 0000-0002-3404-6301
Thierry Castel - id ORCIDs: 0000-0001-9650-9474
Maé Guinet - id ORCIDs: 0000-0001-9904-4692
Annabelle Larmure - id ORCIDs: 0000-0003-4552-0491
Christophe Lecomte - id ORCIDs: 0000-0001-9729-0013
Claire Mosnier - id ORCIDs: 0000-0003-0210-3460
Bernard Nicolardot - id ORCIDs: 0000-0003-1852-4243
Wilfried Queyrel - id ORCIDs: 0000-0002-0901-2425
Corinne Tanguy - id ORCIDs: 0000-0001-5606-1214
Patrick Veysset - id ORCIDs: 0000-0002-8914-0143
Anne-Sophie Voisin - id ORCIDs: 0000-0002-0979-7162

Authors' contributions

Marjorie Ubertosi: Conceptualization, funding acquisition, project administration, supervision, visualization, writing original draft
Gilles Brunschwig and Christophe Lecomte: Conceptualization, funding acquisition, project administration, supervision, visualization, writing review and editing
Candice Laroche: project administration, writing review and editing
Aymeric Mondière and Eglantine Thiery: Investigation
Bernard Nicolardot, Anne-Sophie Voisin, Maé Guinet, Wilfried Queyrel: Conceptualization, experiment, writing review and editing
Thierry Castel, Annabelle Larmure: Software and Writing review and editing
Denis Chapuis, Jean-Philippe Goron, Anne Jarousse, Jean-Pierre Manteaux, Claire Mosnier, Marie-Sophie Petit, Corinne Tanguy, Marie-Hélène Vergote, Patrick Veysset: Writing review and editing

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.

Acknowledgements

The PSDR 4 Bourgogne Franche-Comté project teams would like to thank the BFC region and its agents, as well as the support staff at the INRAE BFC centre.

Declaration of financial support

The studies presented in this article received financial support from the 4th PSDR programme (INRAE, Bourgogne-Franche-Comté and Auvergne-Rhône-Alpes Regions, ANR Legitimes, PIA PeaMUST, European Union / FEADER) as part of the "POEETE and ProSys" projects.

References

Bertholon J., Laroche C., Ubertosi M., 2020. Comment répondre à l'autonomie protéique sur les exploitations en polyculture-élevage ? [vidéo], écriture C. Colson, A. Cuenot, N. Déhé, G. Joly, C. Moureau et M. Sow, Réalisation EDUTER AgroSup Dijon, Collection PSDR 4 - ProSys, https://www.youtube.com/watch?v=BCYwbfNR7zY.

Carnoye L., Michaud F., Tanguy C., Vergote M.H., 2019. La transition agroécologique en grandes cultures en Bourgogne Franche-Comté. Un essai de caractérisation des différentes formes de pratiques alternatives, Colloque international AFEP-IIPPE, Lille, 3-5 Juillet.

Castel T., Lecomte C., Richard Y., Lejeune-Hénaut I., Larmure A., 2017. Frost stress evolution and winter pea ideotype in the context of climate warming at a regional scale. Oilseeds and fats, Crops and Lipids 24, D106.

Castel T., Lecomte C., Richard Y., Lejeune-Hénaut I., Larmure A., 2019. Évolution rétrospective du risque gélif hivernal en climat tempéré suite au réchauffement climatique. Bourgogne-Franche-Comté Nature. 29, 323–332.

Cavan N., Castel T., Pergaud J., Angevin F., Colbach N., 2020. Et demain? Robustesse des stratégies innovantes de gestion des adventices face au changement climatique. Innovations Agronomiques 81, 209-225. doi.org/10.15454/fqye-3778

Comifer, 2013. Calcul de la fertilisation azotée. Guide méthodologique pour l'établissement des prescriptions locales. Cultures annuelles et prairies. Comifer, Paris, 160 p.

Dee D.P. *et al*., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society 137, 553–597.

Fosse J., Aussilloux V., Grémillet A., Mesqui B., 2019. Faire de la politique agricole commune un levier de la transition agroécologique. France stratégie, 31 p.

Garcia E., 2018. Analyse des déterminants socio-économiques au développement des pratiques agroécologiques, et notamment à l'insertion des légumineuses dans les assolements en Bourgogne-Franche-Comté. Mémoire de Master 2 mention Développement Agricole Durable : Sécurité alimentaire pour le développement, Université Paris Sud. 95 p.

Gerbaux F., Muller P., 1984. La naissance du développement agricole en France. Économie Rurale, 159, 17-22.

Guinet M., Nicolardot B., Revellin C., Durey V., Carlsson G., Voisin A.S., 2018. Comparative effect of inorganic N on plant growth and N_2 fixation of ten legume crops: towards a better understanding of the differential response among species. Plant Soil 432, 207-227.

Guinet M., 2019. Quantification des flux d'azote induits par les cultures de légumineuses et étude de leurs déterminants – Comparaison de 10 espèces de légumineuses à graines. Thèse, école doctorale Environnement et Santé, 251 p.

Guinet M., Nicolardot B., Voisin A.S., 2020a. Provision of contrasted nitrogen-related ecosystem services among grain legumes. Agronomy for Sustainable Development 40, 33.

Guinet M., Nicolardot B., Voisin A.S., 2020b. Nitrogen benefits of ten legume pre-crops for wheat assessed by field measurements and modelling. European Journal of Agronomy 120, 126151.

Guinet M., Queyrel W., Voisin, A.S., Jeuffroy M.H., Petit M.S., 2021. Retour d'expériences sur des systèmes de culture innovants intégrant des légumineuses en Bourgogne-Franche-Comté. Collection PSDR 4- ProSys, 70 p.

Isbell F., Calcagno V., Hector A., Connolly J., Harpole W.S., Reich P.B., Scherer-Lorenzen M., Schmid B., Tilman D., Van Ruijven J., 2011. High plant diversity is needed to maintain ecosystem services. Nature 477:199–202.

Köpke U., Nemecek T., 2010. Ecological services of faba bean. Field Crop Research 115, 217-233.

Latour B., 1991. Nous n'avons jamais été modernes. Essai d'anthropologie symétrique, Paris, La Découverte. 210 p.

Lecomte C., Giraud A., Aubert V., 2003. Testing a predicting model for frost resistance of winter wheat in natural conditions. Agronomie 23, 51-66.

Martel G., Ramette C., Bouvarel I., Buteau A., Fontanet J.M., Mischler P., 2020. NiCC'El. Un outil pour caractériser le niveau d'interaction entre cultures et élevage d'une exploitation et identifier les voies d'amélioration. Innovations Agronomiques 80, 33-40. doi.org/10.15454/pkpw-8e95

Mitchell R.K., Agle B.R., Wood D.J., 1997. Toward a Theory of Stakeholder Identification and Salience: Defining the Principle of Who or What Really Counts, Academy of Management Review 22, 853-886.

Mosnier C., Duclos A., Agabriel J., Gac A., 2017. Orfee: A bio-economic model to simulate integrated and intensive management of mixed crop-livestock farms and their greenhouse gas emissions. Agricultural Systems, 157, 202-215.

Polge E., Torre A., 2015. Contribution à l'évaluation des dispositifs de gouvernance territoriale en Amazonie brésilienne : une analyse des dynamiques d'interactions. 52ème Colloque ASRDLF, 7-9 Juillet, Montpellier.

Power A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos Trans R Soc B 365:2959–2971.

Quinio M., 2015. Assessment of current climate risks on pea crop in France, based on the approach of ecoclimatic indicators. Mémoire de Master ISARA-Lyon, 53 p.

Quintana-Seguí P., Le Moigne P., Durand Y., Martin E., Habets F., Baillon M., Canellas C., Franchisteguy L., Morel S., 2008. Analysis of Near-Surface Atmospheric Variables: Validation of the SAFRAN Analysis over France, Journal of Applied Meteorology and Climatology, *47*, 92-107.

Rivaud A., Mathé J., 2011. Les enjeux cognitifs du défi environnemental dans les exploitations agricoles. Économie Rurale 323, 21-35.

Salembier C., Elverdin J.H., Meynard J.M., 2016. Tracking on-farm innovations to unearth alternatives to the dominant soybean-based system in the Argentinean Pampa. Agronomy for Sustainable Development 36, 1–10.

Salembier C., Meynard J.M., 2013. Evaluation de systèmes de culture innovants conçus par des agriculteurs : un exemple dans la Pampa Argentine. Innovations Agronomiques 31, 27-44.

Solanet G., Levard LM., Castellanet C., 2011. L'impact des importations européennes de soja sur le développement des pays producteurs du Sud. Campagne Alimenterre. CFSI, GRET, AFAC, 95 p.

Skamarock W.C., Klemp J.B., Dudhia J., Gill D.O., Barker D.M., Duda M.G., Huang X.Y., Wang W., Powers J.G., 2008. A description of the Advanced Research WRF. Version 3. National Center for Atmospheric Research, Rapp. tech. 125 p. Boulder - Colorado, USA.

Sleutel S., De Neve S., Németh T., Tóth T., Hofman G., 2006. Effect of manure and fertilizer application on the distribution of organic carbon in different soil fractions in long-term field experiments. European Journal of Agronomy, *25*(3), 280-288.

Taylor K.E., Stouffer R.J., Meehl G.A., 2011. An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society 93, 485–498.

Thiery E., Brunschwig G., Veysset P., Mosnier C., 2020. Mise en place d'une filière foin de luzerne valorisant les complémentarités plaine-montagne : détermination du prix d'intérêt pour le producteur et les acheteurs. Renc. Rech. Ruminants, 2020, 25, 326-329.

Tibi A., Therond O., 2017. Evaluation des services écosystémiques rendus par les écosystèmes agricoles. Une contribution au programme EFESE. Synthèse du rapport d'étude. Inra (France).

Ubertosi M., Prudhon M., Coffin A., Wager M., Badot J.M., Lucot E., 2020. Impacts de systèmes de culture sur la qualité de l'eau, Analyse croisée de dispositifs expérimentaux en Bourgogne-Franche-Comté. Projet PSDR4 ProSys Bourgogne Franche-Comté, Série les 4 pages PSDR4. www6.inrae.fr/psdr-bourgogne.

Van Vuuren D.P., Edmonds J., Kainuma M., Riahi K., Thomson A., Hibbard K., Hurtt G.C., Kram T., Krey V., Lamarque J.F., Masui T., Meinshausen M., Nakicenovic N., Smith S.J., Rose S.K., 2011. The representative concentration pathways: an overview. Climatic Change, 109, 5-31.

Vergote M.H., Tanguy C., Garcia E., 2019. Les collectifs producteurs de savoirs pour l'action : retour d'expériences sur l'insertion de légumineuses dans l'assolement en Bourgogne Franche-Comté. Innovations Agronomiques 74, 105-120. dx.doi.org/10.15454/vrxqlw

Voisin A.S., Guéguen J., Huyghe C., Jeuffroy M.H., Magrini M.B., Meynard J.M., Mougel C., Pellerin S., Pelzer E., 2014. Legumes for feed, food, biomaterials and bioenergy in Europe: a review. Agron Sustain Dev 34:361–380.

Ziegler D., Héduit M., 1991. Engrais de ferme : valeur fertilisante, gestion, environnement. ITCF et ITP, Paris, 35 p.

This article is published under the Creative Commons licence (CC BY-NC-ND 4.0)
https://creativecommons.org/licenses/by-nc-nd/4.0/
When citing or reproducing this article, please include the title of the article, the names of all the authors, mention of its publication in the journal Innovations agronomiques and its DOI, and the date of publication.