Institute for Food and Resource Economics

University of Bonn

Discussion Paper 2019:2

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Integrated assessment of legume production challenged by European policy interaction: a case-study approach from French and German dairy farms

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Abstract

Legumes can limit the impact of agricultural systems on the environment by limiting N fertilization, diversifying crop rotation and substituting imported protein-rich feed. However, their production remains low in the European Union, which led to specific policies. France established Voluntary Coupled Support scheme for legumes. Germany did not introduce a coupled support, but provides more favorable implementation of the Nitrates Directive for legumes by allowing spreading manure on these crops. Our study assesses economic and environmental impacts of the coupled support and measures of the Nitrates Directive affecting legume production in France and Germany. We employ the bio-economic model FarmDyn, parameterized for a typical dairy farm in France and Germany. Legumes are introduced as cash crops and on-farm feed, highlighting interactions between crop and animal productions. Different levels of coupled support per hectare were analyzed and the French versus the German implementation of the Nitrates Directive were compared. Results suggest that voluntary coupled support leads to an increase in legume production but to a lesser extend in the German farm than in the French farm, due to higher opportunity costs of legumes. In both farms, the increase in legume production leads to limited environmental benefits: nitrogen leaching and global warming potential slightly decrease. In the French farm, the German implementation of the Nitrates Directive fosters legume production. Thus, this study shows that allowing manure spreading on legumes can help reaching high legume production in livestock farms. However, this further increase in legume production does not lead to environmental benefits. Thus, allowing manure spreading on legumes to increase their production should be justified by other goals such as improving the protein self-sufficiency of the farm.

Keywords: Protein crop, Mathematical programming, Bio-economic model, Global warming potential, Nitrates Directive

JEL classification: Q18, Q53, D22

1 Introduction

Increased legume production can limit the impact of agricultural systems on the environment in several dimensions (Drinkwater et al., 1998). As legumes can fix atmospheric nitrogen (N), they need no, or limited, N fertilisation and may even supply N to the soil, reducing N fertilisation needs of the following crop (Peoples et al., 2009). They can contribute to crop diversification and thus to reduced pesticide application (Nemecek et al., 2008). Additionally, legumes used as protein-rich feed can substitute vegetable meals, often derived from imported crops and linked to loss of natural habitats (Sasu-Boakye et al., 2014).

After decades of a declining trend, legumes, including forage legumes and soybeans, covered on average less than 4% of the utilised agricultural area (UAA) between 2012 and 2017 in the European Union (EU) (Eurostat, 2018). That reflects firstly that their use in feed can mostly not compete against substitutes such as imported soybean meal (Häusling, 2011). Second, at the scale of the European agro-food chain, legumes suffer from a lock-in situation that tends to favour cereal and non-legume oilseed crops (Magrini et al., 2016), while sales of legumes face high transaction costs (Jouan et al., 2019). Third, legumes are generally less profitable for farmers compared to other major crops such as wheat and rapeseed, even if, at the rotation scale, their profitability is equivalent (Preissel et al., 2015). Farmers are also reported to assess their production risk as higher (von Richthofen et al., 2006), though there is no consensus in the scientific community that the yield variability of legumes exceeds that of other crops (Cernay et al., 2015; Reckling et al., 2018).

Since 2014, in the light of their advantages but low crop share, European member states can establish Voluntary Coupled Support (VCS) for legumes under the Pillar I of the European Common Agricultural Policy (CAP). That measure helped to reverse the downward trend in legume production but heterogeneously across member states and regions, reflecting that this measure was differently implemented. For instance, both France and Germany count legume acreage with a factor of 1 towards the Ecological Focus Area (EFA) requirement as part of "Greening". However, only France introduced VCS for legumes, reaching 145 million euros in 2017 (European Commission, 2017). The VCS might explain why the French area of legumes nearly doubled between 2013 and 2017 but only increased by 35% in Germany. It is also interesting to notice that the share of legumes in arable land in France is half as large in regions focused on livestock production compared to regions specialized in arable crops (Eurostat, 2018). This may be due to the French implementation of the Nitrates Directive (latter called "French ND") (91/676/CEE), which prohibits manure application on most legumes, discouraging their production in farms with high stocking densities. The German implementation of the Nitrates Directive (latter called "German ND") allows spreading manure on legumes as long as the mandatory N fertilisation planning at the farm scale is respected.

This study aims at assessing environmental and economic impacts of key policy measures affecting legume production, comparing in detail a French and German case study. We focus on the interactions of two different policy fields: VCS for legumes and national implementations of the European ND, while taking into account the “Greening” measures. Our hypothesis is that first, implementing a minimum VCS per hectare in France and Germany, will increase legume production in both countries. Second, that implementing the German ND in France, will lead to a further increase in legume production in France. Third, that these increases have positive environmental and economic implications at farm-scale. Fourth, that an increase in VCS would foster these developments. To test these hypothesis, we employ the bio-economic programming farm-scale model FarmDyn (Britz et al., 2014).

So far, only few studies analysed policies directly designed to increase legume production with farm-scale models (Cortignani et al., 2017; Helming et al., 2014). Studies using bio-economic models to analyse the ND and nitrate related policies are more common (Belhouchette et al., 2011; Kuhn et al., 2019; Peerlings and Polman, 2008). Other tools were also employed to study this directive, such as N flow models (Cardenas et al., 2011)) or agent-based models (Van der Straeten et al., 2011). Nevertheless, to the best of our knowledge, there is no analysis considering measures related to legume production, and the implementation of the ND, as an example for environmental policy interactions (Nilsson et al., 2012). Besides, impacts of legumes production are so far mostly analysed in arable cropping systems (Nemecek et al., 2008; Reckling et al., 2016), except for Schläfke et al. (2014), Helming et al. (2014) and Gaudino et al. (2018) who also considered legumes as feed in livestock farms. Finally, as far as we know, the study of Küpker et al. (2006) is the only one comparing in detail different farms in France and Germany, even though these countries being the main milk producers in EU. Other models at the European scale cover also the French and German productions (Louhichi et al., 2018), but as they are far more aggregated, they do not take into account detailed measures e.g. differentiated implementations of the ND according to countries. Thus, our study addresses several gaps in literature by (1) considering jointly multiple policies affecting legume production, (2) by introducing legumes as cash-crops and on-farm feed, highlighting interactions between crop and animal productions, and (3) by developing an integrated assessment of representative dairy farms in two European countries, France and Germany, whose regulations on legumes and manure management differ.

The paper is structured as follows: the second section describes the method implemented by presenting the model FarmDyn, how we introduced data related to legume production and the ND, and by describing the two analysed case-studies. The third section presents the results. The fourth section includes a discussion where policy implications and the limitations of our approach are developed. Finally, the fifth section concludes by summarizing the main conclusions.

2 Method

2.1 *Overview of the FarmDyn model*

Mathematical programming models represent a valuable tool to analyse technical changes or the introduction of (new) crops as they describe in detail farm management and investment decisions (Britz et al., 2012; Jacquet et al., 2011). Among them, bio-economic models aim to assess both economic and environmental indicators and their trade-off by accounting for joint production of agricultural outputs and environmental externalities (Janssen and van Ittersum, 2007). Bio-economic models have been introduced at different scales, from the field to whole regions (Gocht et al., 2017; Lehmann et al., 2013). At farm scale, bio-economic models have the advantage to simulate in detail the decision-making process of the farmer, considering technical as well as work-time or financial constraints. In the context of the European agriculture, farm bio-economic models are particularly used for assessing policies (Reidsma et al., 2018).

FarmDyn is a highly detailed single farm bio-economic model, building on fully dynamic mixed integer linear programming. It is written in the General Algebraic Modelling System (GAMS Development Corporation, 2018). The model provides a framework for the simulation of economically optimal farm-level plans and management decisions, as well as related material flows and environmental indicators (Lengers et al., 2013). Thereby, farm management decisions such as adjustments of crop shares, feeding practices, fertiliser management and manure treatment are depicted with a monthly resolution. FarmDyn maximises the farm net present value under (1) the farms' production feasibility set, (2) working-time and (3) liquidity constraints as well as (4) environmental and policy restrictions. By assuming a rational, fully informed and risk-neutral farmer, the simulation results entail best-practice behaviour. The extension of the linear programming with a mixed integer approach allows capturing indivisibilities e.g., of stables and machines.

In the underlying study, the comparative-static version of FarmDyn is used. We consider that the machinery pool used for legumes is already available to manage the benchmark crop rotation. Thus, the use of the simpler static version model seems appropriate and eases model application and result analysis. Therefore, indivisibilities in investments are considered but investment costs in buildings and machinery are annualized and herd dynamics are depicted by a steady state model (e.g., the number of cows replaced in the current year is equal to the number of heifers raised for replacement).

Indicators on farm performance are implemented such as the total profit of the farm, the protein self-sufficiency (i.e., the ratio between protein produced to feed the herd, and total protein consumed by the herd), and different environmental indicators. The global warming potential (GWP) of the farm is calculated by measuring the emission of different greenhouse gases and expressing their GWP as a factor of carbon dioxide. Thereby, emissions arising on-farm (e.g., from fertilisation and manure storage), as well as emissions related to the usage of inputs such as diesel or feeds are considered. Since the ND aims to protect water quality by preventing nitrates polluting water bodies, we include an indicator for nitrogen leaching (latter called “N leaching”). It calculates a probabilistic value for N leaching by considering different sources of N, e.g., fertilisation and manure application, mineralisation, as well as the nutrition deduction by the crops following the model SALCA -NO_3 (Richner et al., 2014).

2.2 *Case-studies and data implemented*

We analyse as case studies one French and one German intensively managed dairy farm (Table 1), located in Pays de la Loire (PDL) in France and North Rhine-Westphalia (NRW) in Germany. Intensive dairy farms where chosen as they combine features salient for the analysis: high quantities of manure produced per ha of land such that manure management restrictions from ND are relevant; the possibility of using both grain and forage legume as feed; and compared to pig farms, more constrained feed choices linked to structural characteristics of the farm (e.g., part of fodder area). The case studies are defined based on longer time series data from agricultural institutions and extension services. The French farm is based on the farm type “1b Pays de la Loire”, from Inosys Réseaux d’Elevage (IDELE, 2016) as one of the most common types of dairy farms in that region. Quite detailed data are available for this farm-type, such as crop rotation, stable inventory, and grass management. Besides, the crop rotation of this farm corresponds to the main crop rotation of PDL (Jouy and Wissocq, 2011). The German farm is based on farm type « Niederrhein NR_SB » from (Steinmann, 2012), one of the most common types of dairy farms in NRW. Since no information on typical crop shares is provided by that source, the crop rotation of the German farm is taken from Kuhn and Schäfer (2018) who derived typical crop rotations for different farm-types in NRW, based on data from agricultural census and expert interviews. For both farm types, yields are based on regional data, and input and output prices on national ones (mean 2013-2017) (Agreste, 2018; AMI, 2019; IT.NRW, 2019; KTBL, 2019; La Dépêche - Le Petit Meunier, 2018).

The German farm has a lower share of grassland than the French farm as well as a higher stocking rate (Table 1). Further, the milk as well as the crop yields are higher for the German farm. Thus, overall, the German farm is managed more intensively than the French farm.

Table 1: Description of the dairy farms implemented in the FarmDyn model

	French farm	*German farm*
Arable land [ha]	49	60
Grassland [ha]	27	20
Number of dairy cows	62	75
Stocking rate [$cow.ha^{-1}$]	0.82	0.94
Breed	Holstein	Holstein
Milk yield [$kg.cow^{-1}.year^{-1}$]	8 600	8 800
Crops	Grassland, wheat, silage maize	Grassland, wheat, silage maize

2.3 *Introduction of legumes related data*

We cover three legumes in FarmDyn model: peas, faba beans and alfalfa (Table 2). As for the other crops, data on yields, and on input and output prices based on (Agreste, 2018; AMI, 2019; IT.NRW, 2019; KTBL, 2019; La Dépêche - Le Petit Meunier, 2018). German input prices for legumes that are rarely traded are calculated using the method available in (DLR Westerwald Osteifel, 2011). Peas and faba beans can either be used as feed or sold as cash crops, while alfalfa can only be used as feed. In the French region, a cooperative offers a dehydration service to its members: alfalfa is harvested by the cooperative, dehydrated and then returned to farmers as a conserved fodder of high nutritional quality (Leterme et al., 2019). It is assumed that this technique could become available in Germany (Kamm et al., 2016). CO2eq emissions from the dehydration were taken into account in the model (Corson and Avadí, 2016).

Table 2: Characteristics of legumes implemented in the FarmDyn model

		Alfalfa	*Faba bean*	*Pea*
Yield [$t.ha^{-1}$]	France	10.2	3.0	4.1
	Germany	8.5	4.2	4.7
Selling price [$€.t^{-1}$]	France	-	208	212
	Germany	-	177	198
Buying price [$€.t^{-1}$]	France	-	270	246
	Germany	-	297	306
N from mineralisation of residues	France	25	30	20
	Germany	20	10	10

One of the main advantages of legumes is their positive effect on following crops: legumes have the ability to fix nitrogen and hence fertilise the following crops by mineralising their residues. Thus, N from legume residues enters in the fertilisation balance, in addition to N from manure and synthetic fertilisers, as shown in equation (1).

$$Nneed_c . X_c \leq \mathrm{Nmanure}_c + \mathrm{Nsynt}_c + NLeg_c \tag{1}$$

Where, for each arable crop c, $Nneed_c$ is the need for N, X_c is the cropping area, and $\mathrm{Nmanure}_c$, Nsynt_c as well as $NLeg_c$ are, respectively, N available from manure, synthetic fertilisers, and mineralisation of legume residues.

As the FarmDyn model is used as a comparative-static model, N stemming from mineralisation of legume residues is introduced as an additional pool of N, integrated at the farm scale (equations 2 to 4) and not explicitly modelled by providing N to following crops:

$$\sum_c NLeg_c = NLegPool \tag{2}$$

With $$NLegPool = \sum_{leg} X_{leg}.NcarryOver_{leg} \quad (3)$$

$$NLeg_c < X_c.NcarryOver_{leg} \quad (4)$$

Where, for each arable crop c, $NLeg_c$ is N available from mineralisation of legume residues, $NlegPool$ is the pool of N available at the farm scale from mineralisation of legume residues; X_{leg} is the cropping area of each legume at the farm; $NcarryOver_{leg}$ is the quantity of N mineralised from residues of each legume. Data on N from mineralisation of residues is based on national documentation on the balance of N fertilisation (BMEL, 2017; Comifer, 2011).

The mineralisation of legume residues also adds another source of N that might pollute the environment through leaching. This additional source of N is integrated in the calculation of N leaching according to the model SALCA-NO_3 (Richner et al., 2014).

2.4 *Differentiated implementation of the Nitrates Directive in the FarmDyn model*

As all European directives, the ND (91/676/CEE, (European Council, 1991)) must be implemented into national laws, which implies differences across member states. For our analysis, we introduce the key aspects of the French and the German ND, which are implemented in PDL and NRW (BMEL, 2017; DREAL Pays de la Loire, 2018) into FarmDyn (Table 3). Apart from slightly different blocking periods for the application of manure, the main divergence relevant for this study is the possibility of spreading manure on legumes or not. In France, it is forbidden to spread manure on grain legumes (e.g., peas, faba beans) but not on forage legumes (e.g., alfalfa). In Germany, it is possible to spread manure on legumes as long as the surplus of the nutrient balance at the farm gate does not exceed 50kgN.ha^{-1}. Both, the French PDL region and the whole of Germany are designated as nitrate vulnerable zones where organic N application is limited to 170kgN.ha^{-1} on farm level.

Table 3: Main measures under the Nitrates Directive implemented in by France and Germany

	France	*Germany*
Threshold of organic N application	170kgN.ha-1	170kgN.ha-1
Surplus of nutrient balance authorized at the farm gate	No regulation	50kgN.ha-1
Threshold of organic N application on legumes	Alfalfa: 200kgN.ha-1 Grain legumes: 0kgN.ha-1	No regulation
Fixed blocking periods of N application	Crop planted in autumn: 15.11-15.01	Grassland: 01.11-31.01

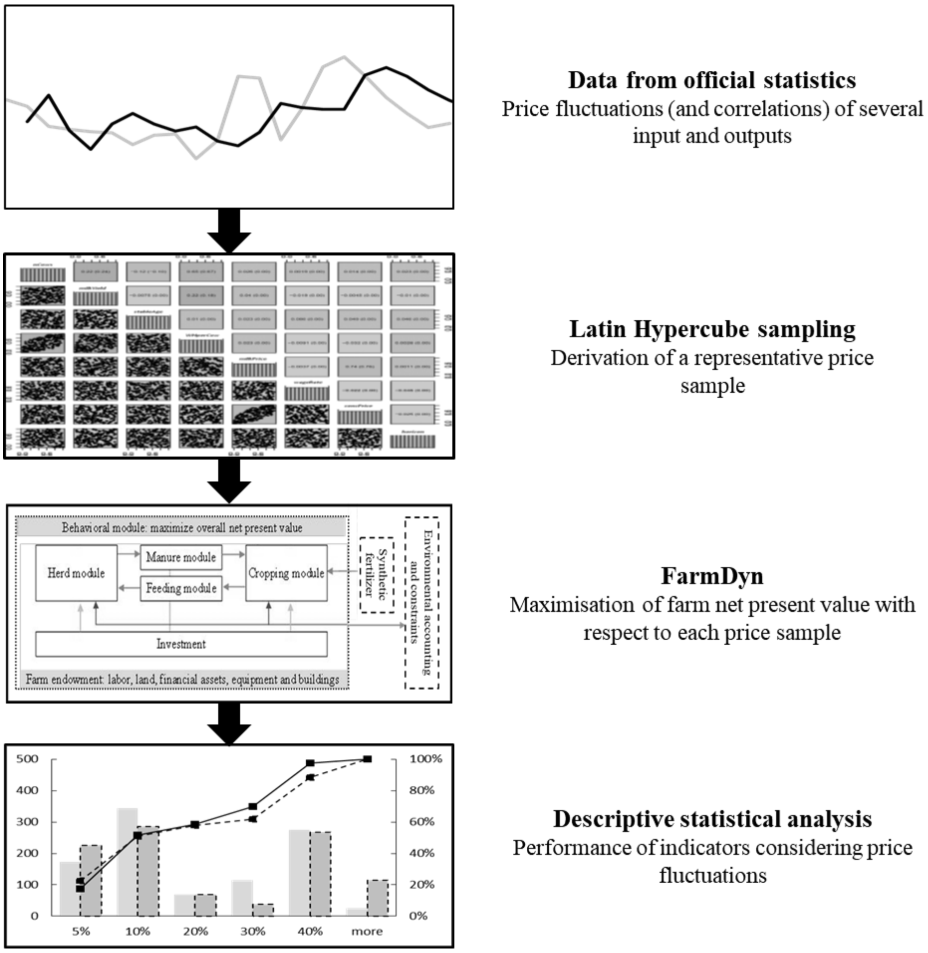
	Crop planted in spring: 01.07-15.01 Pasture and alfalfa: 15.12-15.01 Rapeseed: 01.11-15.01	Arable land: 01.10-31.11
Minimum manure storage capacity	4 to 6.5 months	LSUf.ha-1 <3: 6 months LSU.ha-1 >3: 9 months

2.5 *Calibration procedure and sensitivity analysis*

Each farm is calibrated by adjusting the working-hours available on the farm, as well as the grazing periods for the herd and the energy content of grass. In the German farm, the yield of wheat is adjusted within a 5% tolerance level. The size of the herd is fixed according to the number of dairy cows in the observed farm types.

A sensitivity analysis is conducted on the selling price of wheat and the buying prices of soybean meal and concentrated feeds, identified as being the main substitutes for legumes (Charrier et al., 2013). We adopt a meta-modelling approach (Kuhn et al., 2019; Lengers et al., 2014) to assess the effectiveness of the policy measures at different price levels (Figure 1). First, a representative price sample is generated by Latin Hypercube sampling (LHS). The sampling is based on observed price fluctuations (between 1995 and 2017) derived from official statistics (Eurostat, 2019). The price fluctuations are applied on the initial average prices, giving price ranges for each good. For each tested policy scenario (see section 2.6), 1000 prices samples are randomly drawn out of the price ranges in order to obtain a representative sample. Thereby, price correlation between the respective goods is taken into account. Second, FarmDyn is used to simulate the optimal farm-level plan and maximize the farm net present value with respect to each price sample. Third, the results are used in a descriptive statistical analysis to determine the performance of key indicators considering feasible price fluctuations.

Figure 1: Overview of the sensitivity analysis performed, adapted from (Kuhn et al., 2019)



2.6 *Scenarios*

We define a baseline scenario (VCS0) with no VCS for legumes and with the French ND in the French farm and the German ND in the German farm. In the first scenario (VCS100), we implement a VCS for legumes in both countries, keeping the national implementations of the ND. Even though the total VCS budget for legume is stable among years in France, the VCS per hectare depends on the legume variety and on the total area of legume cultivated during the year. Therefore, we chose to implement the minimum level established in France[1]: 100€.ha^{-1} for peas, faba beans and alfalfa. In the second scenario

[1] The French VCS budget supports five species and usages of legumes (grain legumes, forage legumes, soybean, legumes for dehydration, and legumes for seed), each having its own sub-budget. While the VCS budgets are usually stable from year to year, the VCS per hectare vary with the acreage of each legume. Thus the VCS per hectare is usually different between grain

(VCS100ge), the German ND is introduced in the French farm, the VCS of 100€.ha^{-1} still being available. Lastly, we define a set of scenarios where the VCS per hectare is increased in both farms, with steps of 10%, starting from 110€.ha^{-1} to 300€.ha^{-1} (VCS110 to VCS300), under the French or the German ND in the French farm, and the German ND in the German farm. This increase in VCS per hectare per is deliberately extreme in order to explore impacts of increasing VCS and the implications of resulting legume shares not yet observed in farms.

3 Results and Discussion

Unless specified, the following quoted values represent the median of our sample.

3.1 *Legume shares and manure spreading*

In the baseline scenario (VCS0), both farms produce three crops in addition to pasture: wheat, maize for silage, and one legume. However, the legume species is different according to the farm: while the French farm produces peas, the German farm produces faba beans. These legumes are present in the farms only to comply with the greening regulation and represent 5% of the arable land in both farms (Table 4). The introduction of VCS of 100€.ha^{-1} in the French and German farm increases the share of legumes in the arable land. However, the results of the sensitivity analysis suggest that the legume share of the German farm remains lower compared to the French Farm (Figure 2). The share of draws, where the German farm grows legumes only to comply with the greening regulation, is particularly high. This difference can also be observed through the median: in the French farm, the median of the legume share doubles to reach 10% of arable land, whereas the legume share in the German farm reaches 7% of arable land (Table 4). Legumes substitute mainly against wheat, while the acreage of maize remains quasi constant. Alfalfa is not yet produced with this level of VCS.

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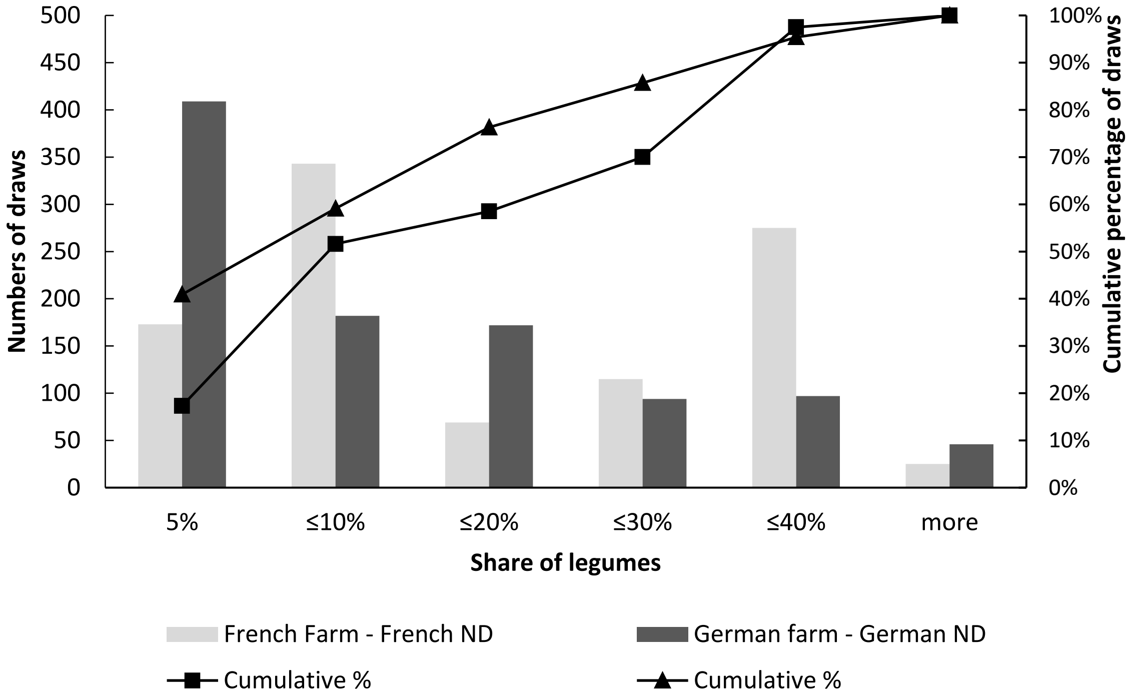
legumes (e.g., peas, faba beans), and dehydrated alfalfa. However, a minimum per hectare for possibility of fungibility is implemented. It guarantees that, if a part of the VCS budget for legumes is assigned to another farming sector (e;g., sheep), the VCS per hectare of legumes is minimum of 100€.ha-1 (DGPE/SDPAC/2018-20).

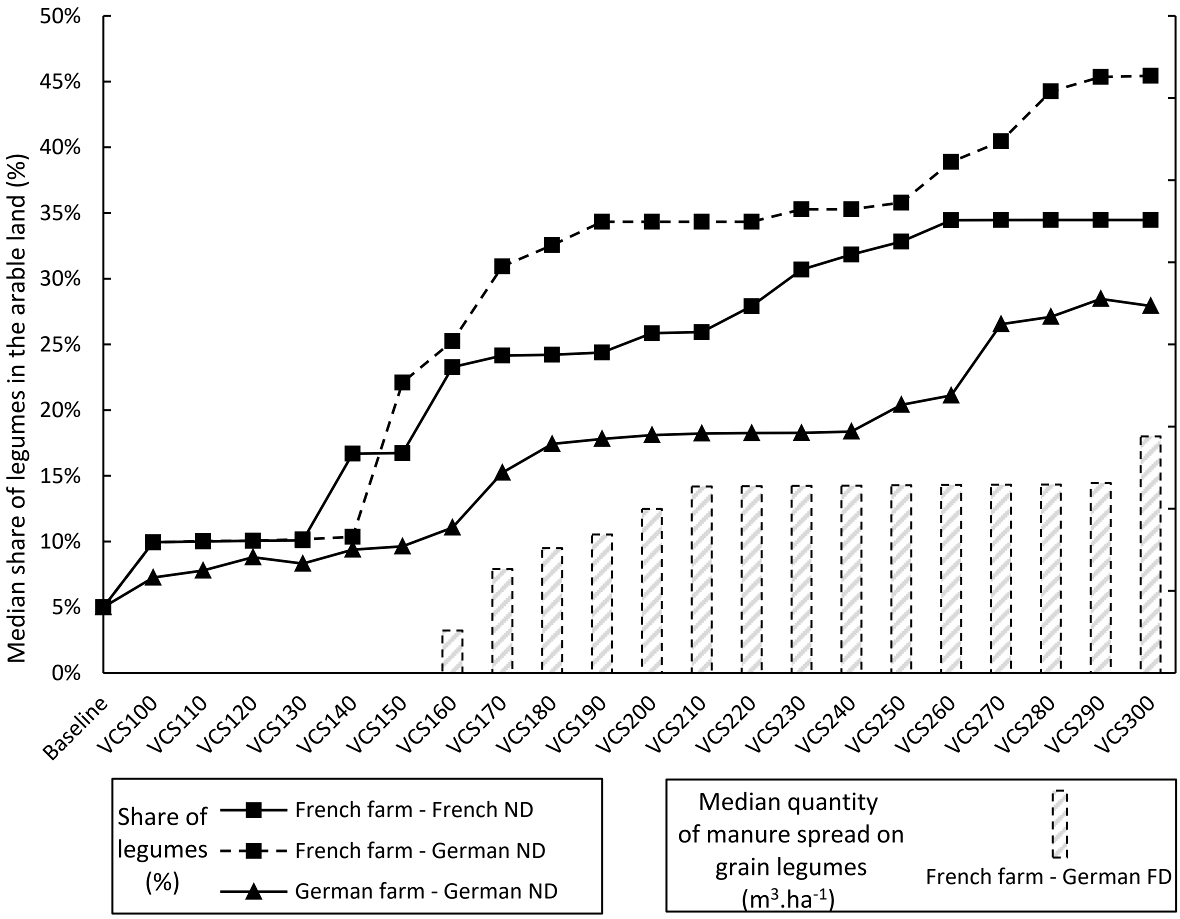
Figure 2: Distribution of share of legumes among the 1000 draws implemented in the sensitivity analysis, for the French farm and the German farm with VCS of 100€.ha^{-1}



When the VCS per hectare gradually increased from 100 €.ha^{-1} to 300 €.ha^{-1} (scenario VCS300), the legume share continues to increase (Figure 3). This increase is still more moderate in the German farm and, in the French farm, differences between the implementation of ND begin to appear after VCS130. Under the French ND, the legume share grows consistently from scenario VCS140 until the share reaches its maximum in VCS260 with 34% of arable land. Except of scenario VCS140, the legume share under the German ND is always significantly higher and reaches 45% of arable land in VCS300, which is 11 percentage points higher than under the French ND. This reflects that under the German ND, the increase in the legume share is not restricted by the need to keep spreadable areas, as it is possible to spread manure on grain legumes. Under the German ND, spreading of manure on grain legumes begins under VCS160 with 3m^3.ha^{-1} of manure, and reaches 14m^3.ha^{-1} in VCS300 (Figure 3). From VCS220 to VCS250, the gap of legume share is lowered between the ND: the share of alfalfa increases under the French ND, as spreading manure on alfalfa is allowed, even under the French ND. In all cases, the acreage of maize remains constant such that the share of wheat is reduced. In VCS140, the differences in the median of legume shares reflect different periods where manure spreading is allowed. Nevertheless, these differences are much more limited in their minimum and maximum values (see Table 4 for VCS150).

In the German farm, the legume share slowly increases to reach a maximum of 28% in VCS300 (Figure 3). As in the French farm, legumes (faba bean) substitute for wheat at quasi-constant maize production. The lower increase in the German farm is mainly due to the high prices and yields of wheat that increase the opportunity costs of legume in the German farm. It is interesting to notice that the median quantity of manure spread on legumes is equal to 0 in all scenarios (Table 4). Overall, the results suggest that VCS are an effective policy to foster substantially legume production, but to a lesser extend in Germany. These results are in line with findings of Helming et al. (2014) analyzing the effect of different policy measures aiming at fostering legume production in Europe. They found a maximum increase of +15% in legume area with subsidies from 210 €.ha^{-1} to 422€.ha^{-1} and thus concluded that besides other measures, subsidies on legumes are an effective tool to increase legume share. However, their study is limited in scope as the results are not detailed by type of farm. It is necessary to stress out that, in our study, the sensitivity analysis shows large ranges of legume shares in both farms. Thus, the effectiveness of the VCS still depends highly on the economic context. Besides, in the French farm under the German ND, the legume share reaches high level, with a median 45% (maximum at 63%) in scenario VCS300. Thereby, the share of grain legumes (38%) is above the recommended maximum share of legumes in the crop rotation (25%). However, such high shares do exist in organic systems in the EU (Pelzer et al., 2019).

Figure 3: Share of legumes and quantity of manure spread on grain legumes (medians), per farm and implementation of the Nitrates Directive (ND), under the Voluntary Coupled Support (VCS) scenarios for legumes



3.2 *Input use and economic indicators*

The increase in legume share decreases the use of inputs. On the one hand, the use of own-produced legumes in feed increases, which leads to a decrease in purchased feed, and thus a rise of the protein self-sufficiency (Figure 4). In the French farm, the protein self-sufficiency increases from 67% in the baseline scenario, to reach 71% in scenario VCS220, under both NDs. Then, up to VCS300, the German ND fosters an additional increase to 74% while it consistently remains at 71% under the French ND. This gap is mainly due to the upcoming production of alfalfa under the German ND that is mainly used for feed. The additional production of grain legumes is mainly sold under both ND and thus, does not promote a further increase in protein self-sufficiency. In the German farm, the increase in protein self-sufficiency is particularly high, with a baseline value lower than in the French farm: it increases from 60% in the baseline scenario, to 71% in VCS300. In both farms, most legumes are used as feed, and not sold to the market. This reveals a better profitability of legumes as intermediate goods (i.e., own-produced feed) than as final goods (i.e., cash crops). This is coherent with the results of Schläfke et al. (2014) who found a higher potential of legumes in dairying as on-farm feed than as cash crop. However, with increasing subsidies, the production of grain legumes exceeds the herd's needs and thus, grain legumes are sold as cash crops.

On the other hand, the application of synthetic N fertilizer decreases, resulting from the first increases in the legume share. In the baseline scenario, the application of the synthetic N fertilizer per hectare (i.e., urea and ammonium nitrate) is higher in the German farm (183kg.ha^{-1}) than in the French farm (125kg.ha^{-1}). With VCS of 100€.ha^{-1}, it decreases by 16% in the French farm, and by 7% in the German farm. The decline in the application of synthetic N fertilizer continues and even accelerates with higher shares of legumes. With VCS of 300€.ha^{-1}, it is reduced by 73% and 81% in the French farm, respectively under the French and German ND, and by 66% in the German farm, compared to the baseline scenario. Two factors explain these decreases. First, legumes provide N through the mineralization of their residues. Second, the overall N demand is lower as there is less wheat produced, this crop having high fertilization needs.

3.3 *Environmental and economic indicators*

This increase in the legume share, associated to a decrease in the use of inputs, lead to a slight improvement of environmental indicators in both farms (Figure 4). In the French farm, N leaching decreases differently between the two NDs, from its initial value at 36kgN.ha^{-1}. Under the French ND, N leaching decreases almost continuously to reach a maximal decrease of 16% in VCS300, whereas, under the German ND, it decreases only by 5%. This is due to the spreading of manure on grain legumes, leading to over fertilization and thus, additional N leaching. GWP also decreases with higher share of legumes. It decreases by 5% in VCS300 under the French ND but only by 2% with German ND. This lower decrease in GWP under the German ND is explained by two factors: higher input purchases and a higher production of alfalfa that causes emissions trough the dehydration process.

Regarding farm profit, it increases by 4% under both NDs. However, the share of VCS in the farm profit also rises, to reach respectively 5.7% and 7.4% under the French and the German ND in VCS300. Overall, the total VCS allocated under the German ND is higher than under the French ND (as the legume share is higher), whereas the decrease in GWP is lower. Thus, the reduction costs diverge widely. Under the French ND, the costs increase from 26€.tCO_2eq in VCS100 to 130€.tCO_2eq in VCS300, whereas, under the German ND, the costs increase from 190€. tCO_2eq in VCS100 and reach 1,040€.tCO_2eq in VCS300

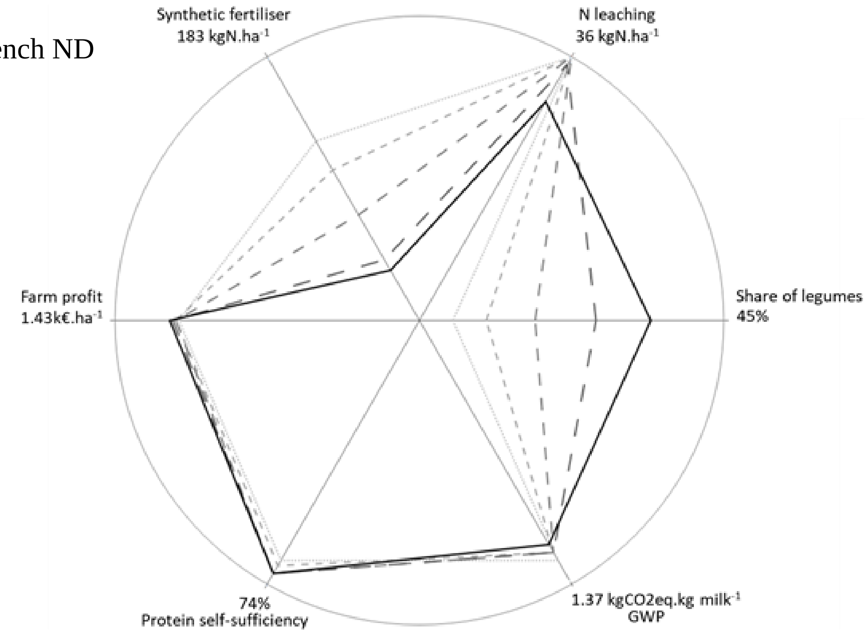
In the German farm, the improvement of environmental indicators is similar. Starting from a higher value than in the French farm (183kg.ha^{-1}), N leaching decreases by 5% between the baseline scenario and VCS300. GWP decreases by 7%, from 1.37 to 1.26 kgCO_2eq.kg milk[1]. The farm profit slightly increases by 3%, with a simultaneously rising share of VCS in the profit from 0.4% in VCS100 to 4.4% in VCS300. Thus, the decrease in GWP in the German farm is similar to the French farm under French ND, but with lower VCS expenditure. Accordingly, the reduction costs of GWP are lower in the German farm, starting at 12€. tCO_2eq in VCS100 and increase to 81€. tCO_2eq in VCS300.

With currently 27€.tCO_2eq, the price of European Emission Allowances is almost always lower than the reduction costs of the French farm (European Energy Exchange, 2019). In contrast, the costs of reduction of the German farm fall below the price of the European until VCS170.

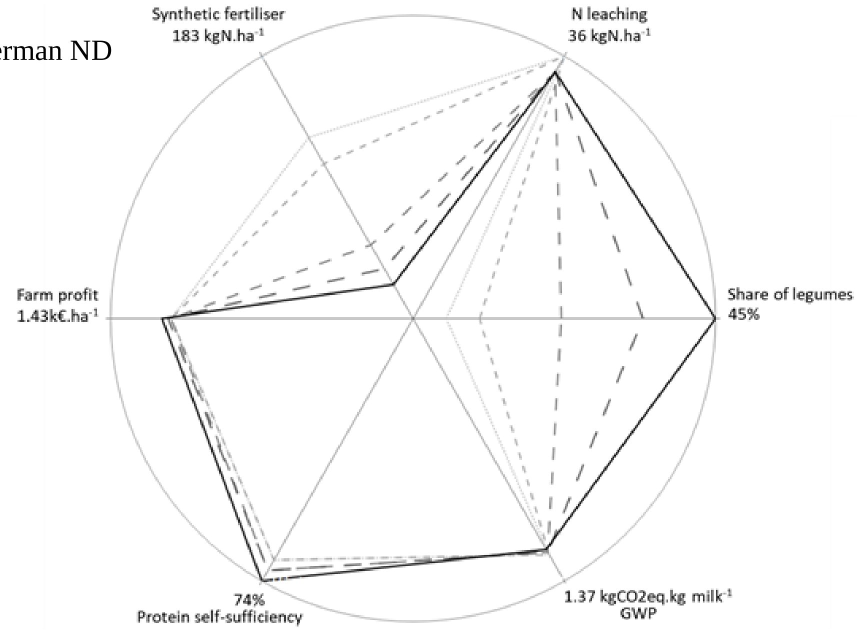
The increasing reduction costs reflects that the marginal environmental benefit of increasing VCS is limited: the main decrease in GWP takes place in the scenario VCS100. Indeed, as it is enteric fermentation and not inputs, or fertilization, that is the main source of GWP in the farms, the increase in the legume share has only limited impacts on this indicator. This is coherence with the study of Gaudino et al. (2018) in which the reduction in GHG was mainly achieved by herd reductions. Besides, the slight decreases in N leaching are coherent with the study of Nemecek et al. (2008), who focused on environmental impacts of legumes only in cropping systems. Similarly to the study of Dequiedt and Moran (2015), an in-depth economic analysis of the potential of legumes used as feed to mitigate climate change, and the cost associated will be necessary.

Figure 4: Integrated assessment of farms, across specific scenarios and Nitrates Directive (ND) implementation. Reference points of indicators are set by their maximum value observed in the study

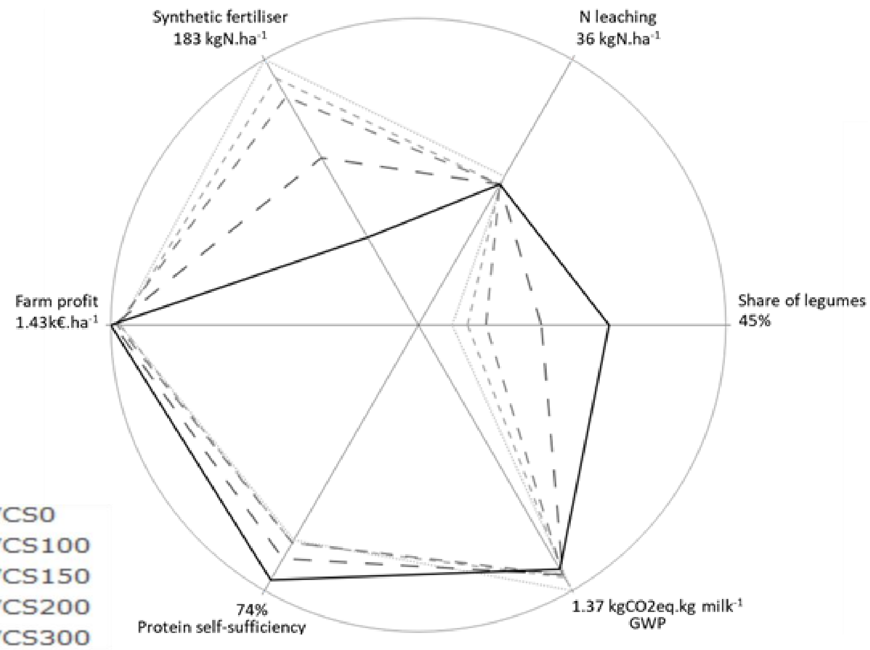
French farm – French ND

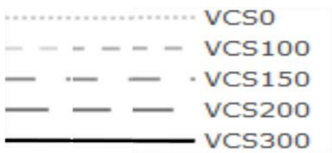


French farm – German ND



German farm





3.4 *Policy implications and future research*

This study is the first one assessing the interactions of two key policy measures affecting legume production in Europe: VCS for legumes and the national implementation of the ND. Thanks to the sensitivity analysis, different price contexts on five inputs or outputs are integrated. We found that VCS represent an effective tool to provoke a first increase in legume production. However, high VCS per hectare are needed to reach high share of legumes. Thus, we recommend a combination with other measures (e.g., taxation of N synthetic fertilizer) in order to foster legume production. Even though substantial reductions in input use are associated to high shares of legumes, linked with high VCS, improvements in the environmental indicators studied, N leaching and GWP, are rather limited. Thus, high VCS for legumes are not economically justified with regards to these indicators. However, other agronomic and environmental goals (e.g., pest management, biodiversity, protein self-sufficiency), could justify them. Besides, with lower VCS, the costs for first GWP reductions are rather limited, especially in the German farm, which is managed more intensively than the French farm. Compared to the price of the European Emission Allowance, VCS can thus be efficient tool.

Under certain conditions, the implementation of the German ND in the French farm leads to a further increase in the legume share: until + 7 percentage points. Even though this provokes a reduction in input use, it does not lead to an improvement of environmental indicators. However, the implementation of the German ND could be more relevant in farms facing higher stocking rates. In fact, allowing manure to be spread on legumes promotes further legume production, but only if manure spreading area becomes restricting. Thus, with higher stocking rates, the possibility of spreading manure on legumes could lead to the introduction of legumes in farms, and thus to first improvements of environmental indicators. Nevertheless, limits should thus be set regarding the maximum amounts of manure allowed on these crops in order to avoid a rise of N leaching.

The main limitation of the study is the restriction to two specific case studies at the farm scale. As the implementation of farms is based on various assumptions, results might differ with other farms types, in other regions, or under different price contexts. Nevertheless, the sensitivity analysis carried out makes it possible to integrate different price contexts on wheat as output, and on four inputs. Another solution would be to include multiple representative farms, which differ by their size and different mixes of resources, in order to aggregate the results at the regional scale (Weersink et al., 2002). However, working at the farm scale made it possible to study a poorly researched issue: the protein self-sufficiency. Indeed, producing legumes is one the main lever to decrease the purchases of protein-rich feed such as soybean meal. A will to increase feed self-sufficiency of farms is developing in the EU, linked with the market instability of imported protein-rich feed, and their impact on the environment (European Parliament, 2011). The recent fires in the Amazonia, and the concept of imported deforestation, have highlighted the negative impact of soybean production to feed livestock, which is the first driver of tropical deforestation (Pendrill et al., 2019). Another limitation of the study is that policy feedback is not considered: the total VCS budgets for each legume species are upper bounded at national level. This level must be consistent with the ceiling of all productions benefiting from VCS in each Member State, in order to remain in compliance with the World Trade Organization “blue box” criteria (Regulation No 1307/2013). Thus, VCS per hectare depends on the overall national production of each legume. This introduces an additional risk on legume opportunity costs that is not integrated in the model.

In this study, we focused on the interaction between VCS and the ND, but further policy field could be considered such as interactions between VCS and pesticide policies. Conventional legume production still mostly relies on pesticides, while certain regulations ban pesticides on these crops such as UE 2017/1155 that forbids pesticides on legumes used as EFA. That restriction – which might lead to lower yields and/or higher costs for mechanical plant protection measures – is not considered in our analysis. Besides, as shown in our case studies it is more profitable to use legumes as own-produced feed than to sell them on markets. More studies analyzing the profitability of legumes used as feed, and not only as cash crops should be developed. Also, farmers’ access to new techniques improving digestibility of legumes for livestock, such as toasting, should be strengthened. Beyond the farm level, it would be interesting to study crop-livestock integration through exchanges of legumes (i.e., crop farms selling legumes to livestock farms), or through the export of manure (i.e., livestock farm exporting manure to crop farms) (Moraine et al., 2016; Willems et al., 2016). Finally, we deliberately analyze high levels of VCS to explore implications of high legume shares not yet observed in conventional farms. Such legume shares make farm profit more dependent on subsidies, which is a questionable strategy at a time where high subsidies under the CAP are questioned. Alternatively, the profitability of legumes could be fostered by further development of dedicated agri-food chains. The emerging sector of GMO-free feed, using, among others, legumes produced in the EU, represents an interesting lever to increase legume production in dairy farms.

Table 4: Results of main indicators (median and range) used in the integrated assessment, for selected scenarios, per farm and implementation of the Nitrates Directive (ND)

	French farm - French ND					*French farm - German ND*					*German farm – German ND*				
	VCS0	*VCS100*	*VCS150*	*VCS200*	*VCS300*	*VCS0*	*VCS100*	*VCS150*	*VCS200*	*VCS300*	*VCS0*	*VCS100*	*VCS150*	*VCS200*	*VCS300*
Share of legumes	5% (5- 35)	10% (5- 46)	17% (5- 48)	26% (5-49)	34% (5- 59)	5% (5- 48)	10% (5- 49)	22% (5- 53)	34% (5- 58)	45% (5- 63)	5% (5- 44)	7% (5- 45)	10% (5- 59)	18% (5- 59)	28% (5- 62)
Grain legumes	5%	7%	15%	24%	32%	5%	6%	20%	33%	38%	5%	5%	8%	18%	26%
Protein self-sufficiency	67% (58- 86)	69% (58- 89)	71% (58- 91)	71% (58- 92)	71% (58- 92)	68% (58- 90)	68% (54- 92)	71% (58- 92)	71% (56- 92)	74% (59- 92)	60% (54- 88)	61% (49- 89)	61% (54- 90)	65% (49- 91)	71% (54- 92)
Manure on legumes (m3.ha of legumes-1)	0 (0- 10)	0 (0- 15)	0 (0- 15)	0 (0- 15)	11 [a] (0- 15)	0 (0- 19)	0 (0- 20)	0 (0- 21)	10 (0- 21)	14 (0- 21)	0 (0- 14)	0 (0- 14)	0 (0- 20)	0 (0- 20)	0 (0- 21)
Synthetic fertiliser (kg.ha-1)	125 (35- 131)	105 (23- 131)	74 (22- 131)	42 (21- 131)	34 (11- 131)	127 (22- 134)	108 (21- 136)	52 (17- 134)	34 (13- 136)	24 (8- 134)	183 (34- 185)	170 (29- 188)	157 (18- 185)	116 (17- 189)	61 (11- 184)
Farm Profit (k€.ha-1)	1.13 (1.05 - 1.25)	1.14 (1.07 - 1.27)	1.15 (1.09 - 1.25)	1.16 (1.10 - 1.26)	1.17 (1.13 - 1.26)	1.14 (1.05 - 1.27)	1.15 (1.08 - 1.29)	1.15 (1.09 - 1.27)	1.16 (1.11 - 1.27)	1.18 (1.14 - 1.27)	1.39 (1.25- 1.64)	1.39 (1.27- 1.61)	1.40 (1.29- 1.63)	1.41 (1.31- 1.62)	1.43 (1.34- 1.63)
Share of VCS in profit	0.0% (0- 0)	0.6% (0.3- 2.4)	1.4% (0.4- 3.7)	2.9% (0.6- 5.0)	5.7% (0.9- 9.1)	0.0% (0- 0)	0.6% (0.3- 2.5)	1.9% (0.4- 4.0)	3.8% (0.6- 5.8)	7.4% (0.8- 9.6)	0.0% (0- 0)	0.4% (0.3- 2.1)	0.8% (0.4- 4.1)	1.9% (0.6- 5.5)	4.4% (0.8- 8.5)
N leaching (kgN.ha-1)	36 (22-41)	36 (19-41)	36 (19-41)	35 (19-41)	30 (18-41)	36 (20-39)	36 (19-42)	34 (19-48)	34 (19-48)	34 (17-52)	20 (7-23)	19 (7-23)	19 (6-31)	19 (6-32)	19 (6-36)
GWP (kgCO2eq.kg milk-1)	1.25 (1.06 - 1.69)	1.21 (1.04 - 1.69)	1.21 (1.03 - 1.69)	1.20 (1.02 - 1.69)	1.16 (1.01- 1.65)	1.23 (1.05 - 1.70)	1.23 (1.04 - 1.81)	1.22 (1.03 - 1.70)	1.22 (1.02 - 1.77)	1.21 (1.02 - 1.68)	1.37 (1.06 - 1.68)	1.30 (1.05 - 1.70)	1.29 (1.04 - 1.71)	1.29 (1.04 - 1.69)	1.26 (1.02 - 1.71)

[a] Manure spread only on alfalfa; The minimum and maximum values are in brackets;

4 Conclusion

Despite their contribution to a more sustainable agriculture, legume production remains low in the EU. This study is the first assessing economic and environmental impacts of two key policy measures affecting legume production in the EU: VCS for legumes and the national implementations of the ND. It compares in detail a French and German dairy farm, taking into account legumes as own-produced feed and as cash crop. When VCS are implemented, the legume production increases, but in a more limited in the German farm than in the French one, due to higher opportunity costs of legumes. In both farms, the increase in legume production leads to limited decrease in N leaching and GWP. In the French farm, the implementation of the German ND leads to a further increase in the legume share, but only when manure spreading area becomes restricting. Thus, we show that allowing manure spreading on legumes can help increasing the production of legumes in dairy farms with high stocking rates. However, environmental indicators are not substantially improved as it can lead to an over fertilization of legumes, and thus, additional N leaching. Therefore, allowing manure spreading on legumes to increase their production should be justified by others goals such as improving the protein self-sufficiency of the farm.

Funding

This study is part of the LIFT ('Low-Input Farming and Territories – Integrating knowledge for improving ecosystem-based farming') project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 770747. It is also financed by the SOS-PROTEIN project (co-financed by two French regions, Brittany and the Pays de la Loire, and the European Agricultural Fund for Rural Development 2014–2020 (PEI 16.1))

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