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Re-designing organic grain legume cropping systems using systems agronomy

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ABSTRACT

Crop production in Europe is intensive, highly specialized and responsible for some negative environmental impacts, raising questions about the sustainability of agricultural systems. The (re)integration of grain legumes into European agricultural systems could contribute to the transition to more sustainable food production. While the general benefits from legume cultivation are widely known, there is little evidence on how to re-design specific cropping systems with legumes to make this option more attractive to farmers. The objectives of this study were to describe the constraints and opportunities of grain legume production perceived by farmers, explain the agronomic impacts of current grain legume cropping, explore technical options to improve grain legume agronomy, and to re-design current grain legume cropping systems in a participatory process with farmers. A co-design approach was implemented with farmers, advisors and scientists on 25 farms in northern Germany, that were part of two large demonstration networks of about 170 farms supporting grain legumes across Germany. We used the DEED research cycle (Describe, Explain, Explore and Design) as a conceptual framework combining on-farm research, crop rotation modelling, and on-station experiments. From it, we identified nine agronomic practices that either were novel or confirmed known strategies under new conditions, to re-design grain legume cropping systems at the field and farm level. The practices included (i) inter-row hoeing, (ii) direct seeding into a cover-crop, (iii) species-specific inoculation, (iv) cover crops to reduce leaching, (v) reduced tillage, (vi) soybean for increased gross margins, (vii) cultivars for food and feed use, (viii) flexible irrigation, (ix) grain legumes with cover crop to enhance subsequent crop yields. We also demonstrate how to complement knowledge of farmers' perceptions (Describe step) and formal knowledge from classical on-station experiments and modelling (Explain step) with on-farm research including the local views of farmers (Explore step) to identify tailored options for specific farm contexts rather than prescriptive solutions (Design step) to intensify legume production. This approach therefore contrasts with traditional methods that are often solely participatory and qualitative or model/experimental-based and quantitative. Hence, our results provide new insights in how to re-design cropping systems using a combination of participatory and quantitative approaches. While participatory approaches are common in developing countries, this study shows their potential in an industrialized context with large-scale farmers in Europe. These novel findings can be used as a starting point for further adaptations of cropping systems and contribute to making grain legume production economically and environmentally more sustainable.

1. Introduction

Intensification and specialization of farming in Europe is responsible for negative environmental impacts and has raised large concerns about the sustainability of agricultural systems (Scherer et al., 2018). The (re)integration of grain legume crops into European agricultural systems could contribute to the transition to greater sustainability in agricultural production and reduce some of the negative impacts (Voisin et al., 2014). A legume-rich diet has health benefits for humans and livestock, but legumes are greatly under-used in most

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Western diets (Foyer et al., 2016). While the general agronomic, environmental and economic benefits from legume cultivation have been reviewed extensively (e.g. Watson et al., 2017), there is little evidence on how to re-design specific cropping systems with legumes to make this option more attractive to farmers.

While grain legumes were grown on 14.5% of the global arable cropped area in 2014, they were grown on only 1.5% in Europe (Watson et al., 2017). Production is constrained by a variety of pests, diseases and weeds, resulting in relatively low mean yields (Döring, 2015; Watson et al., 2017). While their temporal yield stability is lower than in winter crops, it is similar to that of other spring crops (Reckling et al., 2018b). Low market value makes domestic legume crops less profitable when current protein supply chains focus on relatively cheap imported soybean products (Meynard et al., 2018). Other drivers contributing to the small area of grain legumes are the specialization of farms on a few, profitable crops, unpredictable policy support, and lack of awareness of the positive rotational effects of legumes at the cropping system scale (Zander et al., 2016).

Improving the agronomy of grain legumes could be the first step for re-designing cropping systems. Doré et al. (2011) suggested diversifying the sources of knowledge and methods in order to design cropping systems more effectively towards ecological intensification. Methods with relevance for re-designing cropping systems with grain legumes include the following.

(i) Dynamic and static modelling: Dynamic crop modelling simulates the processes and impacts of crop production (Jones et al., 2017), but few models are calibrated for grain legumes or accurately simulate the processes of crop rotations (Kollas et al., 2015; Yin et al., 2017). Rotational effects and indicators other than crop yield are important, so static and rule-based models are an alternative to evaluate rotations and different management practices (Reckling et al., 2016b; Ballot et al., 2018). These have a wider application and can include more agronomically important indicators than dynamic models, but have the limitation of not representing soil-crop processes in detail.

(ii) On-station experimentation under controlled field conditions is the classical method for testing hypotheses relevant to different production practices (Doré et al., 2011) such as the effect of inoculation with rhizobium on yield and nitrogen fixation in grain legumes.

(iii) On-farm research including farmer-managed trials is regarded as a new avenue in agronomy (Doré et al., 2011). On-farm research is used for re-designing cropping systems by unravelling processes and testing treatment responses (Falconnier et al., 2016), for on-farm variety trials (Schmidt et al., 2018) and for demonstrating new production systems (Leclère et al., 2018). It is often performed in combination with action research or group analysis with local evaluation by stakeholders (Bloch et al., 2015; Lacombe et al., 2018; Leclère et al., 2018; Prost et al., 2018). While on-farm demonstrations are widely used in applied research projects across Europe, the other forms of on-farm trials including the systematic analyses of treatment responses across environments and farm types (e.g., Franke et al., 2019 and systematic evaluation by farmers and scientists, have been rarely published in international journals (e.g., Leclère et al. (2018) but in local magazines. There are many more published examples of on-farm research with grain legumes under tropical conditions (Falconnier et al., 2016; Franke et al., 2019; Ronner et al., 2016; van Vugt et al., 2018) than for Europe.

Designing cropping systems can involve one or several of the methods mentioned above. The DEED research cycle (Describe, Explain, Explore and Design) is a general conceptual framework for the design of cropping systems by operationalizing systems agronomy (Giller et al., 2011). It involves participatory work with farmers, modelling and experimentation. The DEED cycle supports the understanding of the complexity of farming and the generation of tailored options to re-design the cropping systems of individual or groups of farmers. The cycle consists of four steps: (i) Describe current production systems and their constraints, (ii) Explain the consequences of current farm management, (iii) Explore options for agro-technological improvement and (iv) Design improved management systems (Giller et al., 2011). The cycle is used for co-learning by farmers, advisors and scientists, to identify which options fit best, and it thus provides a farm-specific solution by using a combination of methods, e.g., crop rotation modelling with on-station and on-farm research. The involvement of the actors in all steps of the cycle supports the local relevance of the designed options (Descheemaeker et al., 2016; Falconnier et al., 2017; Sinclair, 2017). Participatory work using the DEED cycle is common with smallholder farmers in Sub-Saharan Africa and Latin America (Giller et al., 2011; Dogliotti et al., 2014; Descheemaeker et al., 2016; Falconnier et al., 2017; Ronner, 2018). We know of no examples where the full DEED cycle has been used explicitly in European agricultural studies but in related forms (Rossing et al., 1997; Vereijken, 1997). Design cycles are often used in modelling studies (e.g., Groot et al. (2012). While most studies on design in agronomy have focused on the development of cropping systems, Prost et al. (2018) emphasize the importance of examining the way that the designed options are actually implemented by farmers and continuing the design process over time.

The aim of this study is to introduce a novel approach for the re-design of cropping systems with a focus on the agronomic implications. The specific objectives were (1) to describe farmers' perceived constraints on, and opportunities for, grain legume production, (2) to explain the agronomic impacts of current grain legume cropping, (3) to explore technical options at the field scale to improve grain legume agronomy, (4) to identify practices for re-designing current grain legume cropping systems, (5) to evaluate the role of different methods in agronomy and (6) to evaluate the contribution of the DEED research cycle for the re-design of grain legume cropping systems in a participatory research project. Northern Germany was selected as a case study area because we have already found significant trade-offs between economic and environmental impacts for integrating grain legumes into cropping systems in parts of this region (Reckling et al., 2016a). The present study builds on an active researcher-farmer cooperation in two large demonstration networks supported through the German protein crop strategy with a focus on narrow-leafed lupin (*Lupinus angustifolius* L.) (NL lupin) as an established crop and soybean (*Glycine max* (L.) Merr.) as a potential novel crop in the area.

2. Methods

2.1. Study area and farm characteristics

On-farm trials, on-station experiments and crop rotation modelling of farming systems across northern Germany were used in this study (Fig. 1). The study area is divided into an eastern part that is characterized by mostly sandy soils and low annual rainfall of around 500 mm, and a western part with often better soils and higher rainfall of around 700 mm. The potential annual evapotranspiration ranges between 702 mm and 777 mm (Zink et al., 2017). Grain legumes were cultivated on 126 500 ha in the study area in 2016, representing 0.8% and 2.4% of the total arable land in the western and eastern parts, respectively (DESTATIS, 2017). NL lupin is well accepted as a crop in some regions within the eastern parts (mainly Brandenburg, Mecklenburg-West Pomerania and Saxony-Anhalt) and was grown on 27 100 ha and soybean as a novel crop on 2 800 ha in the total study area. Pea, faba bean and other unspecified grain legumes accounted for 60 000 ha, 25 000 ha and 11 600 ha, respectively (DESTATIS, 2017).

The participatory study was implemented with organic farmers, advisors and scientists that were part of or associated with two large grain legume demonstration networks, the soybean network (funded

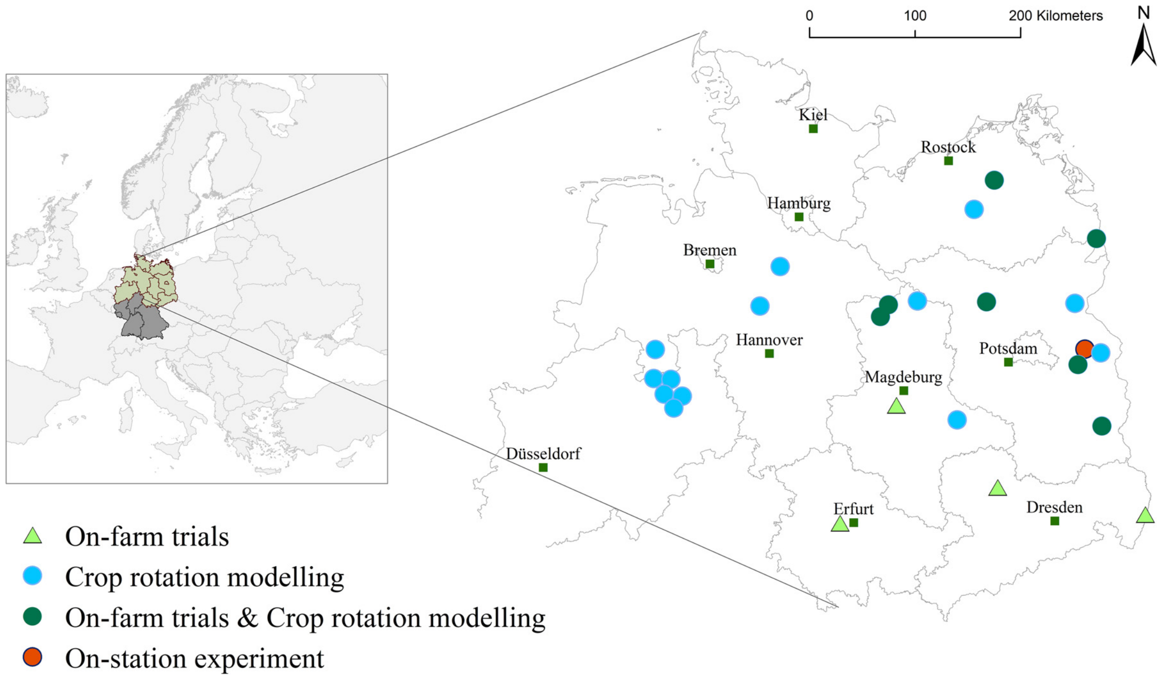

Fig. 1. Map of the study area in northern Germany and the location of the farms participating in the on-farm trials and crop rotation modelling, and the location of the on-station experiment.

2013–2018) and the lupin network (funded 2014–2019). These networks comprised around 170 organic and conventional farms across Germany, of which 25 organic farms were involved in this study (Fig. 1). Twenty-three farms participated in the survey, 20 in the crop rotation modelling (see Table S1 for the farm characteristics), 11 in the on-farm trials, and one experimental farm in the on-station experiments. The organic farms were medium- to large-scale with arable land ranging from 16 ha in the western part to 3570 in the eastern part and an average area cultivated with lupin of 1 to 250 ha per farm. Farms were mainly mixed with arable and livestock activities, including dairy, pigs, sheep and poultry. Farmers were interested and open for innovations. They participated in regular monitoring of their fields and activities, and explored alternative practices through testing technical options at field scale (see Section 2.2.3).

2.2. Steps in the design process of legume cropping systems

We used the DEED research cycle (Fig. 2) for the co-design of cropping systems with farmers, advisors and scientists in this study following four steps: Step 1, we **D**escribed current production constraints and opportunities with grain legumes by collecting farmers views through a structured survey and qualitative focus group discussions during regular field days; Step 2, we **E**xplained the impacts of current grain legume rotations using crop rotation modelling and on-farm monitoring; Step 3, we **E**xplored alternative practices through testing technical options at the field scale based on farmers' constraints and opportunities in on-farm trials and on-station experiments; Step 4, we re-**D**esigned grain legume cropping systems by identifying strategies evaluated as "successful" using workshops with farmers, advisors and scientists. Finally, we drew general conclusions beyond the case study, describing the lessons learned from bringing together different methods into one conceptual framework with the aim of advancing systems-based agronomic research.

2.2.1. Step 1. Describe current production constraints and opportunities with grain legumes

To describe farmers' production constraints and opportunities with grain legumes, a survey was conducted with 23 organic farmers with a focus on NL lupin. The semi-quantitative survey covered (i) information on current grain legume production constraints, (ii) potential opportunities and interests seen by farmers to potentially improve production or other services, and (iii) collected input data from 37 fields needed for the crop rotation modelling (see 2.2.2), i.e., rotations, yields and crop management. The surveys were completed by farmers with the support of five advisors. Details on the survey design are provided by Bergmann (2016) for the eastern part and by Rieps (2017) for the western part of the study region. We documented the discussions of farmers, advisors and scientists at four annual field days in 2014–2017 on production constraints and potential strategies to overcome these with reference to the on-station experiments and on-farm trials.

2.2.2. Step 2. Explain the impacts of current cropping systems with grain legumes

Based on the identified constraints and opportunities in step 1, we used ROTOR 3.0 (available at: www.zalf.de) to evaluate the 37 rotations with grain legumes. ROTOR was initially developed and validated for organic farming systems in northeastern Germany (Bachinger and Zander, 2007), and has subsequently been further developed and applied to assess cropping systems in other parts of Germany and Europe (Stein-Bachinger et al., 2015; Topp et al., 2017). ROTOR estimates yields, nitrogen and carbon balance, nitrogen leaching and different weed infestation risks (perennial, winter & spring annual weeds) and was used to assess these indicators for the farmers' rotations. In the model, yield is estimated based on a site-, crop-, and pre-crop-specific static yield equation developed by Bachinger and Zander (2007). It calculates yield considering three levels of N supply from preceding crops (N available from residues after harvest), the German soil rating index, the amount of plant available N in solid and liquid manure and crop specific coefficients of annual N mineralisation rate reported in Bachinger and Zander (2007). The yield function in ROTOR was validated with yield data from organic farms in the study area as reported by Bachinger and Zander (2007). In the present study, the actual yields provided by the farmers were used where available, ROTOR was used to estimate yield only where yields were not reported. The N balance (kg ha^{-1}) was calculated with ROTOR using the following equation:

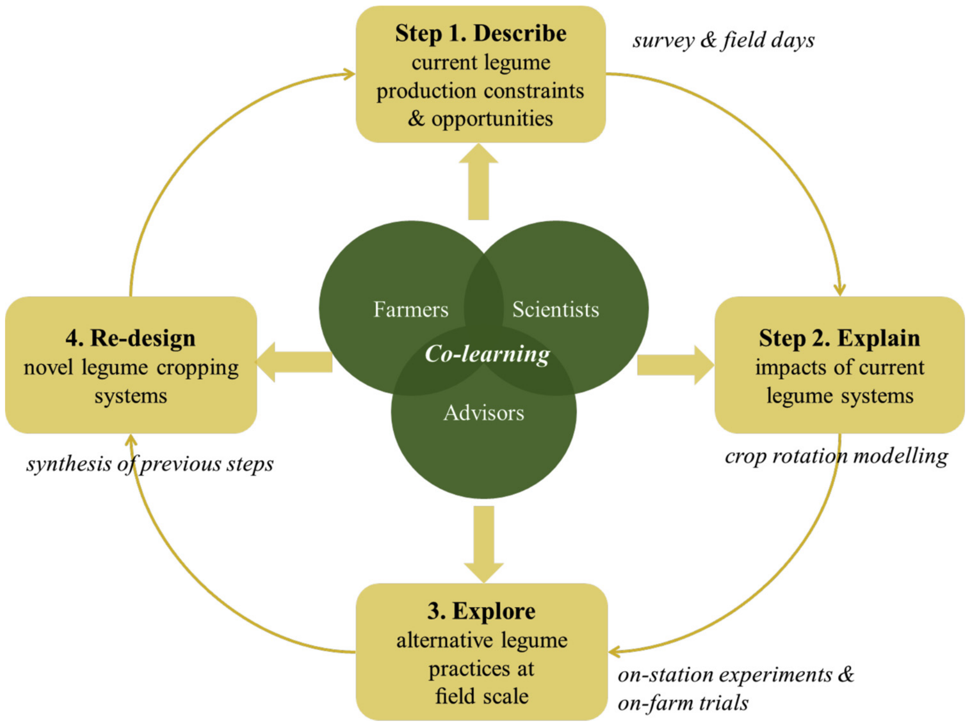

Fig. 2. Different steps of the *DEED research cycle*, the contribution of crop rotation modelling, on-station and on-farm research, and the role of co-learning in this study.

$$N_{balance} = (N_{fixation} + N_{manureT} + N_{seed}) - (N_{removal} + N_{leaching})$$

where $N_{fixation}$ is the BNF of grain and forage legumes calculated as a function of the crop yield, the N content of the crop, the crop-specific ratio of N in shoots to that in residues and roots, the percentage of N derived from the atmosphere (%Ndfa modified by the level of N supply from the preceding crop), the percentage of legumes in crop mixtures, and the ratio of fixed N transferred to grass in grass-clover mixtures. The soil mineral N content is estimated considering N mineralization from preceding crop residues in spring, along with N inputs from plant-available N in manure. $N_{manureT}$ is the total N content in solid and liquid manure, N_{seed} is the N contents in seed, $N_{removal}$ is the N removed from the field in the harvest (grain and biomass) and $N_{leaching}$ is the nitrate-N leaching. Nitrate-N leaching is calculated by dividing the N surplus by the leaching probability during the winter (mean winter precipitation divided by the water holding capacity at rooting depth and a crop-specific leaching coefficient) (Bachinger and Zander, 2007; Reckling et al., 2016b). The algorithms for nitrate-N leaching were validated by Bachinger and Zander (2007) using HERMES, a dynamic model that simulates water and soil nitrogen dynamics (Kersebaum, 1995) and by Reckling et al. (2016b). In ROTOR 3.0 a module was implemented to calculate the soil organic carbon (SOC) balance using static factors for carbon supply and demand following the VDLUFA method (Brock et al., 2013; VDLUFA, 2014). It belongs to the agronomic approaches for quantifying annual SOC development according to Brock et al. (2013) referring to the maintenance of soil productivity without a quantitative link to dynamic SOC change. Weed infestation risk was evaluated based on crop management, i.e., soil tillage, mechanical weed control, undersowing and cultivation of cover crops, along with the ability of the crops to suppress weeds. The assessment is limited to organic cropping systems and does not (yet) consider the effect of different soil types or water deficit gradients on weed infestation across pedoclimatic regions. Bachinger and Zander (2007) provide a detailed description of the algorithms and rules of the infestation module and an overview of the effect of different crop species and tillage operations on the weed infestation risk. The weed infestation assessment in ROTOR was validated for organic rotations by experts and is described by Bachinger and Zander (2007). The assessment uses scores from -4 to +4 where negative values indicate a decrease and positive values indicate an increase in the weed infestation risk. An infestation risk > 1 for summer and winter annual species and > 0 for perennials is defined as a threshold where weeds are problematic, causing yield losses and requiring additional weed control.

Information about the farms used in the assessment with ROTOR is provided in Table S1. More detailed information about the characteristics of the rotations are provided by Bergmann (2016) and Rieps (2017).

2.2.3. Step 3. Explore alternative practices through testing technical options at field scale

On-farm trials were established at 11 farms to test technical options at the field scale, ranging from new cultivars to different tillage practices in four consecutive years (2014–2017). Practices were selected based on farmers' constraints and opportunities identified in an iterative process in step 1 as well as research gaps identified in a literature review (Watson et al., 2017). These trials represented a practical test under farmers' conditions and decision making, and were evaluated as a farm-specific experience. Plots were unreplicated and usually 12 m wide and 100–500 m long. On these plots, new cultivation practices of NL lupin and soybean were tested and compared with one plot representing current farm practice as a control. The effect of inoculation was tested in two consecutive seasons for lupin and soybean using standard procedures for the inoculation and included a visual assessment of roots for nodules and measurement of final grain yield.

Farmers and scientists agreed which issues to test based on current production constraints, e.g., high weed infestation, and opportunities, e.g., a market for specific soybean cultivars that can be used for the human food industry. Monitoring of the soil and crop status was carried out by scientists. Grain yield was assessed by farmers with a combine harvester and a trailer scale. Due to the lack of replication and consistent experimental design, yields were not evaluated statistically. Instead, farmers and scientists evaluated the success of each practice in a joint analysis based on a visual assessment and additional quantitative information such as yield, nutrient analysis and visual weed infestation. Depending on the objective of the trials, a "successful strategy" was defined as increasing yield, reducing weed infestation or allowing reduced tillage. The practices tested were repeated or changed in the following year depending on the importance for success and conclusions. Before the establishment of a new trial in the following season, the results of the previous season were evaluated together with scientists and other farmers during field days on farm and at the on-station experiments at ZALF (as described below), as well as workshops with farmers, advisors and scientists.

At all farms, one field was monitored under current practice to measure grain yields and to document all farming operations for the economic assessment that determined costs and revenues for gross margin calculations according to Wolf and Schätzl (2019). To explore the environmental consequences of soybean cultivation, soil mineral nitrogen was measured before winter and after winter at a depth of 0–30 cm and 30–60 cm to assess the risk of nitrate leaching.

On-station experiments were conducted at the experimental station of the Leibniz Centre for Agricultural Landscape Research (ZALF) in Müncheberg (52°31′N, 14°07′E) to explore soybean as an alternative grain legume. In northern Germany, soybean has been discussed as a novel crop since around 2010 with little uptake or evidence on the agronomic benefits and limitations. Soils at the research station are from glacial deposits and are predominantly sandy loams and loamy sands with a high spatial heterogeneity containing on average 61% sand, 27% silt and 12% clay. The soil pH ranges between 6.1 and 6.9, total soil carbon between 0.4% and 0.7% and the soil water holding capacity is estimated as 200–300 mm in the rooting zone. The average annual temperature is 8.5 °C, the annual long-term average precipitation is 533 mm and the elevation above sea level is 62 m. The experiments were designed by scientists, influenced by farmers and advisors, and based on farmers' constraints and current research gaps from the literature.

An experiment comparing different soybean and NL lupin cultivars and the effect of irrigation was established with a splitblock design with six replicates and the factors cultivar and irrigation during four consecutive years (2014–2017). The treatments included with and without irrigation, three early maturing soybean cultivars of maturity group 000 (Merlin and Sultana for feed use and Protibus for human food use) and one cultivar of NL lupin (Probor). In addition, the soybean cultivar Sultana (2016–2017) and the NL lupin cultivar Probor (2015) were grown with and without inoculation (HISTICK®, BASF, Germany) using recommended practices. Measurements included whole plant biomass, grain yield and additional agronomic observations including plant phenology, plant height, number of root nodules and weed infestation. Before winter (24 November 2015 and 20 November 2016) and in the subsequent spring (20 March 2016 and 7 March 2017), mineral nitrogen was measured in the soil at three depths (0–30 cm, 30–60 cm, and 60–90 cm). After the harvest of NL lupin, turnip rape (*Brassica rapa* L.) was established as a cover crop. After soybean, the soil was left fallow because time before winter was not sufficient to establish cover crops after the late soybean harvest (between the middle of September and the end of October).

Irrigation water was applied with a sprinkler system using the Web-BEREST model (Mirschel et al., 2014) to determine the amounts and timing. Web-BEREST calculates the irrigation water based on the crop demand using the coefficient of actual to potential evapotranspiration. Detailed information on the model assumptions and equations are provided by Mirschel et al. (2014). The dates, applied irrigation amounts, precipitation, temperature, radiation and potential evapotranspiration calculated according to Wendling et al. (1991) are provided in Table S2 for 2015 and Table S3 for 2016. In 2017 no irrigation was needed because of sufficient and well distributed rainfall.

In another on-station experiment at the same site, the pre-crop effect of soybean, NL lupin with the cover crop turnip rape and buckwheat was tested on the grain yield and protein content in the following oat crop. In this experiment a spring oat crop was established on the same plots as the experiment described above following the different pre-crops with 6 replicates, no additional treatments and during two consecutive years (2016–2017). For both experiments, statistical comparison of means was performed with the SAS PROC MIXED procedure.

2.2.4. Step 4. Re-design of grain legume cropping systems

For the re-design of cropping systems with grain legumes, we described practices that potentially lead to agronomic improvements based on the evaluation of all actors in a final workshop in 2017, with 20 participants including organic and conventional farmers, advisors and scientists. Besides the agronomic practices we assessed the contribution, and the pros and cons of the three different methods, crop rotation modelling, on-farm trials and on-station experiments, for designing novel grain legume cropping systems in a qualitative approach following Bloch et al. (2015).

3. Results and discussion

First, we present the results applying the new approach to answer the objectives (1–4) for describing, explaining, exploring and re-designing organic grain legume cropping systems using a case study with farmers and specific cropping systems in northern Germany (Section 3.1). Second, we describe and value the lessons learned from applying the approach to advance cropping systems agronomy beyond the case study addressing objectives 5–6 (Section 3.2).

3.1. Case study on re-designing organic grain legume cropping systems in northern Germany

3.1.1. Describe grain legume production constraints and opportunities (step 1)

In the survey, farmers considered temporal yield instability (mentioned by 21 of the 23 respondents), weed infestation (20 respondents) and yield level (yield gap) (19 respondents) as the three most important production constraints for NL lupin. High yield instability of grain legumes was also mentioned in previous surveys (Von Richthofen et al., 2006; Zimmer et al., 2016b) and Cernay et al. (2015) found lupin to be the most unstable crop in Western, Eastern and Northern Europe, followed by common bean, vetch, faba bean soybean and pea using average yield data neglecting scaling effects. The analysis of yield data from long-term experiments using a scale-adjusted yield stability indicator (Döring and Reckling, 2018), however, revealed that lupin yields were as stable as those of other spring crops and more stable than pea and faba bean (Reckling et al., 2018b). These contrasting findings may reflect the fact that farmers perceive grain legumes to be less stable because of their relatively low market prices and less developed value chains (Preissel et al., 2017; Meynard et al., 2018). Agronomic constraints with pests, diseases, weeds and harvest losses are also likely to be higher at the farm level and are less visible in small plots of LTEs (Kravchenko et al., 2017). Another analysis has indicated that yield stability of grain legumes has decreased over the last 60 years (Reckling et al., 2018a) which needs to be accounted for when re-designing legume-supported cropping systems.

Weed infestation, especially of annual spring weeds such as *Chenopodium album* L., is problematic in lupin because it is a relatively weak competitor. Weed species adapted to the crop growth patterns may increase to intolerable levels over time if the proportion of grain legumes or other spring crops in the rotation is too high (Döring, 2015). Although mechanical weed control is practiced on organic fields, it is not always sufficiently effective. There is a large yield gap in European-grown grain legumes between the yield achieved by farmers and the yield potential obtained with experiments and models that is caused by genetic, management and environmental factors (Loïc et al., 2018). Farmers were also concerned about spatial within-field yield instability (14 respondents) and harvesting challenges (14 respondents), but perceived less constraints with the crop management and rotation design. Within-field crop yield instability is also common in other crops (Maestrini and Basso, 2018). Harvesting challenges are often linked to harvest efficiency, insufficient grain quality, uneven maturity and pod shattering (Loïc et al., 2018).

There has been little research on the adaptability of soybean to different environmental conditions across Europe and it was grown by only a few farmers in the study area. Constraints were related to the choice of early maturing cultivars for cool climates, weed management in general, and sufficient water supply during flowering and pod filling.

Farmers saw opportunities for improving cropping systems with grain legumes and all 23 respondents were interested in the impact and management of weeds. Most farmers were interested in the factors affecting biological nitrogen fixation (21 respondents) and improving the nitrogen balance (19 respondents), 21 respondents in the effect of the legume on the subsequent crops in the rotation, 20 respondents in identifying the site-specific yield potential (yield gap) and in the impacts of grain legumes on the cropping system as a whole, 19 respondents in impacts on biodiversity, and many in tillage options to increase soil organic matter, reduce erosion and increase the flexibility of field operations. Specifically for soybean, farmers were interested in the impact of irrigation on grain yield, in cultivars adapted to their growing conditions and in suitable cultivars for feed and food markets, which could be a reflection of their concerns that water would limit soybean production.

Based on the major constraints, namely high yield instability, weed infestation and large yield gap, along with the opportunities, primarily improving the management of weeds and nitrogen balance, increasing the yield potential and identifying options to utilize the preceding crop effect and reduce soil tillage, a priority list of targets was produced with input from all actors (Table 1). The list included prioritized options that were relevant and feasible for implementation by farmers and could be addressed with rotational modelling, on-farm trials and on-station experiments within the two demonstration networks on soybean and lupin. The prioritized targets included, (i) reducing weed infestation in grain legume rotations, (ii) improving the nitrogen balance by increasing fixation and reducing losses, (iii) reducing soil tillage for increasing flexibility of field operations for optimal sowing, (iv) increasing yields by optimal nutrient supply, (v) identifying yield potential of soybean, (vi) utilizing preceding crop effects most effectively. These targets were guided through the Explain and Explore phases and finally evaluated in the re-Design phase by identifying concrete practices implemented by farmers. In this study we focused on constraints identified in the survey and during discussions with stakeholders in the Describe phase so we did not consider all possible options such as genotypes with improved adaptation to environmental stress. There are other important targets to consider such as improving value-chains that were out of scope of this agronomic study.

3.1.2. Explain current grain legume impacts and explore alternative options (steps 2 and 3)

3.1.2.1. Reducing weed infestation in grain legume rotations. Using ROTOR showed that there is a high risk of weed infestation in rotations with grain legumes. High weed infestation was also perceived by farmers as shown in the survey during the describe phase. All of the 37 rotations assessed with ROTOR had increased risk of weed infestation (score > 0) with summer annual species (84% of the rotations) and winter annual species (76%) (Fig. 3 A). From these rotations with a general weed infestation risk, 19% and 11% exceeded the threshold (score > 1) for summer and winter annual weed species, respectively, where additional weed control is required to secure crop harvest (Bachinger and Zander, 2007). The majority of rotations had high shares of spring crops including grain legumes. These rotations had a higher infestation risk than rotations with a higher proportion of winter crops because tillage in spring enhances emergence of weed species that mainly germinate in spring (Håkansson, 2003). We also identified rotations with a low or reduced infestation risk for both winter and spring annual species, e.g., three rotations had a reduced infestation risk for summer annual species of −0.2, −0.2 and −0.3 and at the same time a relatively low infestation risk for winter annual species of 0.6, 0.6 and 0.8, respectively (Fig. 3A) and two rotations had a reduced infestation risk for winter annual species of −0.2 and −0.4 and at the same time a relatively low infestation risk for summer annual species of 0.7 and 0.8, respectively (Fig. 3A). These rotations were

Table 1
Applying the DEED framework for designing novel cropping systems incorporating grain legumes.

Describe constraints & opportunities *Avenues for optimization*	**Explain** impacts of current farming *Assessing grain legumes in rotations*	**Explore** alternative practices *Testing technical options at field scale*	**Design** novel grain legume systems *Strategies considered to be "successful"*
(i) Reducing weed infestation in grain legume rotations	- Increased weed infestation risk with summer and winter annual weed species of farmers' rotations (M) - Weeds problematic in NL lupin and soybean (F)	- Hoeing between rows with a wider row spacing was tested in NL lupin and soybean (F) - Direct sowing into a mulched winter rye without additional weed control (F) - late sowing of soybean (F)	- Hoeing between rows in NL lupin and soybean with wider rows (practice 1) - Direct seeding of soybean into mulched winter rye, but only with sufficient water availability (practice 2)
(ii) Improving the nitrogen balance by increasing fixation and reducing losses	- Nitrogen balances of rotations were partly negative (M) - SOC balances were positive (M) - Potential risk of nitrate leaching after harvest (F)	- Inoculation of seed with rhizobia was tested for NL lupin and soybean (F) - Cover crops after NL lupin (S) - Undersown grass in soybean (F)	- Inoculation of soybean (practice 3) - Cover crops after NL lupin to reduce nitrate leaching (practice 4)
(iii) Reducing soil tillage for increasing flexibility of field operations for optimal sowing	- Ploughing required more time and energy and reduced flexibility	- Different tillage operations were tested for NL lupin and soybean (F)	- Reduced tillage in spring (practice 5)
(iv) Increasing yields by optimal nutrient supply	- Deficiency of B and S observed in the soil (F)	- B and S fertilizers were tested (F)	- No strategy identified yet
(v) Identifying the yield and economic potential of soybean	- Large range of soybean yields observed on farmers' fields (F)	- Different cultivars were tested (F/S) - Effect of irrigation was tested (S) - Comparison of soybean with NL lupin	- Soybean cultivation to achieve relatively large gross margins (practice 6) - Different cultivars for food and feed use to reduce risk (practice 7) - Rainfed cultivation possible - Flexible irrigation during flowering and pod-filling (practice 8)
(vi) Utilizing preceding crop effects most effectively	- Insufficient information available - Soybean discussed as less effective	- Different pre-crop combinations tested (S)	- Grain legumes with cover crops as preceding crops to enhance growth of subsequent crop (practice 9)

Approaches used were crop rotation modelling (M), on-farm trials and observations (F) and on-station experiments (S).

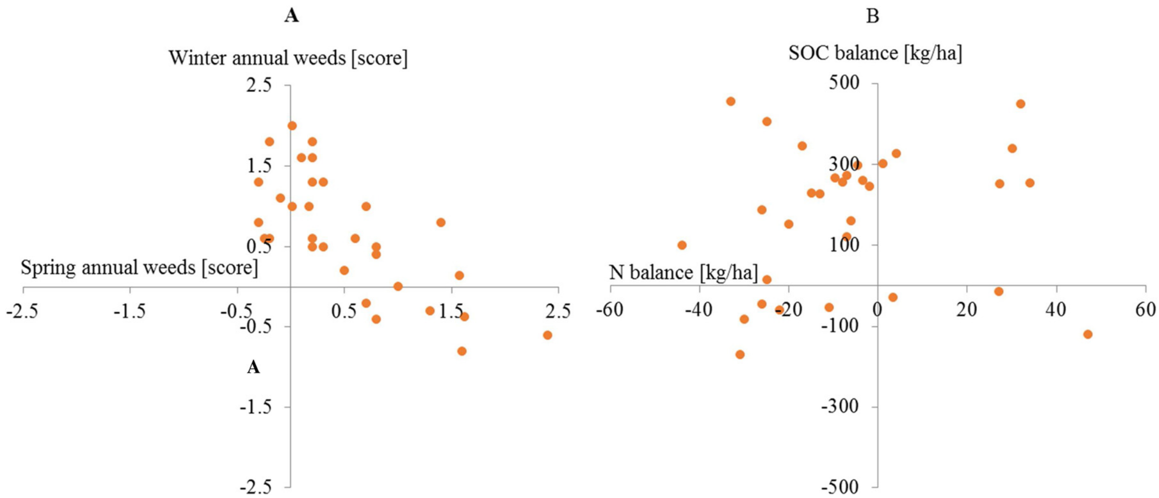

Fig. 3. Results from the crop rotation modelling with ROTOR (Bachinger and Zander, 2007) in 37 farmers' rotations with legumes. (A) Evaluation of the weed infestation risk using scores from -4 (decreasing the risk) to +4 (increasing the risk) for spring annuals and winter annuals with *Chenopodium album* and *Apera spica-venti* as indicator species. (B) N balance plotted against soil organic carbon (SOC).

characterized by large crop type diversity with perennial legume-grass mixtures and a share of both winter- and spring-sown crops. Rotations without grass-clover had the highest risk of infestation with summer annual weeds, because perennial forage crops that are cut several times reduce weed infestation by annual species effectively (Håkansson, 2003). Cover crops after spring crops and undersown grass-clover in cereals reduced the infestation risk of winter annual weeds in the evaluated rotations. This relatively simple weed assessment allows for relative comparisons between rotations but does not consider effects of soil type or water deficit that can be calculated with more sophisticated dynamic models (Colbach et al., 2017).

As part of the *Explore* step, we used on-farm trials to test hoeing between rows of NL lupin with a wider row spacing of 37.5 cm as an alternative to the standard practice with narrow (cereal) rows of 12 cm and 1–2 times harrowing (Table 1). A standard row hoe, common for other crops, was used. Farmers found this strategy to be effective in controlling weeds between the rows without compromising yield. On-farm, the yield was 1.0 t ha^{-1} in the wide and in the narrow row spacing in 2015 and 1.5 t ha^{-1} in both systems in 2016. While these experiments were carried out without true replicates, the systems were tested on large plots and during two consecutive seasons. Additional on-station experiments would be recommended to confirm or reject the conclusions from the on-farm trials. In Australia, wide row spacing has also been practiced by farmers (French, 2016). French (2016) found that lupin grown in wide rows tends to grow taller due to increased intra-row competition between individual plants, improving the harvestability and reducing water use compared with lupin grown in narrow rows. This might be especially relevant in low yield potential environments such as in north-eastern Germany with sandy soils and rainfall around 500 mm. According to French (2016), growing lupin in wide rows could encourage more aphid landings and hence virus spread (although virus infection in lupin plays a minor role in the study area), unless sufficient stubble is retained to cover bare ground between the rows. Weeds growing between the rows (if not removed by hoeing) experience less competition from the crop in wide than in narrow rows (French, 2016). In soybean, wider row spacing was already common practice among organic farmers to allow hoeing and different strategies including harrowing and planting into a cereal cover crop for reducing excessive hoeing were tested. There is a trade-off between planting soybean in narrow rows where increasing early-season crop tolerance to weeds reduces the need for early weed management but provides no option for mechanical weed management at later crop growth stages. Planting the crop in wider rows stimulates weed growth but allows effective weed management at different crop growth stages (Knezevic et al., 2017).

Direct seeding of soybean into a mulched winter rye cover crop that was crimped at flowering was tested on-farm during three growing seasons at two locations. Although weed populations were reduced, yields were generally much lower on-farm with 1.7 t ha^{-1} at one site in 2016 compared to the farmers' usual practice with ploughing and early sowing with 2.9 t ha^{-1}. The operation was not only time-consuming but also required specialist machinery, i.e., a roller-crimper and direct seeder that produces sufficient pressure to sow the seed through the thick mulch layer of the rye into the mostly dry soil. The system worked well only in 2017 with a soybean yield of 3.8 t ha^{-1} in the crimped system on-station when rainfall was plentiful and there was an ideal timing and implementation of crimping and sowing (after two years of experimentation). Under the relatively poor soil conditions with around 61% sand, only 0.6% SOC and several years of intensive tillage, sufficient water in the soil after the rye cover crop in spring and exact timing of crimping and sowing were identified as the main requirements for effective soybean emergence and subsequent growth (Bloch et al., 2016). The system requires further testing and fine tuning of the machinery used by farmers under prevailing conditions, while crimping rye as a cover crop is already widely used in the USA (Davis, 2017) because it effectively contributes to weed management. Davis (2017) also found that successful crop growth and high soybean yield was mainly influenced by optimal soybean establishment after crimping.

3.1.2.2. Improving the nitrogen balance by increasing fixation and reducing losses. Results with ROTOR revealed that 71% of modelled rotations had negative nitrogen balances while only 26% had negative SOC balances (Fig. 3B). The contribution of grain legumes to the nitrogen balance was small because the amount of nitrogen fixed was similar to the amount of nitrogen removed with the harvested grain. Similarly, in a meta-analysis for Europe, Baddeley et al. (2014) estimated N fixation to be similar to grain N production with a positive balance of only 13 kg ha^{-1} for lupin. The management and use of forage legumes and manures were more important drivers affecting the nitrogen and SOC balance in the assessed rotations than the grain legumes due to their larger contributions of nitrogen and carbon to soils. On-farm and on-station, we observed potential nitrogen losses after soybean harvest. On-farm, mineral nitrogen before winter reached 72 kg ha^{-1} (SE 3.8) in 2015 and 46 kg ha^{-1} (SE 4.1) in 2016 as mean over 20 and 16 measurements (Table 2), respectively, indicating a risk of nitrate leaching on sandy soils with a high leaching probability. In the

Table 2
Mineral nitrogen in the soil in kg ha^{-1} (average and SE) measured in on-station experiments and on farmers' fields in the soil before and after winter.

	2015/2016				2016/2017			
	Before winter		After winter		Before winter		After winter	
On-station measurements								
Soybean cv. Sultana	50	(4.6)	28	(4.4)	55	(4.3)	33	(2.1)
Buckwheat	30	(3.7)	33	(5.8)	30	(1.6)	21	(1.3)
NL lupin + cover crop	15	(1.8)	14	(2.8)	33	(2.1)	25	(1.1)
On-farm measurements								
Soybean cv. Merlin	72	(3.8)	15	(1.4)	46	(4.1)	36	(1.6)

following winter wheat crop, the after-winter quantity of mineral nitrogen was much less, 15 kg ha^{-1} (SE 1.4) in 2016 and 36 kg ha^{-1} (SE 1.6) in 2017, indicating that nitrogen may have been lost by leaching. Weather and especially temperature is an important driver affecting nitrogen mineralization (Liu et al., 2017) and the attendant risk of nitrogen leaching. Autumn-sown crops such as winter wheat take up only small amounts of nitrogen before winter, especially when sown late, e.g., after soybean harvest, which increases the risk of nitrogen leaching (Munkholm et al., 2017).

On-station we *explored* alternative strategies to reduce potential nitrogen losses during winter and monitored nitrogen leaching in more detail. On-station as on-farm, large amounts of mineral nitrogen in the soil before and low amounts after the winter indicated a high risk of nitrate leaching after soybean during the winter (Table 2). NL lupin followed by a frost-hardy cover crop (*Brassica rapa* L.) reduced the amounts of mineral nitrogen in the soil and the risk of leaching during winter that has already earlier been found in many other experiments with similar conditions (Justes et al., 1999; Macdonald et al., 2005). Buckwheat as a non-nitrogen fixing reference showed a lower risk of nitrogen losses during winter compared to soybean. While cover crops reduce nitrogen leaching after early harvested grain legumes (Plaza-Bonilla et al., 2015), this option is more difficult to implement with late harvested crops such as soybean. Therefore, one farmer experimented with undersown grass to increase nitrogen uptake after the soybean harvest and to reduce potential losses, but the establishment of the grass was not successful. Undersown grasses are known to be effective catch crops for N (Känkänen and Eriksson, 2007), but are not always popular among farmers because they have been reported to sometimes become weeds and reduce the grain yield.

We showed in on-farm trials and on-station experiments that inoculation with appropriate rhizobia increased soybean grain yields but not those of NL lupin, where no effect was noticed and farmers tend not to inoculate except when NL lupin is grown for the first time (not tested in these trials and experiments). In an on-farm experiment in 2015, there were no differences in grain yield between inoculated and non-inoculated NL lupin (both 1.0 t ha^{-1}). In the on-station experiments, inoculation of NL lupin (with biochar-based *Bradyrhizobium* sp.) did not affect final grain yield but increased dry weight of plants by 22 and 29% under irrigated and rainfed conditions compared to the uninoculated plants, respectively (Egamberdieva et al., 2018). In contrast, soybean grain yields were significantly higher when inoculated in 2017 on-station (0.9 t ha^{-1} without and 3.7 t ha^{-1} with inoculation). Whereas inoculation is known to increase soybean yield and nitrogen fixation (Zimmer et al., 2016c), there is little such evidence for NL lupin on fields where the crop has been grown previously. According to French (2016), inoculation of NL lupin is not necessary even if the previous crop was 5–8 years ago since lupin *Bradyrhizobium* is very robust on neutral to acid soils.

3.1.2.3. Reducing soil tillage for increasing flexibility of field operations for optimal sowing. For farmers, ploughing required more time and energy and reduced flexibility for field operations such as timely sowing, so reducing tillage operations for grain legumes was important. In NL lupin, no significant differences in yield (ranging from 0.95 t ha^{-1} to 1.02 t ha^{-1}) were observed when four different tillage techniques and depths were tested on-farm during 2017. The treatments were a) disc harrow with 10 cm cultivation depth, b) moldboard plough with 20 cm depth, c) chisel plow with 20 cm depth, and d) chisel plow with 35 cm depth. In the year of testing these techniques, the crop suffered from severe drought and weed infestation that probably obscured any differences between treatments. Faligowska and Szukała (2015) also found tillage treatments did not influence lupin grain yield and suggested simplified tillage treatments for this crop. In soybean, reduced tillage in spring before sowing was tested during 2015–2017. In 2015 when both systems were compared directly in on-farm experiments, the yield was 1.0 t ha^{-1} with and without tillage using the variety Herta PZO and 0.9 t ha^{-1} for both systems using the variety Merlin. It was considered feasible to reduce tillage by farmers in order to increase the flexibility of field operations, reduce costs and allow timely sowing compared to the standard ploughing technique, and it had no detriment to yield. In different analyses, reduced tillage has been found to provide several environmental and economic benefits at the farm level that make the implementation attractive to farmers when it does not reduce yields (Pittelkow et al., 2015).

3.1.2.4. Increasing yields by optimal nutrient supply. The sandy soils in the eastern study area have SOC contents below 1% and generally suffer from sulfur (S) deficiency especially in organic systems. Sulfur is especially relevant in legume crops and deficiencies result in lower yields and reduced N_2 fixation (Scherer, 2008). Input of S through deposition in Europe has reduced in recent decades and is expected to continue to decrease until, at least, 2050 (Engardt et al., 2017) making S fertilization relevant. Soil analyses on farms also revealed deficiency in boron (B) and on one farm 0.08 mg/kg soil of B were found on NL lupin fields in 2015 (0.3–1.0 mg/kg would be recommended). Since NL lupin has a high demand in S and B and other nutrients were not deficient, the farmer and researchers had the hypotheses that B or S deficiencies were connected to the relatively low yields of NL lupin of 1.5 t ha^{-1} on these sandy soils so organic-certified S- and B- based fertilizers were tested during 2016. The results showed that larger amounts of these nutrients were found in the above-ground biomass of NL lupin fertilized with them compared to the unfertilized control but that grain yields were similar between treatments (1.3–1.5 t ha^{-1}) and we concluded that these nutrients did not have the expected positive effects on yield under the conditions tested. Other studies in controlled on-station experiments found significant increases in grain yield when B and S fertilizers were applied to grain legumes such as soybean (Devi et al., 2012) but the soils were probably more deficient in these nutrients. Further experimentation with nutrients is recommended during more growing seasons and under controlled on-station conditions before drawing any general conclusions.

3.1.2.5. Identifying the yield and economic potential of soybean. The mean grain yield of soybean was 1.9 t ha^{-1} and ranged from 0.9 to 3.2 t ha^{-1} on 16 monitored farms in the eastern parts of the study area during 2014-2016. The high selling price for organic soybean of 830 € t^{-1}

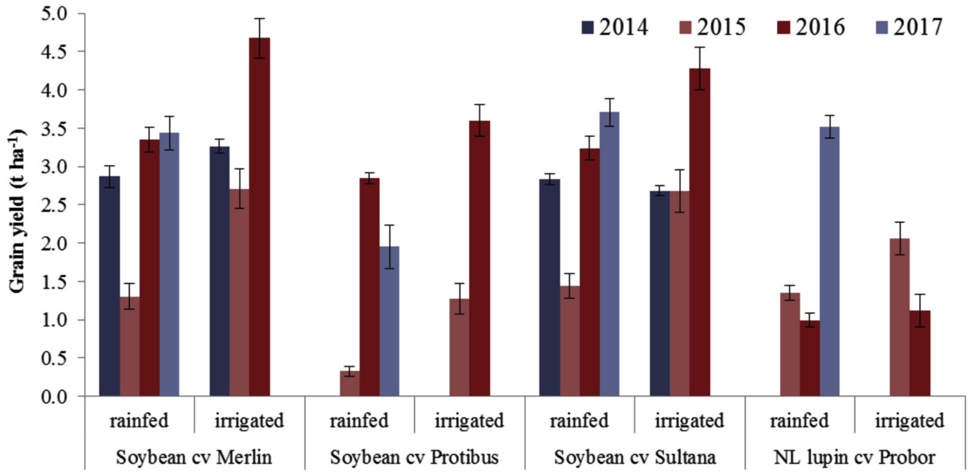

Fig. 4. Grain yield at 86% dry matter of three soybean cultivars and one narrow-leafed lupin cultivar in on-station experiments with and without irrigation from 2014 to 2017 (no irrigation in 2017). Error bars show standard error of the mean.

(700–930 €) made soybean cultivation profitable, with mean revenues of 1672 € ha^{-1} (SE 185 €) and gross margins of 892 € ha^{-1} (SE 176 €) despite relatively high variable production costs of 781 € ha^{-1} (SE 61 €). Conventional farming gave similar mean grain yields of 2.0 t ha^{-1} (1.5-2.8 t ha^{-1}) but selling prices were only 380 € t^{-1} (360–390 €) and gross margins 197 € ha^{-1} (SE 36 €). Across 60 organic farmers in Germany, Wolf and Schätzl (2019) found that soybean production was economically attractive and more competitive than other grain legumes and cereals.

The few soybean cultivars tested on-farm and on-station for feed were less variable in yield and tended to be earlier maturing than the tested food cultivars. Cultivars for food use had a higher protein content and higher market prices (around 100 € difference per t). On-station, grain yields of cvs Sultana and Merlin (both for feed use) were significantly higher with 2.8 t ha^{-1} (Sultana) and 2.7 t ha^{-1} (Merlin) than that of cv Protibus (for human food use) with 1.7 t ha^{-1} under rainfed conditions in the years 2014–2017 (Fig. 4). While the protein content for both Merlin (37%) and Sultana (41%) was lower than for Protibus (44%), the protein yield in kg per ha was higher with 794 kg ha^{-1} and 1109 kg ha^{-1} compared to 626 kg ha^{-1}, respectively. The difference in yield might be due to the choice of the cultivars rather than the use on the market but Zimmer et al. (2016c) also found higher grain yields (3.3 t ha^{-1}) and lower protein content (39%) for the feed cultivar Merlin compared to the food cultivar Protina (2.9 t ha^{-1} and 44%) tested on two sites over three years in eastern and central Germany. While high protein content and other seed quality attributes are required for food-grade soybeans (Zhang et al., 2010), intensified selection for protein content generally results in decreased yield because of the negative association between protein content and seed yield (Scott and Kephart, 1997).

The grain yield, protein content and protein yield of NL lupin cv Probor was significantly lower at 2.0 t ha^{-1}, 30% and 475 kg ha^{-1} than the soybean cultivars. While yields were lower in NL lupin due to severe pest (*Sitona griseus* Fabricius) and weed infestation in 2016, they were comparable with those of the feed-grade soybean cultivars in 2015 and 2017 (Fig. 4). There are few direct comparisons between these species, but grain yields of NL lupin and soybean were comparable and protein content was significantly higher for soybean under less favourable soil conditions in organic agriculture in Luxembourg (Zimmer et al., 2016a).

Irrigation did not affect grain yields significantly in 2014 and was not needed in 2017 because these years were particularly wet with an ideal distribution of rainfall during the summer. In contrast, 2015 and 2016 were particularly dry with a total climatic water balance from May to August of −350 mm and −284 mm, respectively. In these years, soybean grain yields were significantly (54%) higher in the irrigated than in the rainfed treatment (Fig. 4). Thus, rainfed cultivation of soybean is possible in north-eastern Germany, but the use of flexible irrigation equipment stabilizes yield in dry years and reduces the economic risk. While water resources are generally available, building of wells was mentioned as unattractive by farmers because most of their land is rented.

3.1.2.6. Utilizing preceding crop effects most effectively. Although farmers were interested in utilizing preceding crop effects of grain legumes more effectively, little information is available on the effect of NL lupin and soybean as preceding crops by farmers and in the literature (Preissel et al., 2015). Soybean was discussed among farmers and scientists as having less positive preceding crop effects than other grain legumes probably due to a high N harvest index (Jensen et al., 2012; Plaza-Bonilla et al., 2016) which limits the N benefits for subsequent crops. In an on-station experiment where different pre-crop combinations were *explored*, the grain yields of oat following NL lupin with a cover crop, soybean and buckwheat were 3.7 t ha^{-1}, 3.5 t ha^{-1} and 3.3 t ha^{-1}, respectively. Oat yields were significantly greater after NL lupin than after buckwheat (2016 and 2017) and soybean (2016). We did not observe differences in crude grain protein concentration in the oat after different pre-crops. Similarly, Zimmer et al. (2016a) found no differences in the pre-crop effects of NL lupin and soybean on the grain yield and protein content of winter wheat in Belgium and Anderson (2008) found no difference between soybean and winter wheat as preceding crops to winter wheat in the USA. While further preceding crop combinations need to be tested with soybean with the additional aim to preserve nitrogen after the crop harvest in Europe, our results showed that the preceding crop effect of soybean was comparable to other crops.

3.1.3. Re-design grain legume cropping systems (step 4)

In the co-learning process, we contributed to the re-design of farmers' cropping systems through the identification of nine practices (Table 1) that were tailored to specific farming contexts and were already influencing the implementation by farmers during the research project. The practices either were novel, confirmed known strategies under new conditions or provided additional evidence for implementing certain activities. While some practices were tested only during single years, e.g., nutrient fertilizers, others were tested over up to four years, e.g., soybean as an alternative grain legume. Hence results can be interpreted as farm-specific innovations.

(1) Hoeing between rows in NL lupin and soybean with wider rows was

a strategy considered to be successful in soybean and introduced to the cultivation of NL lupin during the project and implemented by some farmers. Since weed infestation was perceived a major risk, this strategy can be used by farmers to reduce this risk.

(2) Direct seeding into crimped winter rye was a strategy for soybean with limited success and possible only when sufficient water was available through irrigation or the cultivation on soils near groundwater. Thus, the implementation is limited to farmers with such conditions and access to a roller crimper and a direct seeding machine. For these farmers, it is an effective strategy to control weeds, reduce erosion and save time during the growing season for other field operations.

(3) Species-specific inoculation. In soybean, inoculation increased the amount of nitrogen fixation and yield, was negligible in cost and easy to implement, so it should be implemented where soybean-is grown. In contrast to some recommendations, inoculation of NL lupin did not provide visible advantages and is recommended only on those fields where the crop is grown for the first time.

(4) Cover crops after NL lupin reduced potential nitrate leaching and are already used by some farmers when the subsequent crop is spring-sown. The results highlight the need to find solutions to implement cover crops after soybean, such as undersowing of grasses or other species as a cover crop, or growing cover crops after soybean cultivars of very early maturity groups.

(5) Reduced tillage in spring with the cultivator instead of the plough allowed more flexibility for field operations, timely sowing and potentially less energy use. One farmer described the benefits as "after the positive results from the on-farm trials with reduced tillage and sowing into mulch, we adopted this practice on all our fields with grain legumes". Since grain legumes are less sensitive to reduced tillage this system could be implemented by more farmers in future while ploughing might still be needed in some cases, for example, to control perennial weeds.

(6) Soybean as a new crop achieved relatively high grain yields, higher protein yields than NL lupin and large gross margins in organic systems, so this species is likely to be grown by more farmers in future. This is supported by an increasing demand for European grown (GMO-free) soybean on the market. Implementation in the study area is constrained by sufficient water supply in dry years, risk of high weed infestation and little agronomic knowledge about cultivars and growing practices.

(7) Growing different soybean cultivars for food and feed use can reduce risk and potentially increase economic returns. Implementation requires good knowledge of the agronomic and genetic factors of different cultivars because few are of maturity group 000 and recommended for northern growing conditions. A farmer summarized the lessons learned as "since the on-farm variety trials within the soybean network, I am not hesitating anymore to grow varieties for food use which have higher market prices". Continued testing in on-farm trials or on-station experiments is necessary, involving partners from the food industry.

(8) Flexible irrigation is a strategy to allow irrigation in dry years, reducing the risk of low yields in rainfed cultivation, and should be used when possible during flowering and pod-filling. Implementation is specifically relevant for soybean where additional costs of irrigation can be compensated by the high market prices of the grain. The use is restricted to farmers that have access to water and irrigation equipment that requires substantial investment and is difficult to implement on rented land.

(9) Grain legumes enhance the growth of the subsequent crop. They are better preceding crops than non-legume crops and should be used in the rotation design. The use of cover crops after early harvested grain legumes such as lupin enhances the pre-crop effect. When the grain legume is followed by a spring-sown crop, implementation of cover crops is recommended and is also a formal requirement in some regional legislation for organic farming. For soybean, strategies still need to be developed.

3.2. Lessons learned to advance agronomy beyond the case study

3.2.1. The role of different methods for the re-design of grain legume cropping systems

The co-design process following the DEED cycle provided new insights into the use of different methods for the re-design of cropping systems with legumes. These insights include the need to complement knowledge on farmers' perceptions (Describe step) with formal knowledge from classical on-station experiments and modelling (Explain step) and on-farm research (Explore step) to identify tailored options for specific farm contexts rather than prescriptive solutions (Design step) to intensify legume production. The approach is different from traditional approaches that are often solely participatory and qualitative (bottom-up) or model/experimental-based and quantitative (top-down). The main added value of the approach described here is the combination of on-farm with on-station research. Four out of the nine practices were first identified through on-farm research (practices 1 and 5–7) and five practices (practice 2–4 and 8–9) were first identified in on-station research (although farmers and advisors contributed to the initial formulation of research gaps). Therefore, one approach alone would have missed around half of the identified practices.

The identified agronomic options should be seen as flexible alternatives to current practice that need to be adapted further by farmers to suit their specific needs rather than as fixed technology packages taken from formal research (Sumberg et al., 2003). During the workshops, farmers, advisors and scientists identified crop rotation modelling as a relevant instrument to highlight problems of the production system such as weed infestation, nutrient deficiencies and SOC losses. Models simultaneously consider different indicators (N, SOC, weeds etc.) that are seldom all measured in the field. They were seen as a tool for the diagnosis of the system and its components, provide useful input for discussions about the farm management and allow *ex-ante* assessments of adaptation options (Topp et al., 2017). Results are useful when their calculation is transparent and relatively simple, such as the assessment of weeds in this study according to the farmers and advisors. Concerns with model results include the risk that farm operations are often too complex to be integrated into models, not all factors can be taken into account and as one farmer expressed it, "the reality at the farm is often over-simplified". Results can be interpreted in different directions which can potentially lead to misuse, e.g., results about the large carbon footprints of specific farming activities. For some farmers, model results are relevant only when the indicators assessed are of economic importance.

On-farm trials were considered to be meaningful for practical farming, especially for the farmer implementing the trials, such as the technical options for weed management. They are rather short-term (1–2 years), flexible and involve farmers from the design phase until the interpretation of the findings, resulting in practical conclusions. On-farm trials allowed co-learning of novel practices from different environments and farm contexts and the testing of new machinery such as the roller crimper, but they were seen as less precise and difficult to reproduce, the results potentially being meaningful for one farm but not for others, reducing the possibility for scaling-up (Sinclair, 2017). This became evident for the strategy of direct sowing of soybean into the crimped rye cover crop, which required specific soil conditions and machinery. Statistical evaluation of on-farm trials without true replicates is limited and this needs to be taken into account when interpreting results and making conclusions from these trials. In contrast, on-station experiments were implemented under controlled conditions, with a fixed design (2–3 years) and with replications that allowed robust analyses. According to the stakeholders, these can be used for testing specific treatments that are of general interest, such as irrigation, crop response to fertilizers, inoculation and cultivars, and allow for detailed measurements of weeds, biomass, grain yield, and soil processes. Although on-station experiments were seen as the most valuable sources of knowledge, the results were considered to be less applicable in practice, e.g., soybean yields were 11% higher in the on-station experiments compared to the farmers' average yields. While innovation is locally driven in on-farm trials in a bottom-up process, on-station experiments and modelling compare innovations across locations and systems. If used complementarily, they offer scope for scaling-up and -out of innovations (Sinclair, 2017).

Participants valued all methods as potentially important and suggested that a combination of methods was more valuable than one alone. Combining the methods might open avenues for agronomy for ecological intensification (Doré et al., 2011) by providing information for model validation from on-station experiments and generate new research questions with on-farm trials to be tested with models and on-station.

3.2.2. Contribution of the DEED cycle to re-design grain legume cropping systems

The DEED cycle was applied once in this study, although with several iterations during the Explore phase by testing and evaluating new practices. An application of several full cycles including the characterization of a new state after the re-design of the systems could improve the design of relevant technologies and tailor them further to the specific needs of farmers (Falconnier et al., 2017). A similar cyclical learning approach was used with smallholder farmers in southern Mali (Falconnier et al., 2017), where a set of crop/livestock options was identified in a co-design process, tested on-farm and appraised, including a participatory ex-ante analysis of the re-designed farm systems. Pursuing the discussion with farmers who continue or discontinue using options provides insight into the relevance, as well as farmers' own adaptations to the options that could further inform the co-design process and move beyond "a measurement of adoption" (Ronner, 2018). Our operationalization of the DEED approach in a European context allowed moving beyond "farmers evaluating and researchers deciding" which options work best (Pircher et al., 2013). The co-learning affected the willingness to experiment with new cropping strategies (Bloch et al., 2015), encouraged exploring solutions to overcome site- and farm-specific constraints (Prost et al., 2018) and contributed to farmers' understanding of their own cropping system functioning (Toffolini et al., 2017). According to Toffolini et al. (2017) the agronomists' involvement in such research processes also influence the production of scientific knowledge. As a result researchers adapt their scientific aims to the farmers' needs while farmers review their goals and means as a result of these interactions (Hazard et al., 2018). Overall, different actors were brought together and new solutions were generated for improving the production of grain legumes that may be relevant for other parts of Europe as well.

Potential pitfalls of the approach include that (i) agronomic practices might be perceived as "novel" by researchers although they are already implemented by farmers, (ii) individual farmers dominate the participatory process so contributions and potential innovations from less dominant farmers do not get attention, and (iii) results could be short-term phenomena and are not supported by long-term observations under controlled conditions. Thorough steering of the co-design process is therefore needed and requires a mutual understanding between researchers and farmers and both need to be ready to leave their comfort zone (Hazard et al., 2018).

4. Conclusion

We conclude that working in a participatory research process with large-scale farmers in Europe in a co-learning process provided new insights into using systems agronomy to re-design legume-supported cropping systems. Our study highlights the need of complementing formal knowledge from classical on-station experiments and modelling with on-farm research including the local views of farmers. We adapted a conceptual framework to facilitate the co-learning between farmers, advisors and scientists to re-design cropping systems using different methods of agronomy and identified potential challenges. Through this framework, we identified a set of nine agronomic practices that are a starting point for further adaptations to suit specific farmers' needs. The practices increase the benefits of the most important services of grain legumes, provisioning of protein, nitrogen fixation and rotational effects, and reduce potential constraints with weeds and nitrate leaching. Implementing these practices contributes to making grain legumes economically and environmentally more sustainable. Options to reduce nitrate leaching after soybean, identify adapted soybean cultivars for the growing food market and implement direct comparisons between grain legume species warrant further investigation.

Author contributions

MR and JB conceived the study. MR performed the analyses, led the writing process, and GB, CW and FS contributed to the conceptual framework and interpretation of the results. All authors were involved in the writing of the paper.

Declaration of Competing Interest

The authors declare no competing financial interests in relation to the work described.

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Appendix A. Supplementary data

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