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Article

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, which currently show low production levels in the European Union, can reduce negative environmental externalities of agricultural systems by lowering nitrogen (N) fertilization and increasing protein self-sufficiency. This has led to the introduction of coupled support in France, in contrast to Germany. However, the German implementation of the Nitrates Directive is more favorable for legumes. Our study assesses economic and environmental impacts of these two policies affecting legume production. We employ the bio-economic model FarmDyn, representing French and German dairy farms. The results suggest that relatively low levels of coupled support can lead to modest increases in legume production, but that more substantial changes require considerable subsidies. Allowing the French farm to apply manure on legumes, as is already possible in Germany, fosters legume production while considerably reducing the use of synthetic N fertilizer and imported protein-rich feed. However, environmental benefits are limited.

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

JEL codes: Q18, Q53, Q12, Q54

1 Introduction

Increased legume production can reduce multiple negative externalities of agricultural production (Drinkwater *et al.* 1998). First, legumes can substitute for protein-rich meals as feed, which are often derived from imported crops and associated with the loss of natural habitats (Sasu-Boakye *et al.* 2014). Second, as legumes can fix atmospheric nitrogen (N), they need no, or limited, N fertilization and may even supply N to the soil, reducing N fertilization needs of the subsequent crop (Peoples *et al.* 2009). Thus, legumes provide both a marketable production of protein-rich feed (and food) and a partially non-marketable ecosystem service by providing N for subsequent crops (Wossink and Swinton 2007). By decreasing directly and indirectly the use of synthetic N fertilizer, legumes can reduce greenhouse gas (GHG) emissions (Jensen *et al.* 2012). In addition to the fixation of N, legumes can provide further ecosystem services (Zander *et al.* 2016). They regulate pests by breaking the cycle of weeds and diseases, leading to reduced pesticide application (Nemecek *et al.* 2008; Angus *et al.* 2015). After decades of a declining trend in their production, legumes, including forage legumes and soybeans, covered on average less than 4 per cent of the utilized agricultural area (UAA) between 2012 and 2017 in the European Union (EU) (Eurostat 2018). This largely reflects lower profitability compared to other major crops such as wheat and rapeseed, although several studies show that their inclusion in rotations does not decrease profits (Preissel *et al.* 2015). In addition, their use as feed generally cannot compete with substitutes such as imported soybean meal (Häusling 2011). At the scale of the European agro-food chain, legumes also suffer from a lock-in situation that tends to favor cereal and non-legume oilseed crops (Magrini *et al.* 2016), while sales of legumes face high transaction costs (Jouan *et al.* 2019).

Since 2014, in light of their environmental advantages and low crop share, European member states can establish voluntary coupled support (VCS) for legumes under Pillar I of the Common Agricultural Policy (CAP). Further, the cultivation of legumes can be acknowledged as a contribution to the requirement of the ecological focus area (EFA) as part of 'Greening'. This helped to reverse the downward trend in legume production but heterogeneously across member states and regions, which mainly reflects differences in the implementation of the policy measures. For instance, both France and Germany count legume acreage with a factor of 1 for EFA, but only France introduced VCS[1] 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, reaching 3 per cent of UAA, but only increased by 35 per cent in Germany. Interestingly, the share of legumes in arable land in France is half as large in regions specialized in livestock production compared to regions specialized in arable crops (Eurostat 2018). This may be due to the French implementation of the Nitrates Directive (later called French ND) (91/676/CEE), which prohibits manure application on most legumes, discouraging their production on farms with high stocking densities (Caraes 2018). The German implementation of the Nitrates Directive (later called German ND) allows the application of manure on legumes as long as the mandatory N fertilization planning at farm scale is respected.

This study aims at assessing environmental and economic impacts of key policy measures affecting legume production in Europe: VCS for legumes and the national implementation of the ND. In particular, the interaction between these measures is addressed, since VCS aims at fostering legume production, whereas the ND can potentially constrain it by regulating N supply. We assess both the interaction and the effects of the policy measures by comparing in detail a French and a German representative case-study farm. Our first hypothesis is that VCS fosters legume production and protein self-sufficiency in both countries. Second, that implementing the German ND in France will lead to a further increase in legume production and protein self-sufficiency in France. Third, that these increases have positive environmental and economic implications at farm scale. We employ the bio-economic programming farm-scale model FarmDyn (Britz *et al.* 2014), to test these hypotheses and to quantify agronomic, economic, and environmental impacts.

So far, only a few studies have analyzed policies directly aimed at increasing legume production with farm-scale models (Helming *et al.* 2014; Cortignani *et al.* 2017). Studies using bio-economic models to analyze the ND and nitrate-related policies are more common

[1]The French VCS budget supports five species and usages of legumes (grain legumes, forage legumes, soybeans, 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 varies with the acreage of each legume. Thus, the VCS per hectare is usually different between grain 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 a minimum of 100 € ha^{-1} (DGPE/SDPAC/2018-20).

(Peerlings and Polman 2008; Belhouchette *et al.* 2011; Kuhn *et al.* 2019). Nevertheless, as far as we know, there is no analysis that jointly considers several policies affecting legume production as we here compare such as here the measures under the first pillar of the CAP and the implementation of the ND, thus providing an example of policy interaction (Nilsson *et al.* 2012). Besides, the impact of legume production has so far mainly been analyzed in arable cropping systems (Nemecek *et al.* 2008; Reckling *et al.* 2016), while fewer studies also consider their production on livestock farms for feed use (Gaudino *et al.* 2018; Jouan *et al.* 2020a). 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 are the main milk producers in the EU. Thus, our study addresses several gaps in the literature by (1) considering jointly multiple policies affecting legume production, (2) introducing legumes as cash crops and on-farm feed, highlighting the potential use of legumes to increase protein self-sufficiency, and (3) 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: Section 2 describes two analyzed case studies, provides an overview of the model FarmDyn, and details how data related to legume production and the ND are introduced. Section 3 presents the results. Section 4 discusses policy implications and limitations of our approach, before a summary of the main conclusions.

2 Method

2.1 Overview of the FarmDyn model

Mathematical programming models represent a valuable tool to analyze technical changes or the introduction of (new) crops as they describe in detail farm management and investment decisions (Jacquet *et al.* 2011; Britz *et al.* 2012). Bio-economic models quantify 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). At farm scale, bio-economic models have the advantage of simulating in detail the decision-making process of the farmer, considering technical as well as work-time or financial constraints. This explains their frequent use in European policy impact assessments (Reidsma *et al.* 2018).

FarmDyn is a highly detailed bio-economic farm-scale model, building on mixed integer linear programming. It provides a framework for the simulation of economically optimal farm-level plans and management decisions, as well as related material flows and environmental indicators.

FarmDyn was applied by Lengers et al. (2013, 2014) to analyze GHG abatement measures in German dairy farming, by Kuhn et al. (2019, 2020) to assess impacts of the German ND for multiple farm types at the level of a federal state, and by Schäfer et al. (2017) for the analysis of biogas production. Lengers et al. (2013, 2014) and Kuhn et al. (2019) combined large-scale sensitivity analysis with a meta-modeling approach, a methodology we follow here. FarmDyn maximizes the farm net present value under (1) the farms' production feasibility set, (2) working-time and (3) liquidity constraints, and (4) environmental and policy restrictions. By assuming a rational, fully informed, and risk-neutral farmer, the simulation results entail best-practice behavior. The extension of the linear programming with a mixed integer approach allows capturing indivisibilities, e.g. related to investments in stables and machines. The following section introduces elements of FarmDyn substantial for the underlying study; a complete documentation of FarmDyn is available online (Britz *et al.* 2019).

In our study, the comparative-static version of FarmDyn is used. The machinery pool used for the necessary field operation to grow legumes is already available, as it is also required to manage the observed benchmark crop rotation. Investment costs in buildings

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 (cows ha^{-1})	0.82	0.94
Breed	Holstein	Holstein
Milk yield (kg per cow per year)	8,600	8,800
Crops	Grassland, wheat, silage maize	Grassland, wheat, silage maize

and machinery are annualized and herd dynamics are depicted by a steady-state model (i.e. the number of cows replaced in the current year is equal to the number of heifers raised for replacement).

Main indicators relate to the total farm profit, protein self-sufficiency (i.e. the ratio between protein produced to feed the herd and total protein consumed by the herd), and different environmental outcomes. The global warming potential (GWP) of the farm is calculated from emissions of different GHGs and expressed by their GWP relative to carbon dioxide. We provide a life-cycle perspective by covering on-farm emissions, for instance, of enteric methane or from fertilization and manure storage, as well as emissions from intermediate input use, such as from diesel or bought feeds. Since the ND aims to protect water quality by preventing nitrates polluting water bodies, we include an indicator for nitrogen leaching (later called N leaching). It calculates a probabilistic value for N leaching by considering different sources of N following the model SALCA-NO_3 (Richner *et al.* 2014).

2.2 Case studies and data implemented

We analyze as case studies one French and one German intensively managed dairy farm located in Pays de la Loire (PDL) in France and North Rhine-Westphalia (NRW) in Germany (Table 1). Intensive dairy farms were chosen as they combine salient features for the analysis: high quantities of manure produced per ha of land, such that restrictions on manure management from the 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. 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 found in the PDL region (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 this source, related data are 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 data (mean 2013–7) (IFIP 2017; French Ministry of Agriculture 2018; AMI 2019; IT.NRW 2019; KTBL 2019). With a lower share of grassland and a higher stocking density, as well as higher crop and milk yields, the German farm is overall managed more intensively than the French farm (Table 1).

In FarmDyn, 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. On the

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 mineralization of residues (kg N ha^{-1})	France	25	30	20
	Germany	20	10	10

German farm, the yield of wheat is adjusted within a 5 per cent tolerance level. The dairy herd is kept fixed at benchmark levels in the analysis.

2.3 Introduction of legumes-related data

Three legumes are implemented to the FarmDyn model: peas, faba beans, and alfalfa (Table 2). Data on yields and on input and output prices for legumes and other crops are extracted from public statistics and professional agricultural press (IFIP 2017; French Ministry of Agriculture 2018; AMI 2019; IT.NRW 2019; KTBL 2019). German input prices for three legumes and concentrated feed are calculated by taking the buying prices for wheat and soybean meal as a basis to determine their value as animal feed, following the method available at DLR Westerwald Osteifel (2011). Peas and faba beans can be either used as feed or sold as cash crops, while alfalfa can only be used as feed. In the French region, a cooperative harvests and dehydrates alfalfa for its members (Leterme *et al.* 2019). It is assumed that this service could become available in Germany as well (Kamm *et al.* 2016). CO_2eq emissions from the dehydration are considered in the model (Corson and Avadí 2016).

One of the main advantages of legumes is their positive effect on subsequent crops. Their ability to fix nitrogen and the mineralization of their residues provide N available to subsequent crops. Thus, for a crop *c*, the per hectare N requirements $Nneed_c$ are covered by four sources[2]: N from previous year legume residues $Nleg_c$, N from manure $Nmanure_c$ and synthetic fertilizers $Nsynt_c$, and N from fixation of legumes $Nfix_c$ covering the N requirements of the respective legume and being zero for other crops:

$$Nneed_c \leq \ Nmanure_c + Nsynt_c + Nleg_c + Nfix_c. \quad (1)$$

The nitrogen need considers unavoidable losses that occur during the application of synthetic N fertilizer. For manure, further N losses arising during storage and application are considered, respecting details of the application technique, the manure type, and the storage facility (Haenel *et al.* 2018). N requirements in FarmDyn are specified for each crop and not for the overall crop rotation, and fertilization activities are depicted with a monthly resolution to reflect environmental and economic impacts, such as seasonal leaching and emissions, labor requirements, and manure storage capacity. The amount of N mineralized from legume residues on one hectare *NcarryOver* depends on the legume *leg* and varies with regional conditions, such as climate and soil. In this study, parameters relating to N from mineralization of residues are based on legal texts (COMIFER 2011; BMEL 2017).

Since FarmDyn is used as a comparative-static model without considering multiple plots, it is not known which crop follows after a specific legume. Therefore, a pool of N *NLegPool*

[2]In order to avoid quadratic terms in FarmDyn, the indicated variables relate to the total hectares of the crops in the model.

Table 3. Main measures under the ND implemented in France and Germany.

	France	Germany
Threshold of organic N application	170 kg N ha^{-1}	170 kg N ha^{-1}
Surplus of nutrient balance authorized at the farm gate	No regulation	50 kg N ha^{-1}
Threshold of organic N application on legumes	Alfalfa: 200 kg N ha^{-1} Grain legumes: 0 kg N ha^{-1}	No regulation
Fixed blocking periods of N application	Crop planted in autumn: 15 November–15 January Crop planted in spring: 01 July–15 January Pasture and alfalfa: 15 December–15 January Rapeseed: 01 November–15 January	Grassland: 01 November–31 January Arable land: 01 October–31 November
Minimum manure storage capacity	4–6.5 months	LSU^{f} ha^{-1} < 3: 6 months LSU ha^{-1} > 3: 9 months

is calculated at farm scale by summing the given per hectare $NcarryOver_{leg}$ multiplied with the area X of each legume *leg*:

$$NLegPool = \sum_{leg} X_{leg} * NcarryOver_{leg}. \quad (2)$$

This total N-pool *NLegPool* is distributed to the different crop areas X (Eq. 3). To avoid implausible distributions to individual crops, on each hectare, their uptake of N mineralized legume residues $Nleg_c$ cannot exceed the maximum per hectare mineralization *NcarryOver* of any legume (Eq. 4).

$$\sum_{c} X_c * Nleg_c = NlegPool, \quad (3)$$

$$\text{with } Nleg_c < \max_{leg} NcarryOver. \quad (4)$$

The mineralization of legume residues adds another source of N that is integrated in the calculation of N leaching according to the model SALCA-NO_3 (Richner *et al.* 2014). The N response from different fertilizers can vary subject to their composition and the N compound. Among other factors, the nitrogen release time and N losses that occur during application or through leaching vary with the type of fertilizer. FarmDyn accounts for differences in the fertilizers in the calculation of N losses, for example by considering emissions from different N compounds, considering among other factors the month and technique of application, pasture grazing, and difference in manure storage facilities and storage times. However, differences in the nitrogen release time of different N compounds on the crop are not considered.

2.4 Differentiated implementation of the ND 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 into FarmDyn the key aspects of the French and the German ND implemented in our case study regions (BMEL 2017; DREAL Pays de la Loire 2018) (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, spreading manure on grain legumes (e.g. peas, faba beans) is forbidden, while it is allowed on forage legumes (e.g. alfalfa). In Germany, there is no threshold on the application of manure on legumes as long as the surplus of the nutrient balance at the farm gate does not exceed 50 kg N 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 170 kg N ha^{-1} on farm level.

2.5 Sensitivity analysis

The effectiveness of implementing VCS for legumes and spreading manure on these crops is assessed based on a sensitivity analysis that considers different price levels. It covers the selling price of wheat and the buying prices of soybean meal and of three concentrated feeds as the main substitutes for legumes (Charrier *et al.* 2013). We distinguish three concentrates according to their raw protein content (12, 15, and 40 per cent). First, observed minimal and maximal prices (between 1995 and 2017) after adjusting for trends are derived from official statistics (Eurostat 2019), and related to the average price over the period. The resulting minimal and maximal fluctuations are applied to the initial average prices (DLR Westerwald Osteifel 2011; IDELE 2016; IFIP 2017; KTBL 2019), giving price ranges for each input (Table A1 in the Supplementary Material). Subsequently, adopting a similar approach to Kuhn et al. (2019) and Lengers et al. (2014), Latin hypercube sampling (LHS) is used to generate a representative price sample. For each tested policy scenario (see Section 2.6), 1,000 price samples are randomly drawn out of the calculated price ranges, assuming a uniform distribution. LHS divides the probability distribution ranges of each good into 1,000 intervals, ensuring an equal probability of each interval to depict closely the probability distribution. From each interval, one price sample is randomly selected and combined to price samples from the other goods (McKay *et al.* 2000). The specific LHS variant applied considers the correlation between the prices from the observed price series (Eurostat 2019) (Table A2 in the Supplementary Material).

For each price sample, FarmDyn simulates the optimal farm-level plan by maximizing the net present value. The sampled results are used in a descriptive statistical analysis to determine the performance of key indicators under the considered price ranges.

2.6 Scenarios

We define a baseline scenario (VCS0) with no VCS for legumes and the national implementation of the ND on each 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 legumes 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 implemented the minimum level established in France: 100 € ha^{-1} for peas, faba beans, and alfalfa. In the second scenario (VCS100ge), the German ND is additionally introduced on the French farm. Lastly, we define a set of scenarios where the VCS per hectare is increased on both farms in increments of 10 per cent, starting from 110 to 300 € ha^{-1} (VCS110 to VCS300), under the French or the German ND on the French farm, and the German ND on the German farm. The highest level does not yet reach the coupled support under the MacSharry reform with, for instance, 73 € ha^{-1} for peas and faba beans (Bues *et al.* 2013). While it is unlikely to return to such levels of VCS, the resulting large shares of legumes, not yet observed on dairy farms, provide original information, particularly on their environmental impacts in intensive dairy systems.

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: peas on the French farm and faba beans on the German farm. These legumes are present on the farms only to comply with the EFA requirement and represent 5 per cent of the arable land on both farms (Table 4). The introduction of VCS of 100 € ha^{-1} on the French and German farms 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 (Fig. 1). The share of 1,000 draws, in which the German farm grows legumes only to comply with the greening regulation, is particularly high. This difference can also be observed in the median. While the median legume share doubles to reach 10 per cent of arable land in France, it increases only to 7 per cent on the German farm (Table 4). Legumes substitute mainly against wheat, while the acreage of maize remains quasi-constant, since it is the main source of fodder for the dairy herd. Alfalfa is not yet produced with this level of VCS.

When the VCS per hectare gradually increases from 100 to 300 € ha^{-1}, the legume share continues to increase (Fig. 2). On the French farm, first differences between the implementation of ND become apparent after VCS130. Under the French ND, the legume share grows consistently until it reaches its maximum of 34 per cent of arable land in VCS260: at this stage, the need to distribute all the manure prevents further increases of grain legumes on which manure application is prohibited. Alfalfa, on which manure application is allowed, has reached at this stage a production level where further substitution for protein-rich concentrates is no longer viable. Accordingly, under the German ND where manure can be distributed also to grain legumes, the overall legume share is higher and reaches 45 per cent of arable land in VCS300. Under the German ND, spreading of manure on grain legumes begins under VCS160 with 3 m^3 ha^{-1} of manure and reaches 14 m^3 ha^{-1} in VCS300 (Fig. 2). From VCS220 to VCS250, the differences in legume shares between the ND are limited. At these levels of VCS, alfalfa becomes competitive and is introduced in increasing levels in the crop rotation. In contrast to grain legumes, the application of manure on alfalfa is also permitted under the French ND, which explains the limited differences in simulated crop shares. The increase in the legume share is always associated with a decline in the share of wheat, such that the acreage of maize remains constant. In VCS140, the median legume share under the French ND exceeds the median share under the German ND. Here, the difference is caused by different periods in which the spreading of manure is allowed.

On the German farm, the legume share slowly increases to reach a maximum of 28 per cent in VCS300 (Fig. 2). As on the French farm, grain legumes (faba bean) substitute for wheat at quasi-constant maize production. The lower increase on the German farm is mainly due to the high prices and yields of wheat, which increase the opportunity costs of legumes. It is interesting to notice that the median quantity of manure spread on legumes on the German farm is equal to zero in all scenarios (Table 4).

Overall, the results suggest that VCS can effectively foster legume production in dairy farms, but that differences in crop productivity or livestock intensity matter, as seen from the lower response in Germany. These results are in line with findings of Helming et al. (2014) analyzing the effect of different policy measures that aim at increasing legume production in the EU. They found a maximum increase of 15 per cent in legume areas with subsidies from 210 to 422 € ha^{-1} and thus concluded that among other measures subsidies on legumes are an effective tool to increase legume share. However, their study is limited in scope since the results are not detailed by type of farm. It is necessary to stress out that, in our study, the sensitivity analysis shows large differences in legume shares on both farms at the same VCS level. Thus, the effectiveness of the VCS highly depends on the economic context. Besides, on the French farm under the German ND, the share of grain legumes reaches 38 per cent in scenario VCS300, which is above the often recommended maximum share of legumes in

Table 4. Results of main indicators (median and range) used in the integrated assessment, for selected scenarios, per farm and implementation of the 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 ($m^3\ ha^{-1}$ legumes)	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 fertilizer ($kg\ ha^{-1}$)	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 (kg N 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 (kg CO_2eq kg^{-1} milk)	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)

Note: The minimum and maximum values are in parentheses.
[a]Manure spread only on alfalfa.

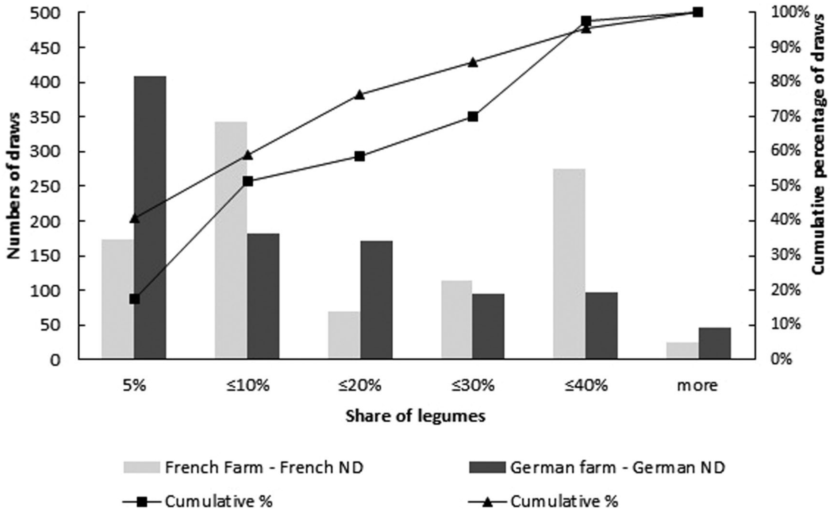

Figure 1. Distribution of share of legumes among the 1,000 draws implemented in the sensitivity analysis, for the French farm and the German farm with VCS of 100 € ha^{-1}.

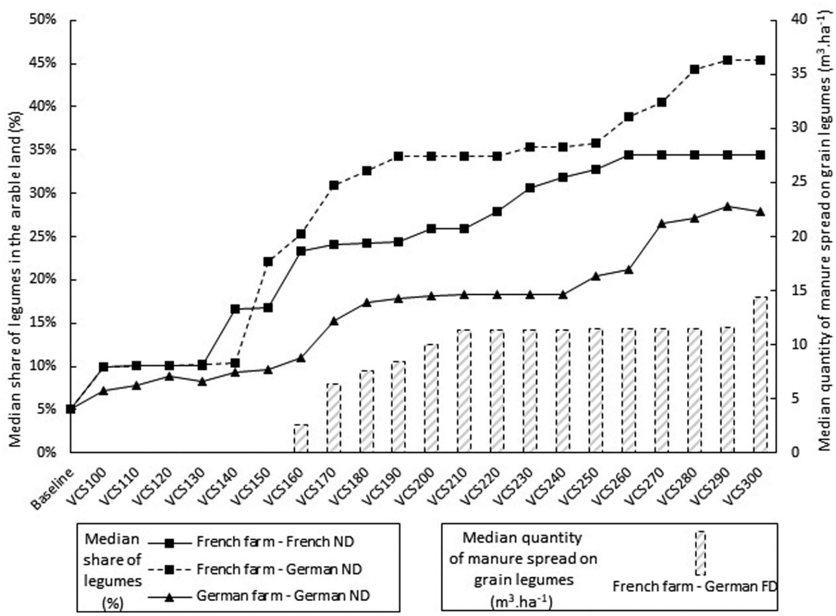

Figure 2. Share of legumes and quantity of manure spread on grain legumes (medians), per farm and implementation of the ND, under the VCS scenarios for legumes.

the crop rotation (25 per cent). However, such high shares do exist in organic systems in the EU (Pelzer *et al.* 2019).

3.2 Input use and protein self-sufficiency

The increase in legume production decreases the use of two major inputs. First, legumes produced on the farm substitute purchased feed and thus increase the farm's protein self-sufficiency (Fig. 3). On the French farm, the protein self-sufficiency increases from 67 per cent in the baseline scenario to 71 per cent in scenario VCS220, under both NDs. Then, up to VCS300, the German ND fosters an additional increase to 74 per cent, while it consistently remains at 71 per cent under the French ND. This gap is mainly due to the additional production of alfalfa under the German ND. On the German farm, the increase in protein self-sufficiency is particularly high, with a baseline value lower than that on the French farm: it increases from 60 per cent in the baseline scenario to 71 per cent in VCS300. On both farms, most legumes are used as feed and are 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 consistent 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, on the French farm (under both NDs) and on the German farm, the production of grain legumes exceeds the herd's needs; thus, grain legumes are sold as cash crops. Although it does not contribute to a further increase in protein self-sufficiency at farm level, it can nevertheless promote protein self-sufficiency at higher such as national scale.

The second input-saving effect is related to synthetic N fertilizer. Under VCS300, its use is reduced by 73 and 81 per cent on the French farm, respectively, under the French and the German ND, and by 66 per cent on the German farm compared to the baseline scenario. This reflects, first, that legumes provide N by mineralizing their residues. Second, the overall demand for N is lower as less wheat is produced, a crop with high N need and requiring higher use of mineral nitrogen, especially compared to maize. However, differences in nitrogen release times between the sources were not considered because FarmDyn does not incorporate sufficient details on relevant soil–plant–atmosphere interactions. To overcome this limitation, a linkage model between FarmDyn and a detailed crop model such as done recently by Kuhn et al. (2020) would be a valuable option.

3.2 Environmental and economic indicators

The increase in the legume share leads to a slight improvement in environmental indicators on both farms (Fig. 3), which partly reflects the associated decrease in input use. On the French farm, reductions in N leaching differ between the two NDs. Under the French ND, N leaching decreases almost continuously to reach a maximal decrease of 16 per cent in VCS300, whereas under the German ND it decreases only by 5 per cent. This gap is due to the spreading of manure on grain legumes, provoking their overfertilization and thus additional N leaching.

The GWP decreases by 5 per cent in VCS300 under the French ND and by 2 per cent with the German ND. The lower decrease under the German ND reflects two factors: higher input purchases and a higher production of alfalfa that causes emissions through the dehydration process. The profit of the French farm slightly increases by 4 per cent, with a simultaneous rising revenue from VCS under both NDs. However, the total VCS allocated under the German ND is higher than that under the French ND (as the legume share is higher). Since the simultaneous decrease in GWP is lower, the GWP abatement costs diverge widely between the NDs: under the French ND, they reach 26 € t^{-1} CO_2eq in VCS100 and 130 € t^{-1} CO_2eq in VCS300, while under the German ND, they reach 190 € t^{-1} CO_2eq in VCS100 and 1,040 € t^{-1} CO_2eq in VCS300.

On the German farm, the improvement in environmental indicators is similar. N leaching decreases by 5 per cent under VCS300 and GWP by 7 per cent, while the farm profit slightly increases by 3 per cent. Even if the decrease in GWP on the German farm is similar to the decrease on the French farm under the French ND, abatement costs are far lower, reaching a maximum of 81 € t^{-1} CO_2eq in VCS300 but only 12 € t^{-1} CO_2eq in VCS100. At this stage, the abatement costs on the German farm are lower than the prices of European Emission

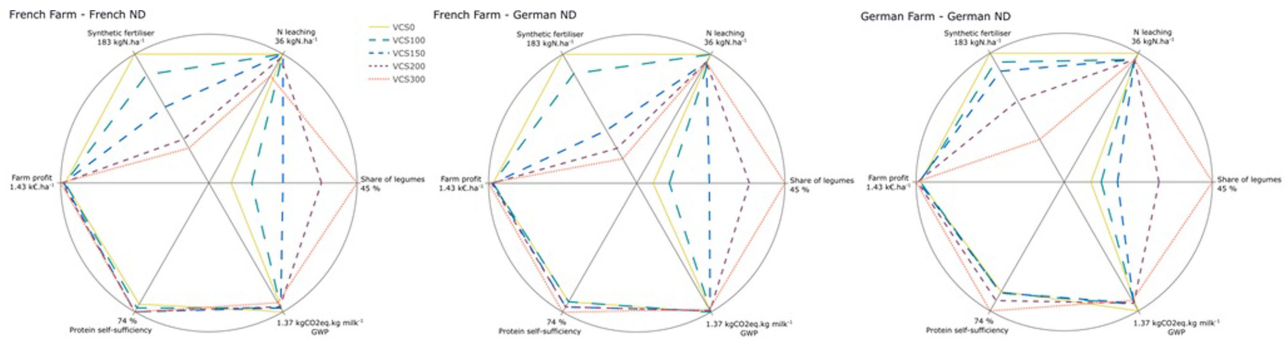

Figure 3. Integrated assessment of farms, across specific scenarios and ND implementation. The chart compares economic and environmental indicators across different levels of VCS for each farm and implementation of the ND. For each indicator, the upper boundary is defined by the maximum value observed in the study, across all case studies and scenarios. The minimum value is set zero for all indicators.

Allowances (observed spot prices in 2019 range between 18 and 30 € t^{-1} CO_2eq) (European Commission 2020).

On both dairy farms, methane from enteric fermentation is the main source of GWP. This explains why increasing the legume share has only a limited impact on this indicator. Similarly, Gaudino et al. (2018) find that reduction in GHGs can be mainly achieved by herd reductions. The slight decreases in N are coherent with the findings of Nemecek et al. (2008), who focused on environmental impacts of legumes in cropping systems only.

3.3 Policy implications and future research

This study is the first one that assesses the interactions of two key policy measures affecting legume production in Europe: VCS for legumes and the national implementation of the ND. In particular, it addresses the issue of interacting policy measures that, on the one hand, aim to promote legume production and, on the other hand, potentially constrain their production by regulating N supply. To do so, we employ the bio-economic model FarmDyn, integrating economic and environmental dimensions of two dairy farms. Based on a sensitivity analysis, the effectiveness of the policy measures is assessed regarding different price levels of five inputs or outputs. We found that relatively low VCS of 100 € ha^{-1} represents an effective tool to provoke a first increase in legume production. Although further research is needed to get a wider picture of the impact of such coupled support, this finding is in line with the recent study of Cortignani and Dono (2020) who investigate levers to develop rotation with legumes as part of the next CAP. However, medium to high VCS must be implemented to reach the shares of legumes targeted in the study of Cortignani and Dono (2020), which raises questions in terms of economic efficiency of VCS. Thus, we recommend a combination with other measures that lower the opportunity costs of legumes in order to foster their production. In particular, implementing a tax on N synthetic fertilizer to internalize their negative externalities might be an interesting option to promote legume production on farms (Henseler *et al.* 2020).

Our study shows that large legume shares induced by high VCS do not lead to substantial environmental benefits in the analyzed dairy farms. This provides a complementary picture to most other studies that focus on legumes on arable farms. Our findings suggest that the impacts of crop diversification on environmental sustainability of livestock farms are limited. However, the inclusion of other indicators, in particular indicators oriented toward biodiversity, might revise this conclusion. The limited impacts reflect that a large part of the externalities analyzed in this study are related to the herd itself: N leaching and emissions from manure handling and enteric fermentation represent the main source of climate-relevant emissions. This suggests more ambitious agro-environmental measures that directly target animal production, such as stricter regulations in terms of livestock density or manure handling. Similarly, other current policies, such as Greening, also seem to reach limited results in terms of improved environmental status (Gocht *et al.* 2017). In these views, the Green Deal may represent a unique opportunity to improve the sustainability of this essential economic sector (Peyraud and MacLeod 2020).

Depending on the level of support and input prices, allowing manure spreading on grain legumes on the French farm, as possible under the German ND, can increase the legume share by up to 7 percentage points. However, it does not lead to substantial improvements of environmental indicators. Thus, this policy change can be justified only by other goals such as improving protein self-sufficiency. Allowing manure application to grain legumes could be more relevant on farms facing higher livestock densities where the manure spreading area is a factor restricting even limited legume shares. Nevertheless, restrictions should be set regarding the maximum amounts of manure allowed on these crops in order to avoid a rise of N leaching. Indeed, a substantial decrease in N leaching requires a new regulatory paradigm: fertilization practices should be adapted to meet the real needs of crops through in-depth monitoring, now possible thanks to the development of big data and new types of sensors (Martins *et al.* 2020).

Even if the improvement in environmental indicators is limited, we still observed considerable decreases in N-rich input uses. High levels of VCS combined with the possibility of spreading manure on grain legumes lead to a considerable decrease in the use of synthetic N fertilizers and soybean meal. Notably, reduced imports of soybean and its meal are on the European political agenda in the context of so-called imported deforestation (European Parliament 2011; Pendrill *et al.* 2019). However, existing World Trade Organization regulation makes it impossible to directly limit imports of soybean. Initiatives from private stakeholders might instead encourage farmers to grow legumes. For example, the development of certified GMO-free milk, produced from animals fed with legumes produced locally, represents an interesting lever to increase the profitability of legumes as feed, while improving the protein self-sufficiency of farms (Jouan *et al.* 2020b). However, this innovation must be supported by policies to ease processing of legumes at farm level, such as investments in specific storage and improved sorting (Meynard *et al.* 2018).

Our study concerns two representative case studies in prominent dairy production areas and gives first insights into the interactions of two key policy measures affecting legume production in Europe. Clearly, a larger sample of farms of different types and from different regions is needed to generalize our findings. However, the strength of our analysis lies in the nature of the sensitivity analysis carried out. It considers the market environment of main substitutes of legumes at farm level: wheat as output, and soybean meal and concentrates as inputs. In addition, it would also be possible to carry out a sensitivity analysis on the yields of legumes, which vary more than those of other crops (Cernay *et al.* 2015). Such an analysis could also consider that a decline of pollinators might reduce legume yields (Biesmeijer *et al.* 2006; Garratt *et al.* 2014). Further research could also include pollinator supporting activities in the assessment, such as floral strips (Häussler *et al.* 2017). Indeed, such landscape infrastructures are already promoted by the 'Greening' as EFA but they could benefit from stricter regulation to increase their implementation (Pe'er *et al.* 2017).

In this study, we focused on the interaction between VCS and the ND. Further policy fields 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 the UE 2017/1155 that prohibits pesticides on legumes used as EFA. This restriction—which might lead to lower yields and/or higher costs for mechanical plant protection measures—is not considered in our analysis, but is mainly irrelevant as the 5 per cent legume level linked to fulfilling the EFA requirement is already found in the benchmark. In addition, our case studies suggest that 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. 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; Jouan *et al.* 2020a). However, when working at regional or even higher scale, policy feedback should be included as the total VCS budgets for each legume species are upper bounded at national level. Indeed, this bound is necessary to remain in compliance with the World Trade Organization 'blue box' criteria (Regulation No. 1307/2013).

Finally, we deliberately analyzed 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 doubtful strategy at a time where high subsidies under the CAP are questioned. Indeed, a considerable increase in the production of legumes on livestock farms requires implementing a set of measures that combine regulatory constraints, coupled support, and investment aid to sectors promoting these crops such as the emerging sector of GMO-free feed.

4 Conclusion

Despite their contribution to a more sustainable agriculture, legume production remains low in the EU. This study assesses 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 a German representative dairy farm, taking into account legumes as own-produced feed and as cash crops. When VCS is implemented, the legume production increases, but to a more limited extent on the German than on the French farm, due to higher opportunity costs of legumes in Germany. On both farms, the increase in legume production leads to limited decrease in N leaching and GWP. On the French farm, the implementation of the German ND associated with high VCS leads to a further increase in the legume share. Thus, allowing manure spreading on grain legumes, as allowed by the German ND, can help to increase production of legumes in dairy farms with high livestock densities. However, it hardly reduces N leaching in our case studies as manure applications exceed the nitrogen needs of legumes. Due to the dominance of methane emissions from enteric fermentation in dairy farms, we observe a limited impact on GHG emissions. Allowing manure spreading on grain legumes to increase their crop share can still be justified by other goals, such as decreasing the imports of soybean for feed. Overall, to considerably increase the production of legumes on livestock farms, it is essential to implement a set of measures that combine regulatory constraints, production subsidies, and investment aid to other sectors promoting these crops such as the emerging sector of GMO-free feed.

Supplementary data

Supplementary data are available at *QOPEN* online.

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Data availability

The model FarmDyn is available at http://www.ilr.uni-bonn.de/em/rsrch/farmdyn/FarmDynDoku/index.html. More information on the version of the model used and on the results files are available from the corresponding author on reasonable request.

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Appendix A. Supplementary material

Appendix A1. Price data used in the sensitivity analysis

Table A.1. Price ranges and average price used in the sensitivity analysis

		Germany			France		
Price	Good	Min	Mean	Max	Min	Mean	Max
Output	Winter wheat	117 €	165 € (1)	230 €	113 €	162 € (3)	216 €
Input	Soybean meal	333 €	429 € (1)	552 €	314 €	393 € (4)	497 €
Input	Concentrate 12% RP	155 €	193 € (2)	234 €	154 €	180 € (5)	211 €
Input	Concentrate 18% RP	184 €	229 € (2)	277 €	212 €	248 € (5)	290 €
Input	Concentrate 40% RP	311 €	387 € (2)	468 €	332 €	389 € (5)	455 €

Note: (1) KTBL (2019); (2) DLR Westerwald Osteifel (2011); (3) French Ministry of Agriculture (2018); (4) IFIP (2017); (5) IDELE (2016). RP refers to the row protein content of the concentrates.

Appendix A2. Correlation matrix

Table A.2. Correlation between the prices of the goods, as considered in the Latin Hypercube sampling

	Soybean meal	Concentrates
Winter wheat	0.65	0.8
Soybean meal		0.9
Concentrates		0.95

Note: Price correlations of winter wheat, soybean meal and the three concentrates are the same for Germany and France. Source: Own calculation based on Eurostat (2019).