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RESEARCH ARTICLE

Transition to legume-supported farming in Europe through redesigning cropping systems

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Abstract

Legume-supported cropping systems affect environmental, production, and economic impacts. In Europe, legume production is still marginal with grain legumes covering less than 3% of arable land. A transition towards legume-supported systems could contribute to a higher level of protein self-sufficiency and lower environmental impacts of agriculture. Suitable approaches for designing legume-supported cropping systems are required that go beyond the production of prescriptive solutions. We applied the DEED framework with scientists and advisors in 17 study areas in nine European countries, enabling us to describe, explain, explore, and redesign cropping systems. The results of 31 rotation comparisons showed that legume integration decreased N fertilizer use and nitrous oxide emissions (N_2O) in more than 90% of the comparisons with reductions ranging from 6 to 142 kg N ha^{-1} and from 1 to 6 kg N_2O ha^{-1}, respectively. In over 75% of the 24 arable cropping system comparisons, rotations with legumes had lower nitrate leaching and higher protein yield per hectare. The assessment of above-ground biodiversity showed no considerable difference between crop rotations with and without legumes in most comparisons. Energy yields were lower in legume-supported systems in more than 90% of all comparisons. Feasibility and adaptation needs of legume systems were discussed in joint workshops and economic criteria were highlighted as particularly important, reflecting findings from the rotation comparisons in which 63% of the arable systems with legumes had lower standard gross margins. The DEED framework enabled us to keep close contact with the engaged research-farmer networks. Here, we demonstrate that redesigning legume-supported cropping systems through a process of close stakeholder interactions provides benefits compared to traditional methods and that a large-scale application in diverse study areas is feasible and needed to support the transition to legume-supported farming in Europe.

Keywords DEED · Environment · Economics · Multi-criteria assessment · Crop rotation · Participation

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1 Introduction

European agriculture with its strong focus on cereal production and an increasing trend for specialization is confronted with a number of agronomic and environmental issues (Zander et al. 2016). Legume crops contribute essential ecosystem services which is why their (re-)integration into cropping systems has been seen to address some of the challenges related to crop specialization (Watson et al. 2017). While the interest in a transition towards more legume-supported systems has risen (Mawois et al. 2019), agronomic and economic constraints with legume production need to be fully considered. Numerous studies have focused on analyzing the impacts of including legumes in cropping systems, either using field experiments or modeling, and have produced important evidence on the effects of legumes in crop rotations (see, e.g., Preissel et al. 2015; Watson et al. 2017; Böhm et al. 2020; Ditzler et al. 2021 for reviews). However, the European area under legume crops is still negligible with <3% of the arable area (Eurostat 2019) indicating a continued reluctance from farmers to grow legumes.

Legume crops have long-term and complex impacts on cropping systems, and the evaluation of these effects is challenging, resulting in a lack of awareness of their positive rotational effects (Zander et al. 2016). According to a survey among French arable farmers, the respondents often do not consider the pre-crop effect of legumes and do not decrease N fertilizer and pesticide use in subsequent crops (Carof et al. 2019). Another survey in Luxembourg showed that farmers can feel under-informed on how to grow legumes and perceive this knowledge gap as an even greater obstacle than economic issues (Zimmer et al. 2016). Research on legumes in European cropping systems focuses on a few legume species and identifies knowledge gaps related to ecosystem services and biodiversity that are not directly related to production (Ditzler et al. 2021). Producing evidence on the multiple impacts of legumes (beyond production) under practical farming conditions and designing legume-supported systems in a collective manner while building on established and empirical knowledge are therefore key to supporting a transition towards more legumes in European farming.

Evidence for options to (re-)integrate legumes is primarily based on "design orientated methods" (Le Gal et al. 2011), using either agronomic models or prototyping methods. The focus of these approaches is on reaching specific targets such as decreasing pesticide use, reduced mineral N fertilizer dependency, or increasing yield stability of grain legumes (e.g., Pelzer et al. 2017). The tools can simulate a large number of options, including an assessment of their performance (e.g., Reckling et al. 2016a). The involvement of the potential users of the systems is often limited to formulating of the systems to be assessed. However, recent analyses advocate for the implementation of "design support orientated methods" (Le Gal et al. 2011) or "step-by-step designs" (Meynard et al. 2012) which rethink the role of farmers and advisors as acceptors of turnkey solutions and support their own design capabilities instead (Prost et al. 2017). These methods require collaboration between actors in the design process to provide the relevant knowledge and expertise (Jeuffroy et al. 2022). Thus, it is crucial that farmers or advisors are actively involved in the process. The focus is therefore shifted from the desired result, e.g., more legumes in rotations, to the process necessary to achieve that result which makes the management of the transition from present to future an essential part of the design process (Prost et al. 2017).

In order to go beyond approaches that produce prescriptive solutions for legume integration that lead to low adoption, a cropping system design is needed that fosters understanding, exploring, and developing options in the local context (Giller et al. 2015). Such a framework is the DEED research cycle, which is divided into four interactive phases: Describe, Explain, Explore, and Design (Giller et al. 2015). Through the participatory work with stakeholders (Fig. 1), complex local farming situations can be understood, and regionally relevant tailored options developed. The DEED framework secures the involvement of relevant actors in the research cycle, which ensures consideration of specific site conditions and local knowledge. This expands the regional relevance of the designed cropping systems making adoption of the proposed options more likely (Descheemaeker et al. 2016), and the communication to decision-makers more powerful. Since legumes are less widely grown than other crops, farmers often

Fig. 1 On-farm evaluation and meetings of researcher-farmer networks in **a** Ukraine (Europe Soya Value Chain Development Group) and **b** Bulgaria (Bulgarian Legumes Network).

lack knowledge related to their management and rotational impacts (Carton et al. 2022). Thus, site-specific conditions and local (knowledge) resources must be considered when designing legume-supported cropping systems. The facilitation of knowledge flows and the involvement of a diversity of actors is crucial in every stage of the process and is often implemented through co-design workshops enabling the integration of three key processes, namely reformulating the design goal, exploring candidate solutions, and locally adapting solutions (Quinio et al. 2022). Here, we redesign cropping systems using a combination of participatory and quantitative methods. This combination allowed us to include many different types of knowledge in the process. Thus, all the stakeholders played a critical role in the design process, including identifying the important local issues, exploring solutions, and evaluating the tested systems. At a regional level, participatory approaches have been used to design legume-supported systems (Pelzer et al. 2020; Reckling et al. 2020). However, a large-scale application in diverse European study areas is so far missing.

The objectives of this study were to redesign conventional cropping systems by introducing grain and forage legumes into existing rotations and assessing their economic, environmental, and production impacts. We redesigned the systems in 17 study areas applying the DEED research cycle and evaluated the approach with feedback from the actors involved.

2 Methods

2.1 Context: study areas and researcher-farmer networks

The 17 study areas were categorized into four broader regions—Central East, Central West, North-West, and Southern Europe (Table 1), representing various climatic conditions and cropping systems, and were characterized by varying proportions of grain legumes in the total arable land area (Fig. 2) from <1 to 30% (NUTS 1 or 2 depending on data availability; Eurostat 2019; State Statistics Service of Ukraine 2020). The area of forage legumes was difficult to estimate because there is a lack of data on the proportion of legumes in temporary and permanent grasslands (Watson and Stoddard 2017), and it is affected by both production systems and management. The researcher-farmer networks were existing groups of farmers and other innovators and were already supported by public initiatives such as the German Plant Protein Strategy (BMEL 2020) and

Table 1 Study areas (countries and Nomenclature of Territorial Units for Statistics (NUTS) 2) and researcher-farmer networks.

Country	Researcher-farmer network name	Study area	Situated in NUTS 2 code
Central East Europe			
Bulgaria	Bulgarian Legumes Network (grain legumes)	Severozapaden	BG 31
	Bulgarian Legumes Network	Severen Tsentralen	BG 32
	Bulgarian Legumes Network	Severoiztochen	BG 33
Romania	Europe Soya Value Chain Development Group	North-West	RO 11
	Europe Soya Value Chain Development Group	North-East	RO 21
Serbia	Soybean Cultivation Group in South-East Europe	Region Vojvodina	RS 12
Ukraine	Europe Soya Value Chain Development Group	Kyiv oblast	
Central West Europe			
Austria	Europe Soya Value Chain Development Group	Burgenland	AT 11
	Europe Soya Value Chain Development Group	Niederösterreich	AT 12
Germany	Schwäbisch Hall Producers (pig production)	Hohenlohekreis	DE 11
	German Soybean Association	Markgräflerland	DE 13
	Brandenburg Farmers' Network (arable and forage crop production systems)	Brandenburg	DE 40
	German Pea and Bean Network	Nordhessen	DE 73
North-West Europe			
United Kingdom	SRUC Dairy Protein Group	Eastern Scotland	UKM 7
United Kingdom	SRUC Dairy Protein Group	Southern Scotland	UKM 9
Ireland	The Irish Grain Legumes Group	Southern, Eastern and Midland	IE 05, IE 06
South Europe			
Italy	Europe Soya Value Chain Development Group	Friuli-Venezia Giulia	ITH 4

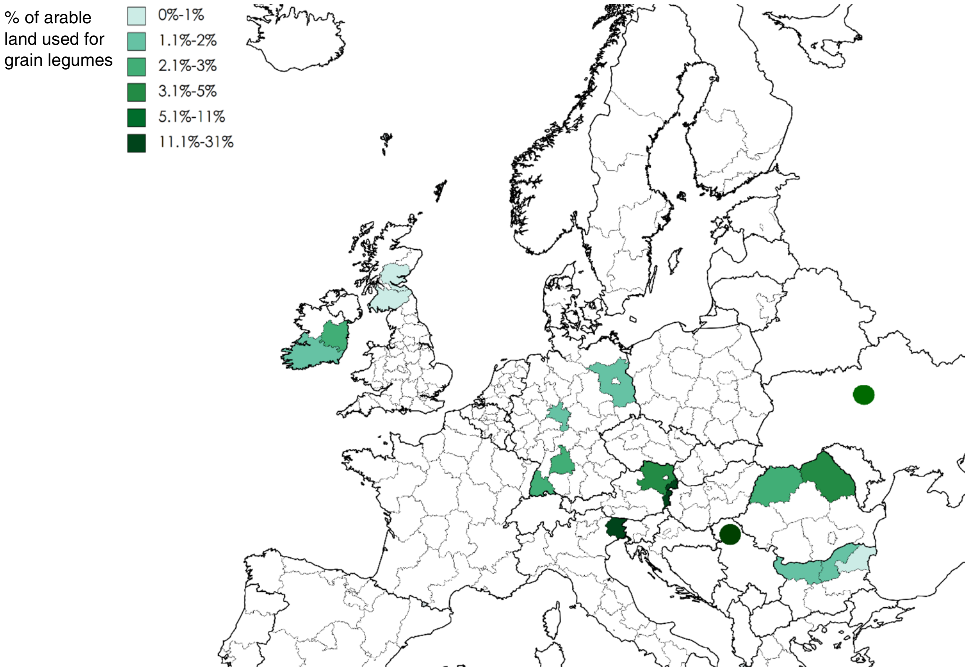


Fig. 2 Map of study areas with proportion of arable land used for grain legumes in 2019 (%). Regions are shown according to Nomenclature of Territorial Units for Statistics (NUTS) 2 (regions in Serbia and Ukraine marked separately).

private initiatives such as Donau Soja. Actors involved in the networks included farmers, researchers, technical advisors, consultants, and downstream value chain actors from a diverse variety of organizations (producers' associations, extension services, research institutes, experimental stations, non-profit organizations). In total, 28 advisors and agronomists involved in the networks and the Legumes Translated project (Murphy-Bokern et al. 2021) acted as representatives of the networks and provided information and feedback. All the networks had a particular interest in regionally adapted legume species, although the particular foci differed between the networks ranging from soybean production in South-East Europe to Scottish dairy production based on regional protein sources (see Table 1 for the list of networks and their focus). Therefore, experiences and practice in legume cultivation were a common feature of all networks ensuring competence related to the design of legume-supported cropping systems.

2.2 DEED approach

Our study followed the DEED approach which enabled us to redesign a set of European cropping systems through the integration of legume crops, building on the existing researcher-farmer networks in diverse local contexts. As defined here, a cropping system involves crop rotation, i.e., the sequence of crops in a defined period, crop management, and production orientation (Reckling et al. 2016b). To apply the framework, we followed four steps.

2.2.1 Step 1: Describe current production challenges and potential services through legume integration

Actors within the networks recorded their local context, goals and activities, ambitions, and objectives for changing current production systems. We systematically analyzed the content of these self-descriptions published by Watson and Murphy-Bokern (2022) during the redesign process using a hybrid approach of deductive and inductive coding (Mayring 2014). The analysis focused on extracting (i) researcher-farmer network understanding of their current production systems, (ii) challenges of these, and (iii) potential services provided by legume integration. The main categories of *challenges* and potential *services* were defined (deductively) based on the first step of the DEED cycle before the first run through the text material. Using an inductive category formation, the subcategories (Supplemental Information (SI.1)) were identified from the self-descriptions.

2.2.2 Steps 2 and 3: Explain impacts of current cropping systems without legumes and explore alternative legume-supported cropping systems

We collected information on locally relevant, conventional cropping systems, including information on (i) current cropping systems without legumes, (ii) at least one locally relevant legume-supported alternative cropping system, (iii) long-term yield data (minimum of 10 years of consecutive crop yield data), and (iv) site conditions in the study areas (soil and weather parameters). Cropping system data included information on crop rotation and crop management with details of inputs (seed, pesticides, fertilizers), outputs (grain, forage, and straw yield), management characteristics (fertilizer and pesticide intensity, machinery use, harvesting method, dates of cultivation step), and crop price, subsidies, and variable costs. Data was collected by representatives of the networks between September 2019 and March 2020. The actors referred to experimental data, expert data based on regional statistics or farming practices. The compiled cropping systems represented selected local practices and were considered relevant by actors. In total, 22 cropping systems without and 31 cropping systems with legumes were provided, offering 31 comparisons with and without legumes.

Economic, environmental, and production impacts of the cropping systems were analyzed by multi-criteria assessment (MCA). The methodology extends the cropping system assessment framework developed by Reckling et al. (2016b), which systematically analyzes cropping options and operates at the scale of the cropping system, ensuring rotational effects can be captured. The framework was adapted to evaluate the practice-based cropping systems and built on a set of indicators (Table 2). Impact areas and indicators were selected by referring to the challenges and services perceived by the actors (see Section 3.1) in order to include the interests of the networks. Moreover, the choice of indicators included both legume-specific (e.g., related to nitrogen and protein) and non-specific (e.g., gross margin and yield stability) indicators, preventing a potential bias towards legumes in the results. The predefined choice of indicators was discussed with the researcher-farmer networks and adapted according to their inputs. Stakeholders are known to appreciate and use results more if the indicators are understood by all users (Cruz et al. 2018); therefore, the indicators chosen used transparent calculations accessing data familiar to all actors.

A set of gross margin (GM, “GM standard,” “GM subsidies,” “GM feed value,” “GM CO_2-tax”) calculations were used as economic indicators. The “*GM standard*” was calculated by subtracting variable costs (costs of seeds, fertilizers, pesticides, variable costs of machinery, and where

Table 2 Indicators and variables used in multi-criteria assessment.

Indicators	Input and output variables
Economy	
Gross margin standard	Input: yield, price, variable costs of inputs (seed, fertilizers, pesticides) and management operations (machinery, irrigation, insurance, drying, cleaning) Output: gross margins in € per ha and year
Gross margin subsidies	Input: yield, price, variable costs of inputs (seed, fertilizers, pesticides) and management operations (machinery, irrigation, insurance, drying, cleaning), subsidies Output: gross margins in € per ha and year
Gross margin feed value	Input: yield, price, variable costs of inputs (seed, fertilizers, pesticides) and management operations (machinery, irrigation, insurance, drying, cleaning), legumes’ feeding value Output: gross margins in € per ha and year
Gross margin CO_2-tax	Input: yield, price, variable costs of inputs (seed, fertilizers, pesticides) and management operations (machinery, irrigation, insurance, drying, cleaning), N in mineral fertilizers, fertilizer conversion factor, CO_2-tax Output: gross margins in € per ha and year
Environment	
N fertilizer use	Input: N in organic and mineral fertilizer Output: N fertilizer in kg per ha and year
N_2O emissions	Input: yield, N in organic and mineral fertilizer, fraction of above-ground residues removed, nitrate leaching Output: N_2O emission in kg per ha and year
Nitrate leaching	Input: yield, N in organic and mineral fertilizer, N mineralization from soil, water holding capacity, and precipitation in winter half-year Output: nitrate-N leaching in kg per ha and year
Biodiversity	Input: crop species, management operations on crop, tillage, fertilization, plant protection, and harvest (frequency, intensity, timing) Output: biodiversity points
Production	
Yield stability	Input: long-term yield data Output: coefficient of variation in %
Protein yield	Input: DM yield, conversion factor crude protein Output: protein yield in kg per ha and year
Energy yield	Input: DM yield, conversion factor gross energy Output: energy yield in GJ per ha and year

applicable costs of irrigation, insurance, drying, and cleaning costs) from the revenues (yield multiplied by the product price), but excluded labor costs, interests, and subsidies. Although labor requirements and costs are important and differ between countries, reliable data on labor were not available for the cropping systems analyzed and the focus of this analysis was on relative comparisons between cropping systems in one region. The "*GM subsidies*" additionally included subsidies that supported legume cultivation based on two of the three instruments that were relevant for legume production in the 2014–2020 period—the voluntary coupled support (CAP pillar 1) and payments derived from specific regional agri-environment-climate measures (CAP pillar 2). The CAP basic payment was excluded as it is paid independently from crop type. The "*GM feed value*" was calculated based on prices that were equivalent to the actual feed value of pea, faba bean, and lupin for pig fattening that were calculated based on farm purchase prices for soybean and wheat as alternative feed ingredients (LLH 2018). This restricts the evaluation to pork feed and does not allow conclusions for dairy or other livestock products. Within the "*GM* CO_2*-tax*," a carbon tax of 50€/t $CO_{2\ eq}$ was assumed and levied on the use of all fossil carbon sources within the manufacturing process of mineral N fertilizers in which 5.62 kg $CO_{2\ eq}$/kg N fertilizers were assumed (Kool et al. 2012).

Three N-related indicators were included in the environmental impact area. "*N fertilizer use*" was calculated based on N fertilizer inputs from organic and mineral N fertilizers. IPCC Tier 1 methodology (IPCC 2019) was used to calculate "N_2O *emissions*." This approach considers direct and indirect emissions from managed soils and crop residues but assumes no direct emissions from N_2 fixation. To evaluate "*nitrate leaching*," we assessed nitrate-N leaching with a modeling approach that is based on soil type, preceding crop, and crop management (Reckling et al. 2016b). "*Biodiversity*" was assessed with the Swiss Agriculture LCA - Biodiversity tool (SALCA BD; Jeanneret et al. 2014). The tool enables assessment of the impacts of different practices on species diversity of eleven indicator species groups: (1) meadow and woody habitat flora, (2) flora of arable fields, (3) birds, (4) mammals, (5) amphibia, (6) snails, (7) spiders, (8) carabid beetles, (9) butterflies, (10) grasshoppers, and (11) wild bees and bumblebees. Inputs to the tool are detailed field-level management information on crop, tillage, fertilization, plant protection, and harvest. The frequency and intensity as well as the timing of management actions are decisive inputs. Tool outputs are scores for each indicator species group that can be aggregated from field to crop rotation and farm level. For the purpose of the MCA, we compared the average biodiversity scores formed by all eleven indicator species groups for all arable crop sequences with and without legume crops. Forage systems were not assessed due to methodological limitations.

Production indicators included "*yield stability*," "*protein yield*," and "*energy yield*." Based on 10 years of yield data (2009/2010–2018/2019) from either field trials or regional statistics, yield stability was calculated with the adjusted coefficient of variation (Döring and Reckling 2018) to compare yield stability of different crops in the assessed rotations per study area. Yield stability was calculated for each crop separately and then averaged over the rotation to derive a rotational index of yield stability and to account for different proportions of crops and varying rotation lengths. The protein and energy yield were calculated from the dry matter yields using standard conversion factors for crude protein and gross energy (Feedipedia 2020; INRA-CIRAD-AFZ feed tables 2020). Conversion factors for the dry matter fraction were obtained from IPCC (2019).

2.2.3 Step 4: Design improved cropping systems

In the research cycle, we supported the design of improved cropping systems in the local networks. We provided the assessment results to the actors for internal discussions, and through two online workshops and an online survey, we evaluated the post-processing of the assessment results as well as the DEED approach from the perspective of the actors. The online workshops took place in December 2020 and May 2021. Before the workshops took place, the MCA results were sent to all researcher-farmer networks. Both workshops started with a presentation by a small team of researchers who also organized the workshops and guided the whole research process. In the first workshop, the presentation focused on an overview of all study areas, an introduction to the calculations within the MCA, and results from example study areas. A report of methods on the MCA was drafted and sent to the networks after the first workshop and an additional indicator (GM subsidies) was calculated due to its decisive role perceived by the actors. In the second workshop, the assessed effects of cropping systems from example study areas allowed a quickly accessible overview for all participants and stimulated discussions. While the first workshop addressed issues on indicator selection, calculation, and the compilation or refinement of initial cropping systems to be assessed, the second workshop focused on discussion of the feasibility of legume-supported systems as well as design and adaptation needs of such systems.

The online survey was conducted in October 2021 as a follow-up to the MCA, workshops, and the whole DEED cycle. The survey addressed (i) actors' perceptions of methods and results, (ii) suggestions for optimizing the assessed cropping systems, and (iii) an evaluation of the DEED approach. The redesign of cropping systems was facilitated by the survey responses and a relevance rating on the single indicator results showed which outputs of the system were weighted more heavily than others. While in both workshops representatives from all researcher-farmer networks were present, actors from all except two networks participated in the survey with a total of ten respondents.

3 Results and discussion

3.1 Production challenges and potential services by legumes

Actors perceived a range of challenges associated with their current production systems as well as opportunities for the provision of services through legume integration (Table 3). Variations between actors' perceptions were minor and they mostly referred to Europe-wide, universal issues. Regional differences were displayed in the weighting of the specific challenges and services.

Actors primarily considered crop rotation problems such as weed, pest, and disease infestation, decreasing performance or yield depression of cereals and oilseed crops, and declining soil quality as major agronomic challenges. In southern Germany, for example, the focus on maize production has led to serious issues with the Western corn root borer (*Diabrotica virgifera virgifera* LeConte; LfL 2021). Actors perceived yield reductions and linked these to the lack of break crops in cropping systems which is supported by Brisson et al. (2010). They suggested that the observed stagnation of wheat yields in Europe in the 1990s could be explained by a reduction of break crops in rotations. Besides crop rotation issues, actors expressed their concerns about the high dependence on mineral fertilizers for crop production and imported protein feed for livestock production systems. Actors also linked economic challenges to these dependencies and referred to high input costs and the exposure to volatile input prices, particularly concerning imported feed. Besides these economic issues, actors also perceived environmental challenges connected to feed imports and intensive fertilizer use, with issues such as land-use changes outside as well as within Europe and inefficient nutrient cycling. Negative effects caused by the reinforcement of specialized agriculture and global agricultural trade have been reported for "commodity supply regions" (IPES-FOOD 2016), where negative environmental and social impacts such as deforestation, loss of biodiversity, or rural displacement can be observed (Zimmer et al. 2016). Additionally in Europe, the disconnection of crop and livestock production has been shown to promote mineral fertilizer imports to crop production areas and feed imports to areas of concentrated livestock production resulting in nutrient surpluses that can cause harmful effects on air, ground, and surface water (Svanbäck et al. 2019).

Actors perceived a range of agronomic services potentially delivered through the integration of legumes and particularly emphasized their rotational effects as a strong opportunity for increasing yields and reducing inputs. In detail, actors referred to the N effect and the combined N savings, yield benefits of following crops, break crop effect, and combined improvements of weed and pest management as well as soil quality. Actors also mentioned diversification of cropping systems and spreading workloads as positive assets. Many actors stressed the value of meeting the on-farm demand for feed and increasing the protein self-sufficiency of their region. Potential economic services were frequently linked by the actors to reduced production costs because of the option for reduced tillage, decreased fertilizer and feed costs, and

Table 3 Summarized actors' perceptions on challenges of current production systems and services through legume integration. For all details, see Supplemental Information SI.1.

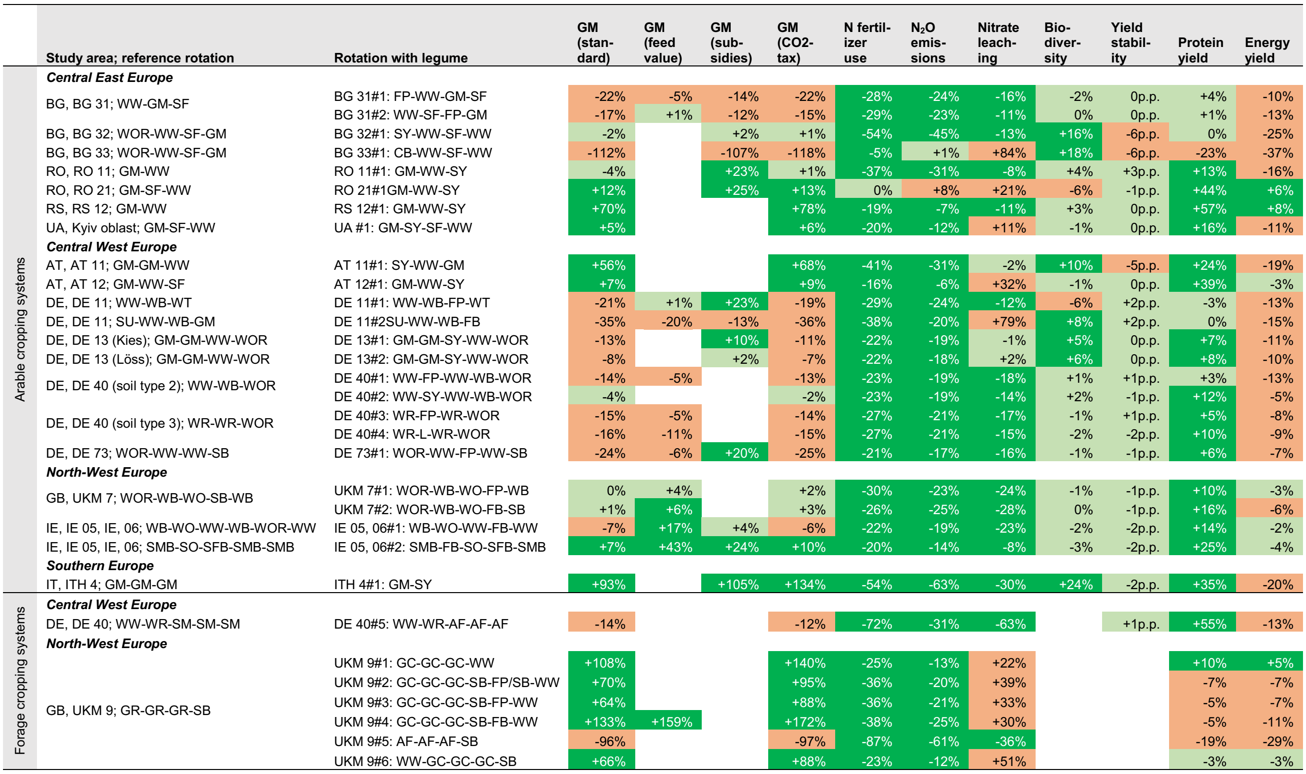
	Challenges	Services
Agronomic	Crop rotation problems (weed, pests, disease problems; yield depressions; declining soil quality)	Pre-crop effects (N effect; break crop effect)
	High N inputs	Diversification
	Deficit in protein	Protein sources for feed
		Spreading of workloads
Economic	High input costs	Reduced production costs
	Exposure to volatile input prices	Reduced exposure to volatile prices
	Green image of animal products at risk in high-value export markets	Enter higher value markets for animal products
		Strong economic performance of soybean, faba bean in certain regions
Environmental	Land-use changes, deforestation	Provision of ecosystem services
	Nutrient surpluses, inefficient nutrient cycling (N losses)	Reduced use of chemical inputs (reduced N losses)
	Pressure on land-use	Reduced ecological footprint of feed
		(Agro)biodiversity benefits
		Climate change mitigation

exposure to volatile prices of these. Livestock connected actors from the Schwäbisch Hall Producers and the SRUC Dairy Protein Group mentioned the opportunity to enter higher value markets for meat, milk, and egg products through the use of locally sourced, GMO-free, and traceable protein feed. Actors in South-East Europe valued the competitiveness of soybean. The environmental implications of increasing the production of legumes were, for example, seen in the provision of ecosystem services and reduced pesticide and fertilizer use combined with a reduction in N losses through leaching and N_2O emissions and a reduced ecological footprint of feed. Previous analysis showed that environmental categories came last when farmers were asked about the benefits of legumes (Pelzer et al. 2019). Despite large public and political attention in recent years, loss of biodiversity was not mentioned as a challenge in current production systems and legumes as beneficial crops for supporting biodiversity were only named by a few actors.

3.2 Impacts of current and alternative legume-supported cropping systems

3.2.1 Economic assessment

In 63% of the comparisons, arable cropping systems without legumes achieved higher standard GM than the legume-supported systems (Fig. 3). All better performing legume systems were either from the study areas in North-West Europe or included soybean. This reflected the perceived high economic performance of soybean and (high-yielding) faba bean by the actors in the respective study areas. The lower standard GMs of grain legume-supported rotations were caused by lower prices and yields of legumes compared to the other crops. Even though we considered the rotational effects, including pre-crop effects that could contribute to higher revenues and lower production costs of subsequent crops (Preissel et al. 2015), in many cases, these could not compensate for the lack of competitiveness at crop level. A previous survey-based study has also shown that recognized pre-crop values of protein crops are not sufficient to



	Study area; reference rotation	Rotation with legume	GM (standard)	GM (feed value)	GM (subsidies)	GM (CO2-tax)	N fertilizer use	N_2O emissions	Nitrate leaching	Biodiversity	Yield stability	Protein yield	Energy yield
Arable cropping systems	***Central East Europe***												
	BG, BG 31; WW-GM-SF	BG 31#1: FP-WW-GM-SF	-22%	-5%	-14%	-22%	-28%	-24%	-16%	-2%	0p.p.	+4%	-10%
		BG 31#2: WW-SF-FP-GM	-17%	+1%	-12%	-15%	-29%	-23%	-11%	0%	0p.p.	+1%	-13%
	BG, BG 32; WOR-WW-SF-GM	BG 32#1: SY-WW-SF-WW	-2%		+2%	+1%	-54%	-45%	-13%	+16%	-6p.p.	0%	-25%
	BG, BG 33; WOR-WW-SF-GM	BG 33#1: CB-WW-SF-WW	-112%		-107%	-118%	-5%	+1%	+84%	+18%	-6p.p.	-23%	-37%
	RO, RO 11; GM-WW	RO 11#1: GM-WW-SY	-4%		+23%	+1%	-37%	-31%	-8%	+4%	+3p.p.	+13%	-16%
	RO, RO 21; GM-SF-WW	RO 21#1GM-WW-SY	+12%		+25%	+13%	0%	+8%	+21%	-6%	-1p.p.	+44%	+6%
	RS, RS 12; GM-WW	RS 12#1: GM-WW-SY	+70%			+78%	-19%	-7%	-11%	+3%	0p.p.	+57%	+8%
	UA, Kyiv oblast; GM-SF-WW	UA #1: GM-SY-SF-WW	+5%			+6%	-20%	-12%	+11%	-1%	0p.p.	+16%	-11%
	Central West Europe												
	AT, AT 11; GM-GM-WW	AT 11#1: SY-WW-GM	+56%			+68%	-41%	-31%	-2%	+10%	-5p.p.	+24%	-19%
	AT, AT 12; GM-WW-SF	AT 12#1: GM-WW-SY	+7%			+9%	-16%	-6%	+32%	-1%	0p.p.	+39%	-3%
	DE, DE 11; WW-WB-WT	DE 11#1: WW-WB-FP-WT	-21%	+1%	+23%	-19%	-29%	-24%	-12%	-6%	+2p.p.	-3%	-13%
	DE, DE 11; SU-WW-WB-GM	DE 11#2SU-WW-WB-FB	-35%	-20%	-13%	-36%	-38%	-20%	+79%	+8%	+2p.p.	0%	-15%
	DE, DE 13 (Kies); GM-GM-WW-WOR	DE 13#1: GM-GM-SY-WW-WOR	-13%		+10%	-11%	-22%	-19%	-1%	+5%	0p.p.	+7%	-11%
	DE, DE 13 (Löss); GM-GM-WW-WOR	DE 13#2: GM-GM-SY-WW-WOR	-8%		+2%	-7%	-22%	-18%	+2%	+6%	0p.p.	+8%	-10%
	DE, DE 40 (soil type 2); WW-WB-WOR	DE 40#1: WW-FP-WW-WB-WOR	-14%	-5%		-13%	-23%	-19%	-18%	+1%	+1p.p.	+3%	-13%
		DE 40#2: WW-SY-WW-WB-WOR	-4%			-2%	-23%	-19%	-14%	+2%	-1p.p.	+12%	-5%
	DE, DE 40 (soil type 3); WR-WR-WOR	DE 40#3: WR-FP-WR-WOR	-15%	-5%		-14%	-27%	-21%	-17%	-1%	+1p.p.	+5%	-8%
		DE 40#4: WR-L-WR-WOR	-16%	-11%		-15%	-27%	-21%	-15%	-2%	-2p.p.	+10%	-9%
	DE, DE 73; WOR-WW-WW-SB	DE 73#1: WOR-WW-FP-WW-SB	-24%	-6%	+20%	-25%	-21%	-17%	-16%	-1%	-1p.p.	+6%	-7%
	North-West Europe												
	GB, UKM 7; WOR-WB-WO-SB-WB	UKM 7#1: WOR-WB-WO-FP-WB	0%	+4%		+2%	-30%	-23%	-24%	-1%	-1p.p.	+10%	-3%
		UKM 7#2: WOR-WB-WO-FB-SB	+1%	+6%		+3%	-26%	-25%	-28%	0%	-1p.p.	+16%	-6%
	IE, IE 05, IE, 06; WB-WO-WW-WB-WOR-WW	IE 05, 06#1: WB-WO-WW-FB-WW	-7%	+17%	+4%	-6%	-22%	-19%	-23%	-2%	-2p.p.	+14%	-2%
	IE, IE 05, IE, 06; SMB-SO-SFB-SMB-SMB	IE 05, 06#2: SMB-FB-SO-SFB-SMB	+7%	+43%	+24%	+10%	-20%	-14%	-8%	-3%	-2p.p.	+25%	-4%
	Southern Europe												
	IT, ITH 4; GM-GM-GM	ITH 4#1: GM-SY	+93%		+105%	+134%	-54%	-63%	-30%	+24%	-2p.p.	+35%	-20%
Forage cropping systems	***Central West Europe***												
	DE, DE 40; WW-WR-SM-SM-SM	DE 40#5: WW-WR-AF-AF-AF	-14%			-12%	-72%	-31%	-63%		+1p.p.	+55%	-13%
	North-West Europe												
	GB, UKM 9; GR-GR-GR-SB	UKM 9#1: GC-GC-GC-WW	+108%			+140%	-25%	-13%	+22%			+10%	+5%
		UKM 9#2: GC-GC-GC-SB-FP/SB-WW	+70%			+95%	-36%	-20%	+39%			-7%	-7%
		UKM 9#3: GC-GC-GC-SB-FP-WW	+64%			+88%	-36%	-21%	+33%			-5%	-7%
		UKM 9#4: GC-GC-GC-SB-FB-WW	+133%	+159%		+172%	-38%	-25%	+30%			-5%	-11%
		UKM 9#5: AF-AF-AF-SB	-96%			-97%	-87%	-61%	-36%			-19%	-29%
		UKM 9#6: WW-GC-GC-GC-SB	+66%			+88%	-23%	-12%	+51%			-3%	-3%

Fig. 3 Economic, environmental, and production effects of changing reference rotations to legume-supported rotations. The colors stress the difference to the reference rotation—dark green: the legume rotation has a by 5% (or percentage points (p.p.)) or more improved result; light green: the difference between legume and reference rotation is between +4 and −4% (or p.p.); light red: the legume rotation has a by 5% (or p.p.) or more worsened result than the reference rotation. AF, alfalfa; CB, common bean; FB, faba bean; FP, field pea; GC, grass-clover; GM, grain maize; GR, grass; LU, lupin; SB, spring barley; SF, sunflower; SFB, spring feed barley; SM, silage maize; SMB, spring malt barley; SO, spring oat; SU, sugar beet; SY, soybean; WB, winter barley; WO, winter oat; WOR, winter oilseed rape; WR, winter rye; WT, winter triticale; WW, winter wheat.

make them appear as profitable as cereal crops in the short term (Carof et al. 2019). However, as N fertilizer prices may increase in the future, the economic relevance of fertilizer savings increases. N fertilizer reductions of 30 kg ha^{-1} were translated to a monetary saving of 22 € ha^{-1} in DE 40#3 with a price of 0.74 € per kg N (average price 2016–2018) resulting in a 16% decreased standard GM; an increased price of 2.86 € per kg N (average price February–March 2022) would raise the monetary saving to 86 € ha^{-1} and would result in the same standard GM of DE 40#3 and its reference rotation. Besides fluctuating prices of inputs, changes in crop prices can contribute to crucial shifts in the GM differences. The consideration of the full economic value of pea, faba bean, and lupin as pig feed positively impacted their economic performance which increased the competitiveness against the reference systems. Either the deficit from the legume-supported rotation to the reference rotation was reduced, the monetary disadvantage was turned into an advantage, or the already given economic competitiveness increased. The strongest effects were observed for the Irish examples in which the difference between the calculated feed value for pork feed (305€ t^{-1}) and the reported market price of faba bean (190€ t^{-1}) was very high. These findings clearly stress the undervaluation of faba bean, lupin, and pea on markets and signal their higher attractiveness for on-farm usage as pig feed or motivate the increase of market prices.

Including subsidies from either voluntary coupled support or agri-environment-climate measures improved the relative economic results of the legume-supported systems. The magnitude of the effects depended on the amount of the payments. This is illustrated by the agri-environment-climate measures for crop diversification in the German federal states Baden-Württemberg and Hessia, where the legume-supported rotations received annual payments for each crop of 75€ ha^{-1} and 110€ ha^{-1}, respectively. Voluntary coupled support in Bulgaria, Romania, Ireland, and Italy also raised the economic performance considerably so that only four of the grain legume-supported cropping systems had lower GM than their reference cropping systems when subsidies were included (BG 31#1, BG 31#2, BG 33#1, DE 11#2). The inclusion of a carbon tax (excluding soil carbon changes) led to smaller effects on the GM than the consideration of the feed value and subsidies. The highest effects were found for the soybean-supported cropping systems in Friuli-Venezia Giulia and the Burgenland (ITH 4#1, AT 11#1) in which particularly high mineral N savings of 115 kg ha^{-1} and 70 kg ha^{-1}, respectively, contributed to lower virtual tax payments compared to their reference systems and therefore an increased economic advantage. Since our carbon tax considered only emissions caused by the manufacturing of mineral N fertilizers, it does not quantify the impact of a carbon tax based on the consideration of a more holistic carbon footprint covering several external emissions (e.g., production and transport of seeds, pesticides), on-site emissions (e.g., machinery emissions, N_2O emissions, and carbon dioxide emissions due to urea hydrolysis), and soil organic carbon stock changes. It was shown that soil organic carbon changes largely impact the carbon footprint of cropping systems and that grain legume introduction can lead to soil organic carbon losses, counteracting their positive impacts in decreasing external and on-site emissions related to N fertilizers (Bonilla et al. 2018).

In forage cropping systems, there was a considerable improvement of the standard GM in the Scottish cropping systems when grass-clover and winter wheat were included in the rotations compared to pure grass stands and spring barley (UKM 9#1, 2, 3, 4, 6). This was the result of reduced production costs, yield benefits, and for a large part also the higher GM of winter wheat compared to spring barley. While there were no specific subsidies in the study regions in Scotland and Brandenburg, the consideration of the carbon tax resulted in an increase of the already given economic competitiveness of the grass-clover systems to the reference system, as the mineral N inputs were reduced by 32 to 43 kg ha^{-1}, which was directly transferred into an economic benefit. The substitution of the reported faba bean market price with the pig feeding value in UKM 9#4 could also increase the economic advantage; however, the carbon tax had a greater effect. Both forage systems including alfalfa (DE 40#5, UKM 9#5) resulted in lower standard GMs, owing to lower yields of alfalfa compared to silage maize and grass in Brandenburg and Scotland respectively. In Scotland, the yield difference was more extreme which caused the considerably reduced standard GM compared to the reference system. The introduction of a carbon tax benefitted the alfalfa rotation in Brandenburg; however, it was still less profitable than the reference rotation. Although the Scottish alfalfa rotation reduced the mineral N input by over 70 kg ha^{-1} compared to the reference rotation, the relative difference between the GMs was not affected through the introduction of the carbon tax.

3.2.2 Environmental assessment

N fertilizer use and N_2O emissions were clearly decreased when legumes were part of cropping (Fig. 3). Model outputs on nitrate leaching were more variable and there were, in most cases, no differences found for the impacts on biodiversity.

The positive environmental performance of the legume-supported systems can be attributed to the reduced need for N fertilizers through the biological nitrogen fixation of legumes (Jensen et al. 2012). Accordingly, our assessment showed that in all except one case, legume rotations decreased the use of N fertilizer compared to their reference rotations by between 6 and 142 kg ha^{-1}. N fertilizer savings were particularly high when lower-yielding soybean (yield between 2.3–4.3 t ha^{-1}) replaced high-yielding and highly fertilized grain maize (yield between 7.8 and 12.1 t ha^{-1}; BG 32#1, AT 11#1, ITH 4#1). Besides the absence of N fertilization in the year of soybean, N fertilizer savings in the subsequent crop in these legume-supported rotations also contributed to these reductions. The potential for savings in the crop following legumes is dependent on the quantity of N fixed as well as on an economic trade-off between securing maximum yields and maximizing N savings (Preissel et al. 2015). The quantity of N fixed depends on genetic, environmental, and management factors, with the highest amounts reported from perennial forage legumes (Carlsson and Huss-Danell 2003). Our analysis of forage systems, especially with alfalfa (DE40#5, UKM9#5), realized very high N fertilizer savings with 121 kg ha^{-1} and 132 kg ha^{-1}, respectively.

N_2O emissions were largely driven by N fertilizer applications and emissions from crop residues. In arable systems, the greatest difference in N_2O emissions of almost 6 kg N_2O ha^{-1} was found in Italy where highly fertilized continuous maize was compared to a maize-soybean system (ITH 4#1). For the forage systems, the Scottish rotation with alfalfa (UKM 9#5) showed greatest reductions with almost 3 kg N_2O ha^{-1} less than the reference rotation with fertilized grass. A considerable reduction of N fertilizer use in the subsequent spring barley also contributed to the emission reduction. The decisive role of N fertilization for N_2O emissions (Buckingham et al. 2014) was shown in all rotation comparisons, since only those legume-supported rotations had comparable emissions to their reference rotations which had similar or only minimally reduced N fertilizer applications (BG 33#1, RO 21#1). While the default IPCC tier 1 methodology has its drawbacks in consideration of site-specific environmental and soil conditions which also impact nitrous emissions, our results are comparable with measurements and allow relative comparisons between systems. Jensen et al. (2012) reported N_2O-N emissions from grain and forage legumes to average 1.3 kg ha^{-1} (ranging from 0.03 to 7.1 kg ha^{-1}), while the emissions from cereals, maize, canola, and pasture were 3.2 kg ha^{-1} (ranging from 0.1 to 12.7 kg ha^{-1}).

While the assessment of N fertilizer use and N_2O emissions clearly reflected the perceived environmental services from the Describe phase, some actors also articulated contributions to reduced nitrate leaching that was shown in some but not all of the legume systems. Despite five and three grain legume-supported rotations that had higher and similar leaching rates, respectively, the remaining 16 systems decreased leaching by up to 20 kg ha^{-1}. This reflects the impact of reduced rotational N inputs lowering the available N in the soil before the leaching period. The asynchrony between crop demand and N supply is a main driver of nitrate leaching and the period after the harvest of the legume bears an increased risk (Peoples et al. 2009). However, cropping systems which use pre-crop effects effectively (early sown winter crops or cover crops) and adapting N fertilization can reduce this risk and were used within legume-supported rotations. Higher leaching from legume-supported rotations reflects higher available N in the soil through N-rich residues of the legumes. For the forage cropping systems, reductions in nitrate leaching were predicted for the alfalfa systems (DE 40#6, UKM 9#5) with decreases of 27 kg ha^{-1} and 3 kg ha^{-1}, respectively. The Scottish rotations including grass-clover (UKM 9#1, 2, 3, 4, 6) showed increased nitrate leaching compared to the reference rotation due to the introduction of winter wheat in these systems which received higher N fertilizer doses than spring barley in the reference rotation (not related to the change from grass to grass-clover).

In the majority of comparisons, there was little difference in the average biodiversity score. Out of 24 comparisons between rotations with and without legumes, only four cases showed absolute percentage variations (+/−) of more than 10% in the average biodiversity score. Seven cropping systems with legumes achieved noticeable higher species diversity scores compared to the reference systems without legumes. The positive effects occurred mainly when maize was replaced by either grain legumes or winter wheat. On average, maize showed particularly low species diversity scores compared to the other crop types (Fig. 4). Two of the legume-supported rotations (RO 21#1, DE 11#1) showed a decrease of 6% in biodiversity scores compared to their reference systems. In both cases, the crop rotations with grain legumes had higher application of plant protection compounds compared to the reference system. In step 1, it was shown that many actors do not recognize the value of

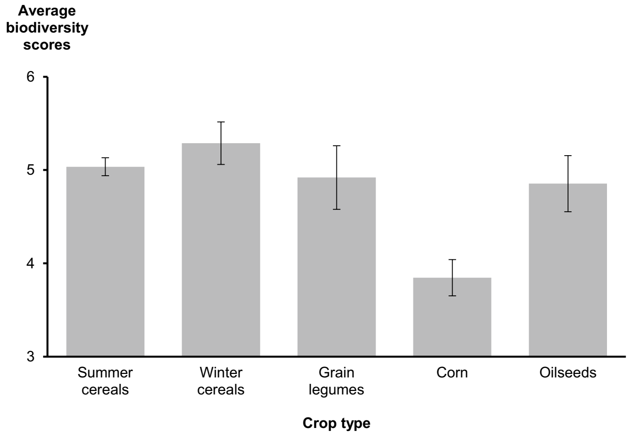


Fig. 4 Average biodiversity scores of the 11 SALCA BD indicator species groups from the Swiss Agriculture LCA-Biodiversity tool for every analyzed crop type within the crop sequence with legumes (error bars show standard deviation).

legumes for supporting biodiversity which may be one reason why more biodiversity supporting crop management is not applied within the crop rotations including legume crops. By looking at the individual arable crops in more detail, it is noticeable that the cereal crops, especially winter cereals, performed best compared to the other crop types. This can be explained by the fact that soil cultivation, fertilization, and plant protection take place when most of the indicator species groups are least vulnerable, mostly in late autumn and early spring. The biodiversity performance of grain legumes relates to their high protein content which makes them an attractive food source for herbivorous arthropods and, in this way, indirectly the whole trophic chain (de la Fuente et al. 2014). Existing knowledge on how the integration of legumes in rotations effects biodiversity is limited, but it indicates that legume crops have the potential to positively impact wild arable flora, insects, and vertebrates (Böhm et al. 2020) as well as supporting below ground biodiversity that was not assessed here. More detailed analyses of the effects of legumes on biodiversity are needed to identify their potential, possibly in combination with other measures such as reducing pesticide applications or promoting semi-natural habitats, to reduce the steady decline in biodiversity (Stein-Bachinger et al. 2022).

3.2.3 Production assessment

Results from reference and legume systems suggested that yield stability was similar in most cases (Fig. 3). A decrease in yield stability compared to their reference systems was only predicted in three legume-supported cropping systems (BG 32#1, BG 33#1, AT 11#1). The decreased stability was related to higher yield variation of soybean and common bean. Previous evaluations have shown that yield stability of legumes is lower than in winter crops, but similar to those of other spring crops (Reckling et al. 2018). Our results also indicated an overestimation of legumes' yield instability in the general perception of farmers that is mentioned as one of the main reasons for not cultivating grain legumes (Zimmer et al. 2016). However, this is the first time yield stability has been evaluated at the rotation scale comparing systems with and without legumes and varying rotational lengths. This also has methodological drawbacks in terms of displaying the realities farmers are facing regarding yield stability for single crops. Even though effects can be balanced over whole rotations, very low yields in 1 year can create a high risk for farmers.

The majority of legume-supported arable cropping systems produced more protein than their reference system in the range of 3 to 363 kg ha^{-1} of crude protein. We found the highest protein gains, compared to the non-legume rotations, in rotations with soybean in Romania, Serbia, Austria, and Italy. In rotations where either pea (BG 32#1,2, DE 11#1, DE 40#1), common bean (BG 33#1) or faba bean (DE 11#2) was introduced, with yield levels of these legume crops being low or modest (2–3 t ha^{-1}), the comparison to the reference rotations displayed only a small increase, no difference or even a decrease in protein yield. The forage cropping systems tested showed diverse effects depending on the specifics of each single rotation. In Brandenburg, substituting silage maize with alfalfa (DE 40#5) led to the protein yield increasing by 444 kg ha^{-1} owing to the high protein content of alfalfa despite lower yields of alfalfa (8.2 t ha^{-1}) compared to silage maize (10.9 t ha^{-1}). In Southern Scotland, the protein yield remained the same or showed a decrease with legumes except in one case, as the reference rotation was based on perennial grasses with a protein content only slightly lower than the grass-clover mixture and alfalfa. The lower yield levels of alfalfa, pea, and faba bean compared to the grass and cereals affected the relative protein yield deficit.

Energy yields of grain legume-supported rotations were mostly lower compared to the reference rotations with decreases between 2 and 39 GJ ha^{-1}. The largest difference was found in the Italian comparison in which a high-yielding, energy-rich crop (maize with a yield of 12.1 t ha^{-1}) was partially replaced by a lower-yielding, protein-rich crop (soybean with a yield of 4.3 t ha^{-1}). Generally, legumes' comparable gross energy content to cereals, coupled with their lower yields, explained the results. In the legume-supported rotations from North-Eastern Romania and Serbia (RO 21#1, RS 12#1), slightly higher energy yields with additional 6 GJ ha^{-1} and 9 GJ ha^{-1}, respectively, were achieved because of increased yields of grain maize and winter wheat following soybean (additional yield: 0.5–2.4 t ha^{-1}). Similar energy yields were achieved in legume systems where the exchanged crop had a comparable energy yield to the legume (AT 12#1) or high-yielding legumes were introduced with considerable yield benefits in subsequent crops (UKM 7#1, IE 05, 06#1, IE 05, 06#2). The comparisons of forage cropping systems with and without legumes showed similar results—energy yields were mostly slightly decreased. For both alfalfa rotations, the similar energy contents of alfalfa and silage maize (DE 40#5) or grass (UKM 9#5) and lower yields of alfalfa (8.2–8.7 t ha^{-1}) compared to silage maize (10.9 t ha^{-1}) or grass (13 t ha^{-1}) caused energy yield decreases by 20 GJ ha^{-1} and 64 GJ ha^{-1}, respectively.

Our indicators on protein and energy yield reflect the nutritional opportunities of legume systems for animal nutrition as well as for human consumption and the potential contribution on the plant protein deficit in Europe. This is only a proxy in terms of human nutrition and specific livestock classes and did not consider differences in varieties and management as well as other nutritional properties (Costa et al. 2021). Our results indicate that protein self-sufficiency can be increased through legume integration with a trade-off for energy production. However, since our analysis focused only on the level of cropping systems, it did not consider the potential of changes in farming systems and value chains. The regional extent of different livestock productions and the related demand for protein are crucial impacts on protein self-sufficiency and it has been shown that an increase in legume production is not always directly translated into increased protein self-sufficiency (Jouan et al. 2020). Therefore, increased protein self-sufficiency needs to be discussed in the context of decreasing livestock production and changes in consumption (Murphy-Bokern et al. 2017).

3.3 Lessons learned for redesigning legume-supported cropping systems

Network actors and researchers found that the assessment of impacts provided clear evidence for several indicators (see Section 3.2). The major concern over protein supply was shown to be alleviated in most legume-supported systems, clearly indicating the potential to overcome the perceived issue of protein deficits at different scales which are accompanied by severe dependencies on external inputs. However, in anticipation of the local relevance and feasibility of the proposed systems, discussions expanded to the potential legume uses that are closely linked to the actual integration in cropping systems (Mawois et al. 2019). The various production foci and regional contexts of the diverse networks allowed specific local needs and issues to be highlighted. While the Irish actors reported a reluctance of feed manufacturers to include more grain legumes such as faba bean, the network Schwäbisch Hall Producers reported on an expanded grain legume use as a valuable pig feed on farm resulting in premium prices for regional pork products. Previous workshops have also shown that mixing actors with different objectives can broaden the discussion (Quinio et al. 2022).

Within the discussions of environmental indicators, benefits from the hybridization of scientific- and practice-based knowledge were shown. The easily accessible indicator of N fertilizer use created clear consent on the reduction of challenges associated with dependencies on mineral fertilizer inputs through legume systems. Researchers and local actors discussed the specifics of the calculations as well as the plausibility of regional assessment results in terms of N_2O emissions and nitrate leaching which allowed sharing of scientific and local knowledge between the participants. Expanding knowledge in design processes is supported through the combination of heterogeneous knowledge (Prost et al. 2017). Details on the biophysical processes impacting nitrate leaching and how they are being integrated in the modeling approach were exchanged and related to local contexts. Factors explaining different N levels were discussed based on considerations of local conditions such as soil parameters that affect leaching probabilities and N mineralization. Network actors linked knowledge on the processes impacting nitrate leaching with farming techniques and possible adaptations of the legume systems with high leaching results were discussed, for example, with the implementation of cover crops or improved fertilization practices. Considerations of interactions between crop management and crop choices were thereby emphasized. This "function-based reasoning" (Quinio et al. 2022) was also visible in discussions about crop choices in order to reduce weed and pest issues. The need for break crops due to a limited number of registered herbicides and the inclusion of soybean as a break crop in maize monocultures were mentioned by Austrian and German actors, supporting findings from step 1. While the effects of legume-supported systems on nitrate leaching were more controversial, actors stressed the value of legume systems for N_2O emission savings shown through the assessment results and thereby fulfilling the previously perceived potential for reduced N losses to the environment from step 1. Within discussions about yield stability, some single actors questioned the practical relevance of the methodological approach, pointing out the need for methods that consider both the single crop and the rotation scale.

Participants discussed the realization of the legume-supported systems particularly related to economic issues and linked this also to local crop performances and farm-economic competitiveness of crops. The poor economic performance of some legumes clearly highlighted the limitations of the proposed legume-supported systems or as one actor expressed it: "why should a farmer grow a crop if it is not profitable?" The lower GMs of many legume-supported systems illustrated the need to overcome these economic issues by, for example, developing regional markets with higher prices. The greater potential of soybean-supported rotations was illustrated by the higher GMs. Austrian actors reported benefitting from high soybean prices which make soybean cultivation particularly attractive and provide greater incentives for designing soybean-supported cropping systems. Besides prices, crop performance was discussed as an important factor for economic results and the adaptations of different legumes to regional conditions resulting in (un) satisfactory crop growth and production results were discussed. Actors suggested that poor crop and market performance of legumes highlighted a need for economic support. They saw a strong need for policy interventions for legumes in the form of direct or indirect measures.

In the workshops, needs and options for changes in explored cropping systems were discussed, but the actual changes were not modeled so that our procedure deviated at this stage from a stringent co-design approach. However, this desire for the networks to redesign the explored systems and continue the design process was followed up with a survey to allow further reflectance on the importance and adaptations of the systems.

The survey showed that the relevance of the indicator results was rated highly overall to support the redesign of cropping systems (Fig. 5). GM standard, N fertilizer use, and protein yield were seen as particularly important with at least nine actors scoring as fairly or very important. This reflects its importance for farmers (GM standard), the relation to other decisive elements such as costs, environment, or policy (N fertilizer use), and the high relevance for feed (protein yield). Considering the MCA results, combined with these views on the relevance of distinct aspects, illustrates the potential actors see for improving the overall productivity of cropping systems in the study areas through the integration of legumes. However, it also highlights the importance of economic improvements if the redesign of cropping systems through the integration of legume crops is to become feasible.

In terms of need for improvements in the legume systems which were designed, six respondents saw the necessity for adaptations while four respondents perceived the assessed legume systems as ready for widespread adoption in their area. Adaptation needs were stated in terms of increased profitability or decreased nitrate leaching and concrete measures were named with changes in market prices or legume yields, e.g., through variety choice, cover crops, fertilization management, or tillage system.

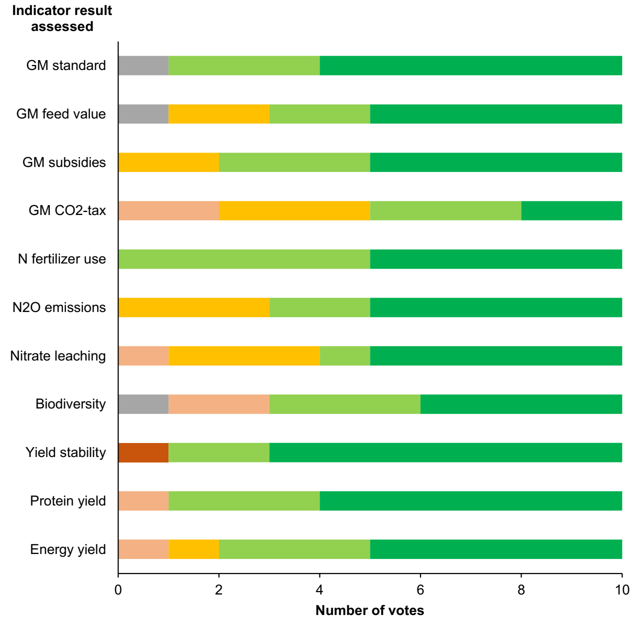


Fig. 5 Relevance of indicator results rated by researcher-farmer networks in the survey. In the survey, each actor could cast one vote per indicator result on a 5-point scale (🟫not at all important; 🟧 slightly important; 🟨moderately important; 🟩 fairly important; 🟩very important) and the additional option ⬜ no opinion.

The feedback from the workshops and survey showed that the legume systems explored provided direction for improving cropping systems. However, there is wide recognition of the need for further adaptations by actors in their local contexts. We could not foster learning loops through consecutive rounds of design and assessment and thereby further refine the design processes which makes a continued development of the systems within the networks important. Therefore, the design process needs to be pursued in the specific study areas, using the findings for adaptations indicated and discussed as well as for designing adequate policy support and market developments. A long-term continuation of the collective work within each researcher-farmer network is important because the Design phase has shown that introducing legumes in crop rotations is a process that takes several years. This phase also supports the assertion that networks are a key component of a robust transition towards increased legume integration (Mawois et al. 2019).

3.4 Evaluation of the DEED framework

By applying the DEED research circle, we went beyond approaches that produce prescriptive solutions that bear the risk of leading to a low impact (Giller et al. 2015). The DEED framework is characterized by the key elements of constant and close collaboration with the potential users of the designed systems, the integration and consideration of local conditions, and the four interactive phases that allow integration of a broad range of methods. In order to evaluate the applicability of the DEED framework in our study context of legume (re-)integration in European cropping systems, we focused on these key elements.

Our operationalization of the DEED approach enabled actors' input in each of the four steps. We described actors' perceptions of challenges and services delivered by legumes in step 1. These were based on their own analysis of their situations. In steps 2 and 3, we ensured actors' contributions through their definition of cropping systems with and without legumes and their impact on indicator choices either indirectly—through building the decision on the previously described perceptions—or directly—through open demand for indicators in discussions with the researcher-farmer networks. The actual implementation of the MCA was concentrated on a small researcher group; however, the transparency and accessibility of methods and results was stressed through a detailed method report that was provided and follow-up discussions with the networks. Thereby, we prevented "a gulf" between modelers and local actors—a pitfall that is often combined with solely model-based approaches (Meynard et al. 2012). In the survey, we evaluated the comprehensibility of assessment results and transparency of assessment methods and found a high approval for comprehensibility (ten confirmed) and transparency (nine confirmed, with one limitation due to the biodiversity assessment). In the survey, actors also assessed the choice of the indicators—six found the choice adequate, three did not know, and one stated that more indicators, such as assessments on the workload or the overall risk of a rotation, should have been included. In step 4, the close collaboration with actors in workshops and their direct feedback from the survey allowed cropping system design to be aligned to issues they considered relevant. This was carried out alongside the collection of ideas and inputs for local adaptations by the actors in both a current and a future context.

Participatory elements were for the most part also perceived as sufficient by the actors from the networks. All ten respondents were content with the influencing options, particularly appreciating the design options for the cropping systems and the impact on the chosen indicators. Six respondents found their local conditions were sufficiently taken into account, three were undecided, and one disagreed. Criticism addressed the lack of country-specific assessment methods for N losses. Moreover, at the farm level the information was not seen as tailored enough to specific situations. The large-scale application of the DEED framework in 17 diverse study areas enabled consideration of opportunities for legume integration in diverse European contexts. However, it also imperatively required the presence of actors deeply rooted in their region. The inclusion of researcher-farmer networks was therefore essential and highly valuable and allowed us to integrate local knowledge. More region-specific methods could have increased the accuracy of the results but could have hampered accessibility and comparability in light of the diversity of areas included.

MCA was a central part of our operationalization of the DEED framework and ten respondents agreed that the MCA is a helpful tool to highlight problems and benefits of cropping systems. The suitability of modeling as a method for cropping system design was assessed as extremely suitable (four), very suitable (one), or moderately suitable (four). On-farm and on-station experiments received slightly higher ratings (each seven votes for very suitable and extremely suitable) and the best rating was found for a combination of all three methods (nine votes for very suitable and extremely suitable). This perceived need for integrating several methods for cropping system design and actors' satisfaction with the MCA as an assessment tool showed the strength of the DEED framework, particularly, if the process is continued over time and the results lead to new experiments in the local contexts. The implementation of selected solutions that emerge from the process within real local growing conditions adds considerably to evaluating their feasibility and informing later design phases (Prost et al. 2018). Such an application of several cycles of the DEED approach was not implemented in our study, but indicates the added value in a continuation of the networks which would further develop legume integration in the specific areas. Overall, we found the DEED framework a highly suitable approach to "weld research-based universalistic knowledge, with local knowledge" (Meynard et al. 2012), help improve current production systems, and show opportunities for solving local problems through legume integration.

4 Conclusion

The transition to legume-supported systems in Europe can benefit from redesigning cropping systems in a process of close stakeholder interactions which has so far only been regionally implemented. Our application of an interactive research process is the first in >15 European study areas and enabled the co-learning between local actors and researchers. It provided key insights into legumes' potential for solving practical challenges of current production systems. The design of legume-supported cropping systems was facilitated and starting points for further adaptations. Based on the key agroecological processes inherent to legumes—biological nitrogen fixation and protein production–legume systems showed clear benefits for environment-friendly production systems and protein supply. To support transition processes for legume (re-)integration, in many situations economic constraints still have to be overcome, indicating a need for innovative solutions at all levels, production, markets, and policy.

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Authors' contributions IN: data collection, performed analyses, wrote draft. CFET: data provision and interpretation of assessment results from regional perspective, performed N_2O emission assessment, reviewed, and edited. JS: data collection, supervision, and advice. LAG: performed biodiversity assessment, wrote the biodiversity section. SK: performed biodiversity assessment, contributed to the biodiversity section. JD, JP: contributed to the biodiversity section. SA, TH, PH, MH, AI, JR, LR, MV: data provision and interpretation of assessment results from regional perspective. CAW: reviewed and edited. MR: data collection, performed analyses, conceptualization, methodology, supervision, and advice.

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Data availability The datasets used in this study are not publicly available, but may be obtained from the authors upon reasonable request.

Code availability Not applicable

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication The authors affirm that human research participants provided informed consent for publication of the images in Fig. 1.

Conflict of interest The authors declare no competing interests.

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