Renewable Agriculture and Food Systems

cambridge.org/raf

Research Paper

*Current address: Carrer Francesca Janoher 4A, 17230 Palamós, Spain.

**Current address: Sofielundsvägen 71, 21434 Malmö, Sweden.

Cite this article: Carton N, Swiergiel W, Tidåker P, Röös E, Carlsson G (2022). On-farm experiments on cultivation of grain legumes for food – outcomes from a farmer–researcher collaboration. *Renewable Agriculture and Food Systems* **37**, 457–467. https://doi.org/10.1017/S1742170522000102

Received: 13 April 2021
Revised: 20 December 2021
Accepted: 8 February 2022
First published online: 11 April 2022

Key words:
Agroecological practices; cropping systems; participatory research; post-harvest handling; sustainability

Author for correspondence:
Georg Carlsson, E-mail: georg.carlsson@slu.se

CAMBRIDGE UNIVERSITY PRESS

On-farm experiments on cultivation of grain legumes for food – outcomes from a farmer–researcher collaboration

Nicolas Carton[1,*], Weronika Swiergiel[1,**], Pernilla Tidåker[2], Elin Röös[2] and Georg Carlsson[1]

[1]Department of Biosystems and Technology, Swedish University of Agricultural Sciences, Alnarp, Sweden and [2]Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden

Abstract

There is a growing interest among farmers and consumers in increasing production and consumption of grain legumes in Sweden. This requires better knowledge among farmers and advisors about suitable species, varieties and management practices for different conditions. Since cultivar suitability and management practices are highly site-specific, farmers need to gain their own experience of new crops and practices. This paper describes a farmer–researcher collaboration in which cultivation of grain legumes for food was investigated in on-farm experiments designed, managed and evaluated jointly by a group of farmers and researchers. Farmers tested innovative practices using within-field species diversity, comparative performance of varieties and methods for weed control. Post-harvest steps such as cleaning and selling the crops were considered by farmers to be integral components of the experiments. The process generated different types of knowledge, including practical knowledge on crop management, strategic knowledge on economic sustainability and knowledge about joint learning through collaboration. The on-farm experiments combined advantages of 'pure' farmer experiments (i.e., context specificity) and 'pure' researcher experiments (i.e., scientific inquiry), facilitating deeper analysis and understanding of outcomes. This enabled efficient knowledge building, adoption of new crops and innovative practices and stimulated further experimentation. The outcomes of this study are that farmer–researcher collaborations using on-farm experiments can stimulate collective learning by stimulating the exchange between participants and combining complementary perspectives throughout the experimentation process. The study also provides recommendations for facilitating on-farm experiments in future work, for instance using collective settings to evaluate the results.

Introduction

Transition toward sustainable food systems requires substantial changes in how food is produced and consumed (Willett *et al.*, 2019). Including more grain legumes in cropping systems and increasing their proportions in human diets are key to this transition, due to the many benefits grain legumes provide in agroecosystems and diets (Voisin *et al.*, 2014; Preissel *et al.*, 2015; Magrini *et al.*, 2018; Röös *et al.*, 2018). Through symbiotic dinitrogen (N_2) fixation, grain legume cultivation reduces the need for synthetic nitrogen (N) fertilizers and the energy use and emissions related to fertilizer manufacturing (Jensen *et al.*, 2012). In cereal-based cropping systems, grain legumes also function as break crops that diversify the rotation, which can reduce weeds, pests and diseases and increase yields of subsequent crops (Preissel *et al.*, 2015; Watson *et al.*, 2017).

However, the potential of grain legumes in contemporary agriculture and food systems is far from being realized, and grain legumes are under-used in European cropping systems (Watson *et al.*, 2017). In 2019, only 2% of Swedish cropland was used for cultivation of grain legumes, mainly faba beans (*Vicia faba* L.) and peas (*Pisum sativum* L.) (Statistics Sweden, 2020).

The proportion of grain legumes in European cropping systems has remained low over decades, despite subsidies, and Europe relies largely on imports of grain legumes. Magrini *et al.* (2016) suggest that public policies, breeding programs and market dynamics have favored domestic cereal production, at the expense of domestic grain legumes. Underestimation of profitability due to difficulties in accounting for agroecosystem services provided by grain legumes (e.g., savings in the use of agrochemicals and yield increases in subsequent crops) may also have reduced interest among farmers in grain legume production (Zander *et al.*, 2016). In addition, there are agronomic constraints associated with grain legume cultivation, such as pests and diseases that limit the frequency of successive legumes in the crop rotation and low competitiveness against weeds (Watson *et al.*, 2017). Beside herbicides, mechanical weeding combined with row spacing and higher seed density can be used to control weeds. Intercropping cereals with grain legumes provide weed suppression (Malézieux *et al.*, 2009; Carton *et al.*, 2020). It can also increase yield or yield stability, especially for grain legumes that are difficult to grow due to weeds or sensitivity to lodging, in particular in systems with limited or no use of synthetic fertilizers and agrochemicals (Watson *et al.*, 2017).

There is clear potential to increase production and consumption of well-known Swedish grain legumes (faba bean, pea) and traditional or novel crops that are currently grown on considerably smaller areas (e.g., common bean, *Phaseolus vulgaris* L.; lentil, *Lens culinaris* Medik.; lupin, *Lupinus angustifolius* L.; gray pea, *P. sativum* var. *arvense* L.) (Röös *et al.*, 2018). However, expanding grain legume cultivation requires increased knowledge among farmers and advisors about suitable species and varieties for different conditions, and about suitable crop management practices regarding e.g., tillage, sowing density, intercropping and establishment of cover crops (Olsson, 2017; Reckling *et al.*, 2020). As knowledge of innovative practices in legume cultivation among agricultural advisors may be relatively limited (Zimmer *et al.*, 2016; Mawois *et al.*, 2019), farmers often need to gain their own experience of all steps in managing new crops.

Field experiments in research are characterized by e.g., small experimental plots (typically 10–150 m^2), use of controls, replicates, randomization and predetermined plans (Hansson, 2019). However, field experiments are in effect performed by farmers world-wide, since experimentation is essential for gaining practical knowledge on farming practices, although in a commercial context (Maat, 2011). Specific constraints, such as pressure of pests and weeds, risks of drought, lodging, etc., can affect crop species differently and can differ between locations and fields. Such constraints cannot always be predicted beforehand from research or advisory services reports or from other farmers' experiences. However, farmer's experiments can generate locally adapted and relevant knowledge among farmers themselves and support their decision making on crop choice and management. Maat (2011) recommends that different approaches of field experiments can be merged by involving farmers, scientists and agricultural advisors. A recent study combining on-farm trials with quantitative approaches in a participatory process involving farmers, advisors and scientists concluded that co-learning among the participants provided many new insights and had great potential to support development of more sustainable cropping systems (Reckling *et al.*, 2020).

In agroecological practices aiming to replace technological and chemical inputs with biological processes, e.g., using legumes to provide N to the cropping system, it is particularly important to adapt practices to local conditions (Christofari *et al.*, 2018). Instead of promoting large-scale implementation of a certain management practice, Catalogna *et al.* (2018) suggest that it is more efficient to support farmers in finding their own solutions. It thus seems highly relevant to hybridize the knowledge and ways of learning of scientists and practitioners (Francis *et al.*, 2011). In this, the complementarity between academic research and on-farm experiments is a promising field of study (Navarrete *et al.*, 2018). However, factors that can enable farmer–researcher collaborative on-farm experiments to become a powerful tool in implementation of novel and/or more sustainable practices must first be identified. A collective approach, in which interactions between farmers take place in a facilitated group setting, could support faster learning and innovations (Kroma, 2006; Murphy, 2012).

The aims of this study were to: (1) describe and analyze the design, management and evaluation stages of on-farm experiments for grain legume cultivation in a collaboration between farmers and researchers; (2) investigate what farmers can gain from their own and other farmers' experiments and from the collaboration with researchers and (3) suggest how on-farm experiments can be facilitated and used as a tool in transition toward food systems relying more on domestic grain legumes.

Methods

Overview

We initiated a collaboration with a group of farmers in southern Sweden to investigate possibilities to produce more grain legumes for food. Farmers were selected based on their interest in testing new grain legume crops or new practices to manage already well-known grain legume crops (section 'Farm selection'). On-farm experiments were planned, performed and evaluated during two seasons (2018, 2019) (section 'Coordination of the collaboration and data collection'). On-farm experiments are defined here as experiments performed on farmers' fields, using farmers' own machinery, and where design, management and evaluation are performed jointly by farmers and researchers, while technical operations are handled by farmers. During the initial workshops, farmers were informed about reimbursement to compensate for increased costs when performing on-farm experiments.

We described and analyzed the experiments using an adapted version (section 'Analysis') of the framework for farmers' experiments developed by Catalogna *et al.* (2018). Using our own experiences as scientists conducting field experiments, complemented with perceptions and inputs from the participating farmers, we then evaluated the types of knowledge gained from the on-farm experiments. Finally, we reflected on our own and farmers' experiences of the process, to identify what makes such farmer–researcher collaborations fruitful and how they can be improved.

Farm selection

An invitation was sent via email to 112 conventional and organic farmers in southern Sweden (mainly the Scania region), describing the intention of forming a farmer group linked to a research project aiming to increase cultivation of grain legumes for human consumption in Sweden. Contact with these farmers had been established in previous collaborations and communication activities, or was initiated via a food company participating in the project which agreed to send the invitation to farmers supplying them with crops. Eleven farmers decided to join the group and, of these, nine farmers conducted one or more experiments during the project (four conventional farms and five organically certified farms). The participating farmers wanted to grow legumes as a way to diversify cereal-based crop rotations and provide inputs of biologically fixed N. Several farmers stressed that an important underlying motivation was to produce more food (*vs* feed), as a response to the growing interest and demand from society and to the low profitability of feed legume production. Several farmers also mentioned a goal of growing grain legumes on a small scale and finding alternative markets that could increase profitability.

Coordination of the collaboration and data collection

The participating researchers organized the meetings and other communications with the farmer group, and coordinated the data collection. The researchers and farmers discussed the objectives of the on-farm experiments during winter (2017–2018) in workshops, via email and in one-to-one conversations by phone (Supplementary Table S1). Farmers decided to perform individual experiments on their farms, as opposed to replicates of a common experimental design on several farms, in order to increase the relevance to their own farm needs and conditions. Suggestions from the researchers regarding interesting practices to test and evaluate in on-farm experiments (Supplementary Table S2) were sent out to farmers, and were followed-up by discussions between farmers and researchers about a suitable design for each experiment. This resulted in agreement on experimental set-ups that combined researchers' interest with farmers' interest, experience, motivations, competence and possibilities. Depending on the farm, the experimental treatments ranged from an entire field as one sole treatment (no within-field comparison) to a treatment in a small part of a field and compared with the rest of the field, or a field divided into two or more parts of similar size with different treatments.

Semi-structured interviews (interview guide is provided in Appendix 1, Supplementary material) based on the descriptive framework of farmers' experiments (Catalogna and Navarrete, 2016) were performed with nine farmers during farm visits in the summer of 2018. Observations and measurements were performed by researchers on two occasions, once in early June and once just before harvest. Depending on the specific experiment, and after discussion with farmers, the researchers measured all or most of the following parameters at least once during the growing season: crop plant density, pod density, spike density (intercropped cereal), crop height, crop biomass, crop lodging, visual estimation of weed pressure, main weed species and total weed biomass. These measurements were performed at 3–4 points per treatment, with each measuring point being $0.5\ \text{m} \times 0.5\ \text{m}$ ($0.25\ \text{m}^2$), in an effort to obtain a representative mean value per treatment. Plant density was measured by counting all plants of each sown species in the 0.25-m^2 square, pod and spike densities were calculated from number of pods and spikes counted on five plants in the 0.25-m^2 square, average crop height was based on five point measurements in each 0.25-m^2 square, lodging and weed cover were estimated by visual assessment in each 0.25-m^2 square according to a 5-grade scale (1: all crop plants standing upright; very low weed cover, 5: all crop plants flat on the ground; very high weed cover). The main weed species in each 0.25-m^2 square were noted, and crop and weed biomasses were measured by cutting all plants within the 0.25-m^2 square at ground cover, sorting into sown species (grain legumes and cereals separately) and weeds, drying at 80°C until constant weight and weighing. Information about the design, management and results of experiments (derived from farmers' and researchers' observations and measurements) was compiled by the researchers and then discussed, evaluated and interpreted collaboratively with the farmers.

Learnings from the 2018 season were incorporated into the planning and design of the 2019 experiments. A second round of interviews focusing on farmers' experience of the project, i.e., critical reflections on the learning process based on the 2018 experiments, was conducted in July 2019 with four of the nine farmers and combined with observations of the new experiments. The same parameters as in 2018 were measured in experiments at the time of harvest in 2019. A final workshop in February 2020 was organized for farmers to present and discuss their experiments and for researchers to collect data on farmers' perceptions of the overall collaboration. In total, nine farmers performed ten on-farm experiments in 2018, and five farmers performed nine on-farm experiments in 2019. Among the four farmers who did not perform experiments during the second year, three of them still produced a grain legume crop but without any comparison of different treatments (crop choice, intercropping or other management options). The most common reason for not performing experiments was the lack of time for the farmer to design, manage and evaluate different treatments – although interested and motivated, some of the farmers needed to prioritize the general crop management and could not focus on experiments. Interviews and measurements were not performed on all farms in 2019 because of the absence of grain legume experiments on certain farms (even if a legume crop was produced, the farmer did not consider it an experiment).

Analysis

The identity of the nine farmers who performed experiments was coded (A–I). All interviews and most workshops were recorded, with the consent of the participants. Data from recordings, field notes and email correspondence were inductively analyzed by summarizing the content under themes adapted from the framework of farmer's experiments (Catalogna *et al.*, 2018). This framework comprises 13 *variables* divided into three stages of the experimental process: design (five variables), management (five variables) and evaluation (three variables) and each variable contains between two and six *modalities*, which describe the characteristics of each experiment. While most of the data in the present study fitted well into this framework, we also encountered some classes of information that could not be attributed to any variable or modality. We therefore adapted the framework slightly to fit our purpose (see footnote to Supplementary Table S4 for a detailed description of these changes).

See Supplementary Table S4 for examples of how the adapted framework was used to describe experiments on two farms, and Catalogna *et al.* (2018) for complete details about the original framework.

Results and discussion

Experimental process

The on-farm experiments that the farmers chose to perform are summarized in Table 1 (a detailed description of all experiments is given in Supplementary Table S3). Below, we give an overview of all experiments (section 'Overview of all experiments') and then describe the experiments conducted by two farmers (A, E), as detailed examples of how experiments were designed, managed and evaluated (section 'Specific experiments on two farms').

Overview of all experiments

Design. Information from the interviews, field observations (when researchers visited the experiments together with farmers) and workshops showed that farmers designed experiments to learn about innovative practices based on within-field species diversity, comparative performance of varieties, practical harvesting techniques, sorting and cleaning of the harvested product. Several farmers tested more than one novel practice at a time

https://doi.org/10.1017/S1742170522000102 Published online by Cambridge University Press

Table 1. Summary of on-farm experiments

Theme	Experiments	Results of the experiments
Develop production of a relatively new crop (lentil), comparing varieties	Two varieties (one known, one new), C, E, F (1 year each).	Later and more uneven maturity of the new variety (C), higher lentil plant density and biomass (E), lower lodging of the new variety (E, F). Tendency for higher grain yield of the new variety.
Develop production of a relatively new crop (lentil), intercropping and post-harvest handling	Intercropping with cereals (A, C, 1 year; F, 2 years), intercropping with faba bean (E, 1 year).	Less weeds by intercropping with cereals compared with lentil sole crops (A, C, F, 1st year), intercropping was almost as efficient as an additional weed harrowing to reduce weeds (C). Less lodging by intercropping with cereals (C, F), slightly less lodging by intercropping with faba bean, but field losses due to late harvest and difficult to sort harvested lentils from faba bean (E). Differences between two cereal varieties in feasibility to sort harvested lentil seeds from cereals (A), easy to sell the lentils at a good price (A).
Try a new crop (gray pea), cultivation practices	Spring gray pea sole crop (B, 1 year) or intercropped with spring cereal (B, 1 year), winter gray pea intercropped with winter cereals (D, 2 years).	Unsuccessful cultivation of spring gray pea due to drought and lodging (B, 1st year) and bird damage (B, both years), successful cultivation of winter gray pea with cereals and new insights into compensation and complementarity in intercrops in response to within-field heterogeneity (D, both years).
Try a new crop (yellow pea), cultivation practices and post-harvest handling	Yellow pea for human consumption produced for the first time by the farmer, although the crop is known in the region. Contract with new buyer (G, 1 year; I, 2 years).	Unsuccessful crop due to drought (I, 1st year), relatively easy and successful cultivation (G, I, 2nd year). Successful collaboration with new buyer made the crop more profitable than peas for animal feed (G).
Develop production of a well-known crop (faba bean), cultivation practices and post-harvest handling	Different row distance and hoeing/harrowing to control weeds (C, H, 1 year each), conventional *vs* no-till and pesticide-free cultivation (G, 1 year), no-till *vs* shallow tillage before establishing the crop (E, 1 year) different preceding cover crops (E, 1 year). Contact with new buyer (G).	Visual observations of less impact of drought in wide rows, but no difference in measured weed and crop biomass (C), no comparison possible due to delayed sowing with narrow rows (H), visual observations of less weeds in conventional cultivation, but no difference in measured crop and yield biomass (G). Extreme drought may have reduced the differences between treatments (C, G). Tillage before preceding cover crop did not reduce weeds (E, 1st year), no difference in crop performance nor weed abundance caused by different preceding cover crop (E, 2nd year). Selling to a new buyer in the emerging food sector generated a considerably higher price than for feed (G).
Other cultivation practices: sowing a cover crop in established crop	Sowing a cereal, grass or grass–clover mixture between rows of the main crop at the time of last hoeing (B, C, D, 1 year each).	Failure to establish cover crop due to drought (B, C), successful establishment despite drought when sowing a grass–clover mixture at larger soil depth than what is common practice (D).

A–I are codes for the different farmers.

(e.g., new crop and intercropping), which was viewed as a better approach than comparing different crops or practices in different years (farmer E). Several, but far from all, experiments suggested by the researchers (Supplementary Table S2) were selected and often modified by the farmers to fit their own interests and conditions, e.g., by adding different tillage methods before sowing or different approaches for chemical weed control. All experiments addressed one or several of the following objectives: (1) learning to grow a grain legume crop that was new or relatively new to the farmer; (2) learning to handle and sell the harvested product, sometimes by establishing relationships with new buyers and (3) developing alternative cropping practices for more well-known crops, to reduce the labor and machinery costs or increase the yield, often with the focus on solving some issues experienced with weed management and lodging.

In new or relatively new crops (lentil, gray pea), the experiments often combined several aims related to agronomy: learning about the crop's growth cycle and potential difficulties (e.g., sensitivity to weather variations, weeds, pests, harvesting technique), trying intercropping and comparing varieties, but also post-harvest steps (e.g., sorting, selling). With faba bean (a relatively well-known crop), the experiments focused on establishment methods and weed control. With yellow pea (also a known crop), the focus was less on management practices and more on establishing a relationship with a retailer selling peas for human consumption. Establishment of a cover crop in a grain legume and the effect of the preceding cover crop were additional themes of interest. The variable 'choice of location and size' for the experiment was discussed in several cases between farmers and researchers. The experiments comprised of one to seven treatments and a maximum of three factors, in a gradient from fully factorial experiments to fully systemic experiments, with several experiments combining features from both. Other experiments consisted of one treatment with no within-field comparison during the same year. The experimental area ranged from approximately 0.5 to 30 ha. There was no control of heterogeneity within the field by replication of treatments, except in one case (farmer F) where planned undersowing of a companion crop in different strips was not done due to drought, unintentionally giving the possibility to use the strips as replicates. The farmers seemed to be aware of the benefits of replicates, but did not see it as a feasible option in practice.

Management. From the interviews, we learnt that farmers found it useful to observe and take measurements in experiments where different treatments were compared, but considered measurements less useful in experiments with no in-field comparisons. Unexpected events encountered were: stopping an experiment because of crop failure (damage by pests, high weed pressure), treatments planned but not implemented (lack of seeds, lack of time, drought) or treatments deemed unsuitable for comparison because of identified bias (difference in sowing date, choice of location). Summer 2018 was unusually hot and dry, which caused deviations from the designed experiments due to e.g., difficulties in carrying out planned mechanical weed control and in undersowing a cover crop in the established crop. Except in such cases of external factors causing deviations or crop failure, farmers rarely adjusted their management once the experiments were underway, as also found by Catalogna *et al.* (2018). On the other hand, farmers' perception of the suitability of the chosen field for the experiment sometimes changed during the management stage (see section 'Specific experiments on two farms'). Post-harvest steps were often an important concern for the farmers, especially in relation to trying a new crop or testing if a new practice made a difference for post-harvest handling (e.g., intercropping). The farmers were also keen to find out whether a market was ready to pay a good price for a crop that was new to them.

Evaluation. The experiments generated results that confirmed the feasibility or identified difficulties in the cultivation of new or relatively new grain legume crops (lodging and weeds in lentil, bird damage in gray pea, drought in all crops in 2018), and led to ideas for new experiments to overcome difficulties. The experiments also provided information about the relative efficiency of new practices (e.g., new methods for tillage or weed control, establishment of cover crops, choice of intercrops) and about soil preferences of crops based on observations of within-field variations. In most cases, the results were discussed to some extent by the farmers themselves, whereas in the study by Catalogna *et al.* (2018) farmers rarely discussed their experimental results. In our study, the inputs from other farmers and researchers during collective workshops probably stimulated discussions of results.

Lentils produced a harvest quality and quantity considered satisfying by the farmers on organic farms and in a conventional conservation agriculture system (minimum tillage), and intercropping with cereals was confirmed to be an efficient strategy for reducing weeds in organic farming (as found by e.g., Wang *et al.*, 2012; Kraska *et al.*, 2020). Intercropping lentil with a cereal reduced lodging in a majority of the experiments and was therefore suggested as an interesting strategy even in conventional farming. The tendency for different yield levels between lentil varieties (Table 1) stimulated farmers' interest in further varietal comparisons in future on-farm experiments. The conclusions from experiments with faba bean were that it is a relatively flexible crop and does not respond strongly to different cover crop managements, sowing patterns and weeding practices. However, it was also concluded that the unusually dry and warm weather in 2018 might have reduced potential differences between treatments. In general, for all crops, observed differences in pest (including birds) damage, weeds, lodging and drought risk between farms and fields confirmed the value of on-farm experiments in generating useful site-specific knowledge (Darnhofer *et al.*, 2010; Maat, 2011; Hansson, 2019). In addition, farmers also expressed that they found great value in sharing results and observations within the group, and that they could generalize and make use of certain outcomes such as the effect of intercropping lentils and cereals on weed abundance or the unsuitability of certain intercrop mixtures due to difficulty to sort the harvested products.

Specific experiments on two farms

The two farms (A, E) for which the on-farm experiments are described in more detail (see Supplementary Table S4) are both located in a peri-urban setting and focus on cereal production. Farm A is organic, with approximately 30 ha arable land (mainly cereals, rotated with ley, grain legumes and mustard) and a focus on landrace cereals. Farm E is conventional, with approximately 250 ha arable land (mainly cereals, rotated with oilseed rape, grain legumes and ley), managed according to conservation agriculture (minimum tillage, cover crops and a relatively diverse crop rotation).

Farm A. The objectives of the experiments on farm A were learning to grow lentil as a high-value crop and testing intercropping as a way to grow cereals with low inputs and efficient weed management in lentil fields. For this farmer, in the beginning of the project (2018) lentil was a relatively new crop and intercropping a relatively new practice. The farmer had tried to grow lentil intercropped with oats (*Avena sativa* L.) in 2017 without success; the oats were eaten by birds and the lentil crop was not harvested. The farmer planned to sort and clean the harvested seeds on the farm and sell the lentils directly to consumers.

In 2018, the farmer wanted to try lentil–cereal intercropping again and used suggestions by researchers to improve the *design* of the experiment. The experiment, with a total size of 1 ha, had a factorial structure with four treatments: intercropping lentil and spelt (*Triticum spelta* L.) with two spelt densities, and comparisons with both sole crops. During the *management* stage, the farmer decided to terminate the experiment because of very high weed pressure. The whole field was then treated as black fallow to control weeds, except for a small area that the researchers used to keep observing development of the lentil crop. The experiment was unsuccessful in terms of providing a harvest, but *evaluation* of the experiment identified several possible improvements. The farmer's evaluation, based on his own visual assessments of crop establishment and observations during field operations, was that the high weed density was due to low cereal density (damage to seedlings by birds), late crop emergence and difficulties in seedbed preparation and mechanical weeding (due to the severe drought in 2018). The measurements made by the researchers on the small area left were initially considered of little value by the farmer but were later acknowledged as useful for observing how the lentils ripened and for comparing lentil and weed biomass with results from other on-farm experiments. The farmer noted a high level of lentil lodging, while the researchers, who had also made observations on other farms, did not consider the degree of lodging in this small lentil plot to be severe. One outcome was the idea to test other cereal species in the intercrop, in order to find one less sensitive to bird damage. The farmer also considered in retrospect that the field where he placed the experiment in 2018 was not suitable for lentil.

In 2019, farmer A set up experiments according to similar objectives and with a similar *design* as in 2018, but in two different fields of approximately 1 ha each. All the treatments were tested in plots of similar sizes. On one field with compacted soil and a large weed seedbank, intercropping lentil and a spring wheat (*Triticum aestivum* L.) landrace was tested, with two different wheat densities and comparison with a wheat sole crop (no comparison with lentil sole crop). The other field, which had a more fertile soil, was used for testing lentil intercropped with spring emmer (*Triticum turgidum dicoccum* L.), with two emmer densities and comparison with a lentil sole crop (no comparison with sole-crop emmer in the same field, but the farmer used a neighboring field for comparison). When *managing* the experiment (both 2018 and 2019), the farmer did not take notes, but relied on small sketches of the fields as experimental maps and mostly on memories to record the practices. He stated 'I don't have the time to do a perfect experiment'. The *evaluation* by the farmer was that the intercrops were successful until harvest, with relatively little lodging even in the lentil sole crop and a satisfactory lentil and emmer yield level. Birds reduced cereal plant density in the wheat landrace, but not in the emmer, which led the farmer to conclude that emmer was less sensitive to bird damage than wheat. The researchers' interpretation of these results highlighted the possibility that other factors than bird preference could have reduced the spring wheat density compared to emmer, since the two crops were tested in different fields.

Post-harvest steps to obtain sellable products of both cereals and lentils were an important part of the experiments. For the lentil–emmer intercrop this was judged successful, since sorting the lentils from the mixture was relatively easy. However, it was not possible to get pure emmer grains, so the farmer produced an emmer flour enriched with a minor quantity of lentils. The lentils were sold directly in the farm shop and via a farmers' market. In comparison, sorting the grains from the lentil–wheat landrace intercrop was not possible with the farmer's equipment, so intercropping wheat with lentil was not a satisfactory practice. These results provided valuable new knowledge, to the farmer as well as to the researchers, about the feasibility of separating harvested lentil seeds from different cereals.

Farm E. Farmer E, who applies minimum tillage, had observed that perennial weeds tend to spread into fields from the edges. He grows faba bean routinely in his crop rotation and sells it as conventional feed for animals. Before the collaboration with researchers, he had already *designed* an experiment with additional tillage on the outer field edges when establishing a rye cover crop (early fall 2017), to test whether this could limit the spread of perennial weeds into the subsequent faba bean crop (sown in spring 2018).

During the first on-farm visit in 2018 (*management* stage), the researchers found the comparison between field edge and the rest of the field to be biased and decided not to perform any measurements there. A discussion about within-field heterogeneity emerged and led to the idea of mapping variability in crop yield and weed abundance. When *evaluating* the experiment, the farmer observed that additional tillage on the field edge did not lead to any improvement in terms of weed control. This conclusion increased the farmer's interest in another alternative to herbicides for reducing weeds: undersowing a cover crop in faba bean.

The difficulty in comparing tillage on the field edge and in the rest of the field was discussed at the workshop in November 2018, where researchers expressed the view that experiments on the field edge are not optimal. However, subsequent re-analysis of the material from interviews and farm visits uncovered a misunderstanding by researchers: the farmer's objective was to compare the effect of extra tillage *on the field edge*, i.e., not with the rest of the field. This exemplifies the risk of misunderstandings arising from farmers' and researchers' different perspectives when discussing the design (i.e., objective) and management of on-farm experiments. Concerning within-field heterogeneity, the measurements by researchers confirmed the farmer's hypothesis that volunteer rapeseed plants (as weeds in the faba bean crop) and soil type (clay content) caused variations in faba bean yield.

Farmer E performed an experiment with lentil for the first time in 2019. The *design* of the experiment included two lentil varieties as sole crops and intercropping one of the varieties with faba bean, distributed on a 1-ha area in the same field as a faba bean experiment (described in Supplementary Table S3). The farmer avoided the first 24 m from the field edge, because the soil was more compacted there. Researchers advised that for lentil, intercropping with a taller erect crop is required to facilitate harvesting. The farmer and researchers considered it interesting to try intercropping lentil and faba bean, to our knowledge the first trial in Sweden. The farmer was aware of the advantages of intercropping legumes with cereals, but was interested in this combination since it allows use of herbicides to control grass weeds.

Lentil sorting and cleaning (performed by another farmer) was considered an important part of the experiment. An objective of the experiment was also to see if buyers would pay a good price for conventional Swedish lentils (one of the first efforts to grow this crop conventionally in Sweden) and to test packing and selling small bags directly to consumers.

The farmer *evaluated* the lentil crop as being successful. The level of weed biomass was very low, which the farmer partly attributed to direct drilling (no tillage before sowing), since the minimal soil disturbance can limit organic matter mineralization and N availability for weeds (Calderón *et al.*, 2001). Lentil density and development were very satisfactory. Harvesting was the most difficult step due to lodging. Intercropping lentil with faba bean only had a minor effect on reducing lodging. This intercrop combination was judged unsuccessful due to different maturation dates of the two crops causing lentil spill before and at harvest, and due to unexpected difficulties in separating harvested lentils from broken faba bean seeds. The farmer decided to try intercropping lentil with oats in the following year, as was first discussed with researchers. It proved possible to sell small quantities of lentils directly to private consumers, but the farmer would need to find another buyer for lentils grown on a larger area. The farmer later found a buyer for a bigger quantity of conventional lentils in 2020. Researchers' measurements and interpretations were in accordance with the farmer's conclusions.

Farmer E documented all cropping practices in the experiments (both 2018 and 2019) using software, linked to maps of all fields and connected to a mobile application. In this software, the farmer could directly enter plans for each field (crop, planned dates and methods for soil preparation, sowing, fertilization, plant protection, harvesting, etc.) and follow-up by entering the actual dates and details of all operations as well as the harvested crop yield and any other observations and results. This was useful when presenting and evaluating the experiments, but the software is not specifically adapted to follow experiments. The farmer collected information on yield-reducing factors such as insect damage to roots, bird damage causing some gaps in the crop stand

and weed infestation (main species and visual evaluation of the density or cover). He took photographs to record, e.g., the uniformity of crops at emergence. He was able to obtain yield estimates in the experiment involving lentils from the machinery used to sort the seeds.

Outcomes of the farmer–researcher collaboration

Knowledge gains

The collaborative work on design, management and evaluation of on-farm experiments generated different types of knowledge regarding possibilities for farmers in southern Sweden to increase their production of grain legumes for food. The knowledge gained can be broadly classified into three types: (1) practical knowledge for crop management (see section 'Overview of all experiments'); (2) strategic knowledge for improved profitability and (3) insights about collective learning through on-farm experiments.

Strategic knowledge for improved profitability. A few of the on-farm experiments included collaboration with new buyers of faba beans and yellow peas for human consumption, which resulted in higher profitability of these crops compared with selling them as animal feed. While this is not completely new knowledge, several farmers stated in interviews and workshops that the collaboration with researchers extended their network and made it easier to come in contact with potential buyers, as the overall research project also included collaboration with food industry. The experiments with lentil also included post-harvest steps, such as sorting and establishing contracts with new buyers. The experience gained by the farmers from this was that lentil is a high-value crop which can easily be sold through existing or new channels once the challenges in cultivation and post-harvest cleaning have been resolved.

Insights about collective learning through on-farm experiments. The workshops organized within this project for discussing experiences, ideas and results were viewed as very rich learning occasions by both farmers and researchers: 'This gives me more than what I observed myself. The experiment is in some way a basis for this sharing of experiences, and it includes everything: economy, planning, practical problems …' (farmer A). Information was shared and exchanged horizontally in an interactive environment, which stimulated emerging ideas and joint interpretations. There was an increasing sense of openness and interest in different perspectives and opinions among participants over time, which can be explained by a combination of several factors. First, the group composition and size were suitable for all participants to get to know each other and engage in the collective learning process. Secondly, the researchers made careful preparations for interviews and workshops, to ensure that these were based on a genuine interest in the farmers' experiences, perceptions and ideas, that the meetings contained both formal work sessions and informal activities for participants to get to know each other, and that the workshops contained exercises and tools developed for participatory learning processes (Eksvärd, 2003). Thirdly, the farmers had joined voluntarily, based on their own interest in new possibilities for producing legumes for food. This interest was shared by the researchers, and the overall common goal of strengthening the sustainability in Swedish grain legume production was likely a key motivating factor which stimulated the learning environment.

The following examples are illustrative of the types of knowledge that emerged in the process. At the workshops, farmers were asked to describe their experiments to the group, and other farmers often asked precise questions about the conditions (e.g., soil type, amount of rainfall) and practices (e.g., sowing densities, inter-row spacing, harvesting conditions) in order to visualize the situation(s). Farmers explicitly compared their experiences from trying the same crops, for instance lentil biomass or plant density on different farms, relative maturation date of varieties, degree of lodging or the ease of sorting harvested seeds from intercrops. It was not always possible to identify the main factors leading to observed differences between farms, but some hypotheses were shared and improved understanding of the biological processes involved. The fact that quantitative measurements (plant density, crop, weed biomass, etc.) had been consistently made by researchers gave value to these comparisons, which would have been questionable if the methods would have differed from farm to farm. Most farmers also clearly stated that being part of the group of farmers exchanging information and learning from each other motivated them to devote extra effort to the experiments (testing more ideas and taking better care of the experiments), which in turn allowed them to learn more. Being part of the group seems to have provided recognition and support for farmers' efforts, e.g., through realizing that others face the same issues (time constraints, low profitability, planning and practical issues). The interest from researchers was mentioned as an extra layer of motivation, creating a feeling of 'being on the right track'.

Another interesting aspect is that when asked at the beginning of the process about their own view on how they could learn more about legume production, farmers often talked about *producing* more. This seemed to change with time, so that the fourth workshop (February 2020; Supplementary Table S1) included several discussion points involving farmers' perceptions of the learning quality of experiments as such, irrespective of agronomic success or failure. A conclusion regarding the learning process was that the collaborative (farmer–researcher and farmer–farmer) discussions and interpretations of results from the on-farm experiments seemed to have stimulated in-depth reasoning in evaluation of results, e.g., by combining farmers' *know-how* and researchers' *know-why* (Ingram *et al.*, 2010).

The farm visits, interviews and workshops also served as learning occasions for the researchers, who gained new practical knowledge about e.g., crop management and sorting of mixed crops in the farmers' contexts. This was perceived as valuable for improving the researchers' ability to understand the site-specific conditions and take these into account when interpreting results from on-farm experiments. Post-harvest handling emerged as a central aspect of on-farm experiments, which is not always considered in field experiments conducted by researchers. The importance of knowing that the crop can be harvested and sold was common across the contexts (crops, treatments and size of experiment) represented by the participating farmers. The experimental designs without within-field comparison bring relatively little information on optimal cropping practices and were therefore at first seen as not very promising by the researchers, but they were successful in providing knowledge and know-how about the post-harvest steps. Indeed, experiments that were not initially considered as experiments from a researcher point of view (i.e., no comparison of different crops or treatments) turned out to be useful sources for sharing experiences among about cultivation and post-harvest handling, and provided new insights

https://doi.org/10.1017/S1742170522000102 Published online by Cambridge University Press

both for the farmers and researchers. Several of the participating farmers expressed appreciation that the collaboration allowed them to share experiences, broaden their network (e.g., new contacts with potential buyers) and learn from each other's experiments. This indicates that farmers generally have limited opportunities for such collective learning activities.

Critical reflections on the collaboration

Strengths. The collaboration with researchers made it possible for farmers to take greater risks in their experimentation, e.g., to try a previously unknown crop, since the research project reimbursed part of the famers' additional costs. All participating farmers agreed that the support from the researchers, the collective analysis of results from researchers' measurements and the communication with other farmers added important values to the individual on-farm experiments, and were strong motivators of their own investment of time in experiments, interviews and workshops: 'I learn a lot by taking part in other farmers' experiments, it contributes to faster development' (farmer B); 'Very interesting to see the results on the other experiments, this has increased my interest to try new crops' (farmer G).

The collaboration also made it possible to combine advantages of 'pure' farmer experiments (without involvement of researchers) and 'pure' researcher experiments (without involvement of farmers), as indicated in the synthesis of advantages and limitations of on-farm experiments involving farmers and researchers (Table 2). Farmer experiments have strong relevance for the local context, with outcomes that are directly accessible for the farmer: 'the experiment is made in the same scale as production, now I know what I can do with my machinery' (farmer E). Experimentation is also important for resilience, as it widens the repertoire of options when facing changes or disturbances and increases learning (Darnhofer *et al.*, 2010). However, lack of time, knowledge or resources for the farmer to carry out measurements (e.g., weeds, yield variations) may lead to evaluations of farmer experiments being based on a general perception, rather than the actual outcomes (Catalogna *et al.*, 2018). Researcher experiments, on the other hand, are highly focused on rigorous scientific design, including isolating specific factors and statistically solid evaluation of outcomes (Hansson, 2019). Feasibility of practices for farmers is often not considered, which limits the access and applicability of results for farmers (Table 2). This study showed that researcher–farmer collaborations in on-farm experiments can overcome several of these limitations.

Weaknesses. Several weaknesses of the approach were identified. Lack of time was stated as the first and most important limitation for farmers in following up on the plans for design, management and evaluation of their experiments, but also for researchers in maintaining active contacts and performing all observations, measurements and analyses. Even though the collaboration motivated farmers to prioritize the experiments, the reality of handling many activities simultaneously often made it difficult for farmers to spend as much time on the experiments as they would have liked. In other words, farmers were sometimes forced to prioritize other crops than the grain legume experiments during hectic periods in the growing season. This was the main reason why fewer experiments were performed in 2019. Other weaknesses included lack of knowledge of the market potential for new crops and difficulties in timely access to seeds for uncommon crops. The farmers sometimes faced specific practical challenges in managing the experiments, especially small experiments with new or minor crops, where small amounts of the harvested product were difficult to handle efficiently. This hindered simultaneous screening of large numbers of legume varieties, in which some farmers had great interest. Finally, collaborations such as these depend on research funding and reach only a limited number of farmers, and it is often highly uncertain if and how collective learning and development through on-farm experiments can be maintained after the end of the collaboration with researchers.

Complementarities. Through the collaboration, it became clear that farmers have a systems view of on-farm experiments, meaning that they almost always consider the post-harvest steps before deciding to set up an experiment. It is therefore crucial that post-harvest handling is feasible and that there is a market for the product. This is a valuable complement to researcher experiments, which often do not consider the feasibility for farmers in handling and selling the harvested products: 'If we had evaluated faba bean/lentil intercropping in small-plot researchers' experiments, we would not have discovered the unexpected difficulties to sort lentils from broken faba bean seeds' (farmer C).

In the experimental process, farmers often made quick decisions based on limited information, i.e., deciding not to continue with a new crop or a new method for weed control after only one observation of failure, even if the failure was explained by field- or year-specific conditions. Farmers may be forced to make quick decisions since they do not have the time or financial margin to repeat an experiment if it does not show clear added value. The external analytical view of researchers can be instrumental for extracting additional knowledge or deriving alternative conclusions from on-farm experiments, as noted by some of the farmers: 'Sometimes you have almost already decided what you want to see. Even when you make an experiment, if you assess it yourself you can influence the results' (farmer G); 'If someone else assesses it, there's a greater chance of changing your mind' (farmer C).

In the workshops where results from the on-farm experiments were discussed, it became clear that also farmers who had not performed experiments with the same crop or practice could contribute to the discussion and showed interest in the results and experiences from experiments on others' farms. Furthermore, experiences and observations from farms where a legume crop had been produced without any comparison of different practices or crop varieties also generated interesting insights for the whole group, e.g., about success in establishing a crop on a certain soil type under a certain management or feasibility of cleaning, sorting and selling the harvested crop. Thus, several discussions during the workshops indicated that the complementarity between farmers' and researchers' measurements, observations and interpretations was valuable for reaching conclusions that could be generalized across the different contexts of the participating farmers. A clear example of this is when one farmer discovered that the grains from a certain intercrop could not be completely sorted and cleaned, which instructed other farmers to avoid trying that particular mixture.

The results from farmer interviews and discussions during workshops revealed great diversity in approaches and perspectives among farmers, ranging from a focus on niche markets and direct contact with consumers to delivering grain legumes as commodities to large food companies. We also observed differences between farmers' and researchers' perceptions of the overall goal of increasing production of legumes for human consumption. The researchers tended to look for answers on how *total Swedish* production of grain legumes can be increased, but

Table 2. Advantages and limitation with farmers' and researchers' experiments

	Advantages	Limitations
Farmers' experiments	• Direct link between the farmer's questions and the design • Acquisition of results directly relevant to the system in which they are tested (pedoclimatic conditions, machinery, etc.) • Inclusion of the whole system in the evaluation, including e.g., crop rotation, post-harvest steps • Results directly transformed into knowledge for action	• Lack of time to anticipate all steps in experiments • Practical constraints linked to the machinery • No or little observation or measurements on the crops • Evaluation of practices based on a general perception, rather than concrete indicators
Researchers' experiments	• Possibility to screen numerous practices in small plots without post-harvest constraints • Possibility to answer complex questions by isolating factors or setting up long-term experiments • Access to variables costly or complex to measure • Statistically solid results • Academically recognized process	• Results difficult to translate to other places and years • No or limited consideration of feasibility • Difficult access to the results and applicability for farmers • Sometimes designed to solve problems that are not directly relevant for farmers • Limited possibility to discover the full range of relevant factors for implementation in practice
On-farm experiments involving researchers and a group of farmers	Advantages of farmers' experiments, plus the following: • Extra motivation for farmers, coming from other farmers and researchers • Knowledge exchange and support among farmers • Increased trust when knowledge comes from a real commercial farm • Inputs from researchers during the design and evaluation stages reduces the risk of unjustified conclusions • Measurements made by researchers: useful information to farmers • Collective evaluation with other farmers and researchers: new perspectives on the results	• Requirement of funding for the researchers or other actors (e.g., advisors) to facilitate the collaboration • Risk that the objectives of the research project and the objectives of farmers are not aligned • Comparisons among farms can be difficult • Difficult to obtain scientific merits (outcomes may not fit the format of scientific publications)

farmers were mainly interested in increasing production on their own farm or increasing their profits based on the same area of legume cultivation. While there are complementarities and synergies between increased legume production on individual farms and at the national level, there can also be goal conflicts, especially for niche crops such as lentil. If overall production increases, prices may decrease and pioneer farmers lose the advantage of uniqueness in delivering a highly demanded product: 'The big actors will destroy the crops' market for us' (farmer B).

The participants expressed that the sharing of results and experiences in the workshops were meaningful and valuable learning occasions for them. These insights should be useful also for other contexts where farmers and researchers or farmers and advisors form groups around on-farm experiments, e.g., to investigate conservation agriculture, integrated pest management, new approaches for nutrient cycling or integration of new crops (not only legumes).

Recommendations. The collaboration made it possible to include reflections from both farmers and researchers on advantages and limitations of different types of experiments (Table 2). Based on these, we identified the following recommendations for on-farm experiments involving a group of farmers and researchers:

- Include considerations of post-harvest handling of the crop when designing the experiments. Being able to sell the harvested product is always important, especially when experimenting with new crops or practices that have impacts on post-harvest steps (e.g., intercropping), and including post-harvest steps can therefore motivate farmers to perform experiments.
- Limit the number of questions investigated in the experiments, to ensure that they can be handled with farmers' resources (especially time) available for design, management and evaluation of the experiment.
- When designing the experiments, validate carefully the coherence of the aim with the experimental set-up (location of experimental treatments, practical feasibility of treatments with the available machinery and time, etc.) and clearly define the measurements to be performed and the responsibility for collecting the data.
- Set up the experiment on an easily accessible field to allow frequent visits and on a sufficiently large area to allow testing of all steps in post-harvest handling, e.g., sorting of intercropped crops. However, the experiment should not be too large, since the risk of losses in case of experimental failure needs to be handled.
- Include at least two replicates for each treatment if the field shows heterogeneity.
- Find a balance between letting each farmer run experiments that are very specific to their context and finding some degree of comparability between farms. The decision to retain a small plot for observations and measurements in an interrupted experiment (farmer A, 2018) is a good example of an agreement that enabled more comparisons between farms and stimulated the collaborative learning process.
- Researchers or research assistants/technicians should take measurements (biomass, crop plant density, etc.), as this provides

https://doi.org/10.1017/S1742170522000102 Published online by Cambridge University Press

additional motivation for farmers and resources for evaluation which most farmers do not possess.

- Evaluate the experiments in a collective setting (farmers–researchers and farmers–farmers), as it is an efficient way of enhancing learning by farmers and researchers.
- Ensure the group has a mixture of competences and endeavor to build trust and create an environment where all are ready to share information. Bring together farmers with different experiences (e.g., both conventional and organic, different length of history as a farmer), since all can gain information and motivation from the exchanges.

As the study was initiated by researchers, and part of a research project with active participation of both researchers and farmers, it was possible to include researchers' critical reflections both on the interpretations of obtained results and on the collaboration itself. This was valuable for analyzing the outcomes of the study, but, it may not be necessary to rely on researchers for initiating and coordinating such collaborations. Farm advisors, who often have knowledge, experience and skills in farmer group collaborations, could replace researchers in this role. Such multi-actor collaborations with on-farm experiments could allow more farmers to benefit from collaborative learning and stimulate the implementation of agroecological practices in cropping systems, in our case through increased cultivation of grain legumes.

Conclusions

Through different pathways, this study generated knowledge with useful implications for the overall aim of increasing cultivation of grain legumes for food. Working collectively with on-farm experiments created learning about practical management of cultivation and post-harvest steps, which can be used directly for increasing commercial legume production. The measurements and data analyses by researchers, which were shared and discussed collectively with farmers, led to new insights and deeper thinking about reasons behind success or failure of different crops or management practices. Farmers considered the thorough assessment obtained through this collaborative analysis valuable for their decision making on increasing legume production. Sharing experiences, ideas and contacts, and the support from participating researchers, also stimulated farmers to conduct further experiments with new crops or new management practices, or to explore new contacts with potential buyers of grain legumes.

Post-harvest steps, e.g., drying, sorting/cleaning, storing, transporting and selling the harvested product, were shown to be always important for farmers considering a new crop and in many cases also when considering a change in cultivation practices. Farmers' experiments are thus often holistic, covering all steps from access to seeds and to selling the crop, and feasibility of post-harvest steps is a logical part of the experimental process. Learning about post-harvest handling can thus be a key motivation for farmers to engage in a collaboration that involves on-farm experiments. This is valuable knowledge for those planning research involving active participation by farmers.

On-farm experiments involving researchers and a group of farmers can overcome several of the limitations in conventional researcher experiments, notably by providing knowledge that is directly applicable to the site-specific conditions of the participating farms. The involvement of researchers can complement farmers' practical know-how by adding critical scientific input to the design, management and interpretation of experiments, thereby facilitating deeper analysis and understanding of outcomes. However, farmer–researcher collaborations in small groups are costly and have limited reach. To widen the scope, farm advisors could facilitate similar collaboration processes, which we found very fruitful for stimulating learning and improving on-farm experimentation – indispensable capabilities in an increasingly unpredictable future.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1742170522000102

Acknowledgements. The authors are very grateful to the farmers who participated in the study. Thanks also to Ana Barreiro and Raj Chongtham for valuable comments on the text.

Financial support. The study was funded by the Swedish Research Council Formas.

Conflict of interest. The authors declare no competing interest.

References

Calderón FJ, Jackson LE, Scow KM and Rolston DE (2001) Short-term dynamics of nitrogen, microbial activity, and phospholipid fatty acids after tillage. *Soil Science Society of America Journal* **65**, 118–126.

Carton N, Naudin C, Piva G and Corre-Hellou G (2020) Intercropping winter lupin and triticale increases weed suppression and total yield. *Agriculture* **10**, 316.

Catalogna M and Navarrete M (2016) An agronomic framework for analyzing farmers' experiments. In *12th European IFSA Symposium*. Harper Adams University, Newport.

Catalogna M, Dubois M and Navarrete M (2018) Diversity of experimentation by farmers engaged in agroecology. *Agronomy for Sustainable Development* **38**, 50.

Christofari H, Girard N and Magda D (2018) How agroecological farmers develop their own practices: a framework to describe their learning processes. *Agroecology and Sustainable Food Systems* **42**, 777–795.

Darnhofer I, Bellon S, Dedieu B and Milestad R (2010) Adaptiveness to enhance the sustainability of farming systems. A review. *Agronomy for Sustainable Development* **30**, 545–555. https://doi.org/10.1051/agro/2009053.

Eksvärd K (2003) *Tillsammans kan vi lära och förändra – deltagardriven forskning för svenskt lantbruk (Together We can Learn and Make Changes – Participatory Research for Swedish Agriculture)*. Uppsala: Centrum för Uthålligt Lantbruk, Swedish University of Agricultural Sciences.

Francis CA, Jordan N, Porter P, Breland TA, Lieblein G, Salomonsson L, Sriskandarajah N, Wiedenhoeft M, DeHaan R, Braden I and Langeret V (2011) Innovative education in agroecology: experiential learning for a sustainable agriculture. *Critical Reviews in Plant Sciences* **30**, 226–237.

Hansson SO (2019) Farmers' experiments and scientific methodology. *European Journal for Philosophy of Science* **9**, 32.

Ingram J, Fry P and Mathieu A (2010) Revealing different understandings of soil held by scientists and farmers in the context of soil protection and management. *Land Use Policy* **27**, 51–60.

Jensen ES, Peoples MB, Boddey RM, Gresshoff PM, Hauggaard-Nielsen H, Alves BJR and Morrison MJ (2012) Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development* **32**, 329–364.

Kraska P, Andruszczak S, Kwiecinska-Poppe E, Staniak M, Rozylo K and Rusecki H (2020) Supporting crop and different row spacing as factors influencing weed infestation in lentil crop and seed yield under organic farming conditions. *Agronomy* **10**, 9.

Kroma MM (2006) Organic farmer networks: facilitating learning and innovation for sustainable agriculture. *Journal of Sustainable Agriculture* **28**, 5–28.

Maat H (2011) The history and future of agricultural experiments. *NJAS – Wageningen Journal of Life Sciences* **57**, 187–195.

Magrini M-B, Anton M, Cholez C, Corre-Hellou G, Duc G, Jeuffroy M-H, Meynard J-M, Pelzer E, Voisin A-S and Walrand S (2016) Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. *Ecological Economics* **126**, 152–162.

Magrini M-B, Anton M, Chardigny J-M, Duc G, Duru M, Jeuffroy M-H, Meynard J-M, Micard V and Walrand S (2018) Pulses for sustainability: breaking agriculture and food sectors out of lock-in. *Frontiers in Sustainable Food Systems* **2**, 64.

Malézieux E, Crozat Y, Dupraz C, Laurans M, Makowski D, Ozier-Lafontaine H, Rapidel B, de Tourdonnet S and Valantin-Morison M (2009) Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development* **29**, 43–62.

Mawois M, Vidal A, Revoyron E, Casagrande M, Jeuffroy M-H and Le Bail M (2019) Transition to legume-based farming systems requires stable outlets, learning, and peer-networking. *Agronomy for Sustainable Development* **39**, 14.

Murphy J (2012) The contribution of facilitated group learning to supporting innovation amongst farmers. *Studies in Agricultural Economics* **114**, 93–98.

Navarrete M, Brives H, Catalogna M, Gouttenoire L, Heinisch C, Lamine C, Ollion E and Simon S (2018) Farmers' involvement in collective experimental designs in a French region, Rhône-Alpes. How do they contribute to farmers' learning and facilitate the agroecological transition? *13th European IFSA Symposium (IFSA 2018)*, Jul 2018, La Canée (Crete), Greece. hal-01832825.

Olsson C (2017) Expanding the grain legume food production in Southern Sweden – Qualitative insights from producers and representatives from the food industry. Degree Project, second cycle (A2E) Agroecology – Master's Programme. Swedish University of Agricultural Sciences, Alnarp. Available at https://stud.epsilon.slu.se/10627/.

Preissel S, Reckling M, Schläfke N and Zander P (2015) Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. *Field Crops Research* **175**, 64–79.

Reckling M, Bergkvist G, Watson CA, Stoddard FL and Bachinger J (2020) Re-designing organic grain legume cropping systems using systems agronomy. *European Journal of Agronomy* **112**, 125951.

Röös E, Carlsson G, Ferawati F, Hefni M, Stephan A, Tidåker P and Witthöft C (2018) Less meat, more legumes – prospects and challenges in the transition towards sustainable diets in Sweden. *Renewable Agriculture and Food Systems* **35**, 192–205.

Statistics Sweden (2020) Production of cereals, dried pulses, oilseed crops, potatoes and temporary grasses in 2019. Final statistics. JO 16 SM 2001.

Voisin A-S, Guéguen J, Huyghe C, Jeuffroy M-H, Magrini M-B, Meynard J-M, Mougel C, Pellerin S and Pelzer E (2014) Legumes for feed, food, biomaterials and bioenergy in Europe: a review. *Agronomy for Sustainable Development* **34**, 361–380.

Wang L, Gruber S and Claupein W (2012) Optimizing lentil-based mixed cropping with different companion crops and plant densities in terms of crop yield and weed control. *Organic Agriculture* **2**, 79–87.

Watson CA, Reckling M, Preissel S, Bachinger J, Bergkvist G, Kuhlman T, Lindström K, Nemecek T, Topp C, Vanhatalo A, Zander P, Murphy-Bokern D and Stoddard F (2017) Grain legume production and use in European agricultural systems. *Advances in Agronomy* **144**, 235–303.

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, Jonell M, Clark M, Gordon LJ, Fanzo J, Hawkes C, Zurayk R, Rivera JA, De Vries W, Majele Sibanda L, Afshin A, Chaudhary A, Herrero M, Agustina R, Branca F, Lartey A, Fan S, Crona B, Fox E, Bignet V, Troell M, Lindahl T, Singh S, Cornell SE, Srinath Reddy K, Narain S, Nishtar S and Murray CJL (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492.

Zander P, Amjath-Babu TS, Preissel S, Reckling M, Bues A, Schläfke N, Kuhlman T, Bachinger J, Uthes S, Stoddard F, Murphy-Bokern D and Watson C (2016) Grain legume decline and potential recovery in European agriculture: a review. *Agronomy for Sustainable Development* **36**, 1–20.

Zimmer S, Liebe U, Didier J-P and Heβ J (2016) Luxembourgish farmers' lack of information about grain legume cultivation. *Agronomy for Sustainable Development* **36**, 2.