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A three-stage approach for co-designing diversified cropping systems with farmers: the case study of lentil-wheat intercropping

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Highlights

- *A three-stage approach was developed and tested for co-designing diversified cropping systems.*
- *Experiments based on this approach are complementary in terms of scale, complexity, representativeness and risk of treatment failure.*
- *Despite the good agronomic performance, post-harvest grain separation limits the adoption of wheat-lentil intercropping by farmers.*
- *The co-designed on-farm experiment showed that wheat-lentil intercrops both sown at 150 kg/ha had higher income and weed control.*

Abstract

There is an increasing need for more sustainable and diversified cropping systems while guaranteeing adequate crop yields and economic viability for European farms. The intercropping of lentils with wheat can be a valuable agroecological practice for stabilizing crop yields and improving weed control; however, this requires better knowledge about the technical viability, suitable varieties, sowing density, management practices for different conditions, and the feasibility of these solutions for farmers. In this paper, we present a three-stage participatory approach aimed at involving farmers in the evaluation and design of knowledge-intensive agroecological cropping systems and apply it to the case of wheat-lentil intercropping. The proposed approach is articulated into three connected stages involving experiments at different scales (plot, field, and farm) and with different grades of interactions among farmers and researchers regarding the design of experiments and the evaluation of the results. In the first stage, we set up controlled plot experiments at an experimental station allowing all interested farmers to observe and comment on the various treatments that were investigated during dedicated events. This stage tested the potential of intercropping to improve the sustainability of the local farming system and provide a solid scientific background to the ecosystem services provided by wheat-lentil intercropping, such as crop production, yield stability, and weed control. While being agronomically beneficial, the technical feasibility and economic benefits of wheat-lentil intercropping have yet to be proven. Therefore, based on the results obtained from the first stage and the feedback of local farmers on the opportunities and weaknesses of the on-station application of wheat-lentil intercropping, a second experiment was carried out using commercial agriculture machines to test the technical viability of intercropping at a larger scale. In the final third stage, we set up a co-designed on-farm experiment aimed at supporting a farmer in establishing lentil-wheat intercropping adapted to the farm conditions. This approach demonstrated that gradually involving farmers in the experimental process, starting from evaluating the most promising agroecological solutions on station to implementing them on farms, supports a successful agroecological transition of farms towards more diversified cropping systems.

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Introduction

Agricultural production and cropping systems are often based on a reduced number of high performing crop varieties that need a large use of external inputs and mechanisation for their optimal development. However, the environmental and economic sustainability of these input-intensive farming systems is increasingly questioned due to their negative impacts on biodiversity, biological soil fertility, water pollution and human health (Hammer *et al*., 2003; Kudsk and Streibig 2003; Reidsma *et al*., 2010; MacLaren *et al*., 2020). Organic farming effectively eliminates the use of mineral fertilisers and herbicides, and more sustainable agricultural systems may benefit from organic farming experiences by adopting, for example, longer and diversified crop rotations with a higher share of legume crops and intercropping practices (Tscharntke *et al*., 2021). A large number of studies reported that (relay) intercropping, *i.e*., the cultivation of two or more contemporary crops in the same field for the entire (or part) of their life cycle, is an agronomic practice that significantly supports a reduction of external input use while maintaining adequate crop production. However, the adoption by farmers appears low for several reasons (Tanveer *et al*., 2017; Lamichhane *et al*., 2023). One obstacle to intercropping uptake and its on-farm implementation is that these cropping practices need to be fine-tuned to the specific farm conditions, otherwise, their efficacy may be not satisfactory for the farmers. Furthermore, the market availability of suitable crops for intercropping is scarce (Mamine and Farès, 2020; Leoni *et al*., 2022). Moreover, the implementation of new agroecological practices such as (relay) intercropping are often labour and knowledge intensive, time and resource consuming and frequently require additional investments in specialised machinery (Hauggaard-Nielsen *et al*., 2021; Lamichhane *et al*., 2023). Another aspect is that intercropping is a long-term investment, and the cost-benefits might not be obvious in the short-term because advantages such as soil fertility enhancement and weed control need to be assessed at the crop rotation level (Nilsson *et al.*, 2022). For the successful on-farm implementation of more sustainable cropping practices, a transitional phase seems necessary, during which elements of crop diversification are gradually implemented while reducing the use of external inputs until a new balance is achieved (Iocola *et al*., 2020). However, during this transitional phase, farmers can be exposed to risks associated with the chosen practice, for example, crop failure, competition between the co-cultivated crops and less effective weed control. These risks can be a barrier in terms of both economic aspects and farmer acceptance (Moss, 2019). The first steps in this transitional phase can therefore be carried out in a research experimental station, allowing preliminary studies to be conducted aimed at assessing the feasibility of the target system under farm conditions without exposing farmers to economic and agronomical risks. Once the efficacy and feasibility of the new agroecological practices have been demonstrated, the innovation can be transferred to on-farm conditions with more chances of success. In addition to the technical barriers, there are often sociological barriers to changing cropping practices (Rodriguez *et al*., 2009). Farmers may be reluctant to adopt intercropping due to their familiarity and comfort with monocultural cropping systems (Mortensen and Smith, 2020), limited knowledge and understanding of alternative practices (Moss, 2019), low perception of the health and environmental risks related to the use of chemical inputs (Pan *et al*., 2020) and social pressure from other farmers to conform to conventional farming methods (Riar *et al*., 2017). Therefore, peer-to-peer interactions between farmers and researchers and co-designing of research experiments, can initiate the transition pathway towards more sustainable cropping systems (Leclère *et al*., 2018; Pagliarino *et al*., 2020; Notz *et al*., 2022). On the other hand, the traditional paradigm of agronomic research, which typically assigns experimental activities solely to scientists, must be transcended to allow farmers and other stakeholders to become more involved in the co-design and evaluation of the experiments (Maat *et al*., 2011). For this purpose, new forms of experimentation at different scales and based on the farmer involvement in the research design and process are currently emerging (Galli *et al*., 2010; Gamache *et al*., 2020; Fieldsend *et al*., 2021; Perinelle *et al*., 2021; Salembier *et al.*, 2023). Moreover, since 2013 the participatory research approach has been incorporated into European agricultural research, such as in the case of the European Innovation Partnership for Agricultural Productivity and Sustainability (EIP-AGRI). In this context, the European project "Integrated Weed Management: Practical implementation and solutions (IWMPRAISE)" was aimed at improving existing but underused IWM solutions to promote their uptake by farmers through their active engagement in the research process (Riemens and Elings, 2022). Based on the analysis of the participatory research experiences carried out during this project a guideline for participatory research was developed to improve the efficacy of participatory research for farmers and researchers. Furthermore, farmers who were interviewed for the IWMPRAISE project identified, among the tools in the pillar 'cropping system diversification', crop rotation and intercropping as important tools for reducing the impact of weeds on crop yield (Riemens and Elings, 2022). In particular, part of the cereal growers involved in the Italian national cluster highlighted their interest in diversifying and re-designing their cropping systems by including grain legumes such as lentils (*Lens culinaris* Medik.) in the crop rotation. Despite the high economic value of lentils, this crop has been overlooked by farmers, especially under organic management, because of low and unstable yields due to lodging and weed susceptibility (Bansal *et al*., 1994; Loïc *et al*., 2018). Instead, lentil-wheat intercropping can significantly reduce legume stem lodging because the cereal culms act as a mechanical support for the companion crop (Loïc *et al*., 2018). Moreover, intercropping can significantly improve weed control, enhance the resilience of the cropping systems to changing climatic conditions and stabilise yield and economic income of the system (Pelzer *et al*., 2020; Koskey *et al*., 2022). This paper presents the three-stage participatory framework that was developed based on the guidelines from the IWMPRAISE project, and the results of a case study on the uptake by farmers of wheat-lentil intercropping in Italy. The case study contains three highly connected experiments on durum wheat (*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.)-lentil intercropping conducted at increasing experimental scales and consequently with different types of farmer involvement: plot, field, and on-farm. Experiments were carried out with different objectives and designed to guide the uptake of wheat-lentil intercropping in Mediterranean low-input cereal-based farms. The first experiment was conducted in the research field station (on-station) at plot scale and it aimed to evaluate the ecosystem services provided by wheat-lentil intercropping. After confirming the environmental and agronomic benefits associated with wheat-lentil intercropping and considering the feedback received directly from farmers regarding this plot experiment, a second experiment was carried out at the field scale on-station aimed to verify the technical feasibility of the intercropping systems using commercial machinery. The third experiment was co-designed with the owner of La Viola farm, and aimed to answer farmers' questions about the optimal intercropping seeding doses

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under his specific farm conditions. The paper analyses researcher-farmer interactions and the main findings, highlighting the on-farm co-design process.

Materials and Methods

Development of the three-stage approach to participatory research

A conceptual framework has been developed for the co-design of agroecological practices supporting cropping system diversification (Figure 1) by distinguishing three complementary research approaches that can tackle this challenge and that optimise the interactions between farmers and researchers taking into account the requirements and characteristics of both professionals. From our previous experiences in performing participatory research in Italy and the international experiences from the IWMPRAISE project, the following bottlenecks of co-design and participatory research were identified for farmers: i) the high risk they run when performing experiments in their fields in terms of economic loss and pests, weeds or diseases that may escape their control, and ii) time consuming operations when different treatments are included in their fields. Researchers, on the other hand, are penalised because on-farm experimentation is often not considered sufficient for scientific publications due to lack of real replications in space and time, and the difficulty in controlling the trials run by farmers. The three-stage framework overcomes all these drawbacks by combining three research approaches and optimising the farmers-researcher interactions in each of them. In the following example, the wheat-lentil intercropping case study is analysed to showcase this approach.

Small scale plot experiments

This stage needs to be carried out on an experimental research station. The experiment aimed to test wheat-lentil intercropping. The trial layout was designed based on questions that researcher had received in the past from farmers and the gaps in knowledge identified by performing a literature review. The scientific evaluation focused on the ecosystem services related to the application of this system such as crop production, yield stability, and weed control. Advantages related to the use of intercropping were expected to reduce the use of external inputs such as mineral fertilisers and herbicides. At wheat maturity (beginning of June) farmers were invited and asked to evaluate the advantages of this system and the main barriers and criticism that can limit the adoption of this practice on-farm. This stage allows researchers to collect and publish scientific data and farmers to compare and become familiar with several agroecological crop management solutions.

Medium scale field experiments

The second stage involves an on-station field trial that simulates real farm conditions. If needed or desired this stage can also be performed on a real farm. In this stage, the research questions and experimental design were formulated based on the key issues identified by the farmers in the previous stage. In this case study, the research questions primarily addressed the technical feasibility of wheat-lentil intercropping under farm conditions, with a specific emphasis on practical considerations such as machinery requirements and other potential technical barriers that could impede the adoption of intercropping at the farm level. This type of trial supports the farmers in deciding which solution to test in their fields, and it allows researchers to focus on the feasibility and applicability of their agroecological innovations. During this stage, discussions take place between researchers and farmers and this forms the basis for the third stage, the on-farm implementation through agroecological co-design.

On-farm field experiments

The third stage consists of the actual co-design of an on-farm experiment. In the case study presented in this paper, the third stage was carried out with Gilberto Croceri, the owner of the "La Viola" farm upon his request. The wheat-lentil intercropping experiment was fine-tuned according to the local environmental and technical conditions through a co-design process. This means

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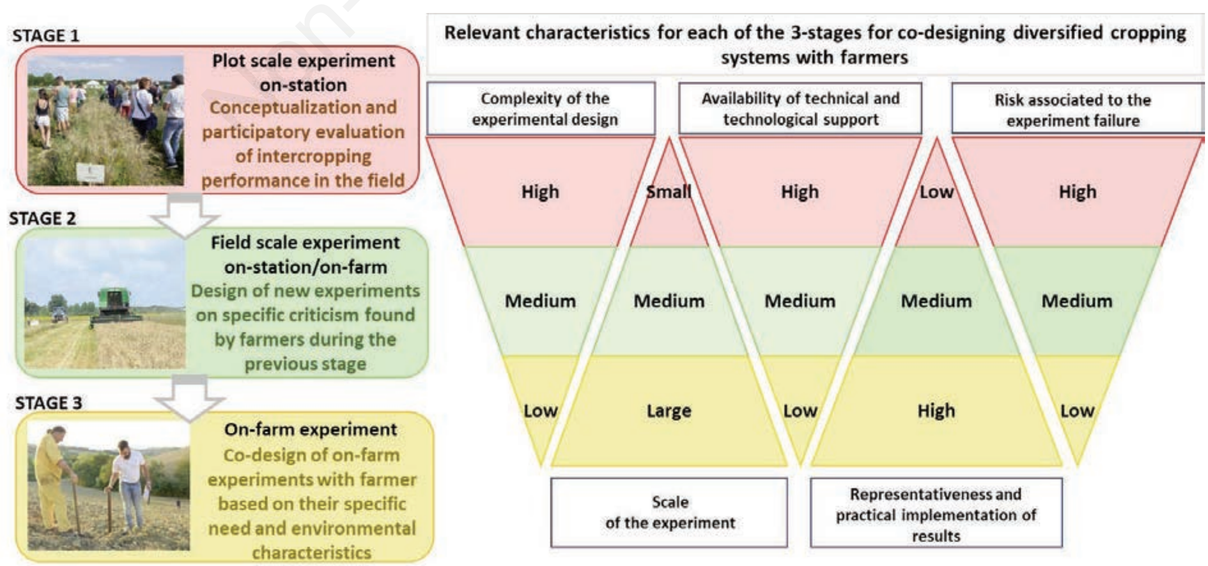

Figure 1. Conceptual framework of the 3-stage approach for the co-design of agroecological practices to sustain cropping system diversification with the farmer and research community, and the main characteristics of the experiments conducted at different scales.

that the specific needs and technological capabilities of La Viola farm were analysed together, and questions were boiled down to one main question that became the objective of the trial. For La Viola farm, the key issue was the determination of the optimal wheat-lentil seeding ratio and aimed to: i) maximise lentil yield and economic returns, ii) maintain an acceptable level of wheat production, and iii) improve weed control. The experiment was repeated for three consecutive years but only the last two were included in this paper (2019/20 and 2020/21).

Small scale experiment: conceptualisation and selection of the most promising solutions

The first stage aimed to test new cropping systems based on the intercropping between wheat and lentils, to improve weed control and support crop diversification. Therefore, a plot experiment was carried out at the Centre for Agri-environmental Research 'Enrico Avanzi' (CiRAA) of the University of Pisa, Italy for 3 years (2018/19, 2019/20, 2020/21) with the scope of evaluating the agronomic performance of relay intercropping of winter durum wheat (cv. Minosse) with lentil (cv. Elsa) in Mediterranean cereal-based cropping systems. The experimental treatments consisted of three crop-stand types (i) sole crop of lentils, (ii) sole crop of wheat, and (iii) relay intercropping of lentils with durum wheat. In the case of relay intercropping, two target densities of durum wheat plants (350 plants/m^2 and 116 plants/m^2) were tested in combination with the standard lentil plant density (180 plants/m^2). Details about this experiment and the scientific results are reported in Koskey *et al.* (2022). A total of nearly 40 participants evaluated all plots during field days "Agroecologia al Centro" organised at CiRAA in the 2018 and 2019 growing seasons. The evaluation took place when the wheat was at or near full maturity. The participants were provided with information about the objectives, experimental design and the recommended path to follow. Farmer, agronomist, scientist, and student categories were consistently the most represented. All the participants were then involved in an open discussion and asked to give their impression on the weed control capacity of this intercropping system. Then, farmers were asked if they would adopt the intercropping between wheat and lentils on their farms and, if not, what critical factors contribute to limiting its application.

Medium scale experiment: implementation at the field scale

Experiment description

During this stage, the research questions and experimental design were defined based on critical aspects identified by farmers during the evaluation of the previous stage. Specifically, this experiment aimed to address the following questions: i) how to effectively implement intercropping under farm conditions using machinery commonly available to farmers, considering the lack of specific intercropping seeding machines with separate hoppers for lentils and wheat? ii) how to efficiently manage the harvesting process of wheat and lentils together, while ensuring the preservation of lentil integrity by appropriately adjusting the combine harvester. This step allowed farmers to see how the trials are managed at the field level while the economic and agronomical risk is still taken by the research institution. The field experiment was carried out in the 2021/22 growing season at CiRAA. Treatments were the same as described in Koskey *et al*. (2022) and the trial involved relay intercropping of durum wheat with lentils tested in strips of 0.1ha. To simulate real farm conditions, the experiment was conducted with the use of commercial agricultural machinery. The seedbed was prepared by shallow plowing at 30 cm followed by rotary harrowing. Durum wheat was sown on 12 November 2021 with a mechanical seed drill (Gaspardo NINA 250) towed with a tractor 70 HP power (FiatAgri 70-90). The working width of the seeding machine was 2.5 m and composed of 21 rows (12 cm inter rows space). In the case of relay intercropping, wheat was sown at 24 cm rows width (same plant density as wheat monocrop but higher plant density in the line) by alternating the opening and closure of the seed distributors. At the end of winter, when wheat was at the tillering stage (BBCH 29), lentil was sown with the same mechanical seeding machine in the wheat inter-row spaces. Therefore, the wheat-lentil inter-rows space was 12 cm whereas the wheat-wheat inter-rows space was 24 cm. For lentil and wheat sole crop, the inter-row space was 12 cm. The experiment was conducted according to low-input management and no fertilizers, herbicides or pesticides were applied. Crops from each strip plot were mechanically harvested using a combine harvester (John Deere 1450 CWS). The cutter-bar was placed 15 cm above the ground and the machine was set as follows: threshing cylinder speed: 800 rpm, chaffer opening: 15 mm, grain sieve opening 3.5 mm, fan speed: 700 rpm.

Data collection

This experiment investigated the technical viability of relay intercropping reproducing real farm conditions with the use of commercial machinery commonly available for farmers (*e.g.*, mechanical seeding machine and commercial combine harvester). Wheat and lentil, both as intercrops and sole crops were tested following a simplified experimental design that consisted of the establishment of four adjacent strips. We estimated both the potential crop yield by hand-harvest of samples and the actual yield using a commercial combine harvester. For the estimation of the potential yield of the system, in late June of 2022, five samples were hand-harvested in each strip in the predefined homogeneous areas. For this experiment, the randomization of strips was not possible and pseudo replicates were used as statistic units (Hurlbert, 1984; Piepho *et al*., 2011). In the case of a simplified experimental design like this, Lacoste *et al*. (2022) highlighted the importance of spatial characterization and digitalization of the field experiment. Therefore, fine-scale soil mapping was used to i) identify homogeneous zones to improve blocking; ii) include the electrical resistivity data as a continuous covariate in statistical models (Piepho *et al*., 2011; Lawes and Bramley, 2012). The choice of soil homogeneous areas (blocks) allowed us to minimise the variability within blocks and maximise variability among them (*Supplementary Figure 1*). The integration of 2D electrical resistivity method and soil analysis was used to produce high spatial resolution soil maps to determine the soil variability of the experimental site. The resulting thematic maps of the field investigated soil physical (clay, sand and silt content, permeability and drainage index, apparent density, available water content) and chemical (pH, total N, available P and soil organic matter content -SOM-) parameters (AgriSoing, www.agrisoing.eu). For the estimation of the potential yield of the system, in late June of 2022, five samples of 0.25 m^2 were hand-harvested in each strip in the predefined homogeneous areas. According to the spatial characteristics of the field, we selected three homogeneous areas for soil texture and chemical fertility: yellow/orange, blue and red (*Supplementary Figure 1*). According to the USDA soil classification in the yellow-orange area the soil is classified as clay-loam (sand: 32%, clay: 28%, silt: 40%, pH: 7.9, available phosphorus (P): 9 mg/kg, total nitrogen (N): 0.92 g/kg, Organic Matter (OM): 1.44 g/100 g). In the blue area soil is classified as loam (sand: 33%, clay: 20.5%, silt: 46.5%,

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pH:8, available P: 10 mg/kg, total N: 0.71 g/kg, OM: 1.13 g/100 g). In the red area soil is classified as sandy-clay-loam (sand: 56%, clay: 28%, silt: 16%, pH: 7.9, available P: 8 mg/kg, total N: 0.52 g/kg, SOM: 0.74 g/100 g). For each sampling point, both crop and weed aboveground biomass were cut at the base in an area of 0.27 m^2. Lentil shoots were carefully hand-harvested to prevent pod opening and grain loss. Biomass samples from the intercrops were separated into weeds, durum wheat, and lentil before processing. Biomass dry weight (g/m^2) was obtained by oven-drying at 40°C until a constant weight. Crops were threshed separately using a research-designed thresher (Vignoli mod. Trident). Grains were weighed to obtain dry grain yield (t/ha). For the actual yield, crops from each strip (0.1 ha) were mechanically harvested using a previously described combine harvester. For each strip, the total grain yield was weighted and stored in a bin. The different components of the total harvested grain were then assessed by randomly collecting seven samples of 100 g each from each grain bin to estimate the weight of: i) marketable wheat kernels, ii) marketable lentil seeds, iii) broken wheat kernels, iv) broken lentil seeds, v) others (including stones, weed seeds, insects, *etc*.). Finally, mechanical harvest efficiency was calculated as a function of the marketable grain as follows (Eq. 1):

$$\text{Harvest efficiency (\%)} = [(\text{Grain yield hand harvest} - \text{Grain yield mechanical harvest})/(\text{Grain yield hand harvest})] \times 100 \quad (1)$$

Large scale experiment: co-design and on-farm implementation

Farm description

La Viola (www.agrilaviola.com) is an organic arable farm located in Torre San Patrizio, Marche (Italy). The farm consists of 10 ha of arable land in a hilly area with loamy to clay soils. The main crops are cereals and grain legumes, cultivated in intercropping. The intercropping is performed between a cereal such as bread wheat (*Triticum aestivum* L.), rye (*Secale cereale* L.), barley (*Hordeum vulgare* L.), and oat (*Avena sativa* L.) and a grain legume such as chickpea (*Cicer arietinum* L.), Indian pea (*Lathyrus sativus* L.), and ancient variety of pea called *roveja* (*Pisum sativum* ssp. arvense). Since all the cereal and legume crops are cultivated in an intercropping system, the companion crops are harvested together and than separated in the farm's processing laboratory. The seed types are separated using sifters based on different grain dimensions and/or densities. After the separation process, wheat is milled to produce high quality flour in a farm-owned mill, and together with the other cereals and grain legumes, the products are sold directly or to local organic shops.

Experiment description and co-design with the farmer

The experiment was repeated for two consecutive growing seasons, 2019/20 and 2020/21 in La Viola Farm. The co-design process of the experiment with the farmer was structured into four phases.

Definition of the objectives

The objective of the experiment was determined by the farmer. The farmer expressed interest in incorporating lentils into the crop rotation to promote crop diversification and because of its high economic value. Prior to the experiment, lentils had already been cultivated as a pure stand crop on the farm. Although the farm achieved higher production levels (averaging 0.5 t/ha) compared to local standards, manual harvesting was often necessary due to lodging issues. The farmer was particularly interested in exploring the potential of lentil-wheat intercropping aimed to mitigate legume stem lodging and reduce the negative impact of weeds on lentil cultivation. Therefore, this on-farm trial aimed to optimise wheat-lentil intercropping in the local conditions of La Viola cropland by selection of the optimal wheat-lentil seeding ratio to i) maximise lentil yield and economic margin, ii) preserve an acceptable wheat production yield, iii) improve weed control for lentil cultivation.

Co-design of the experiment

The farmer collaborated with the research group to design the experiment. The selection of experimental fields was based on criteria determined by the farmer, including a preference for south-exposed fields to minimise the risk of winter frost damage and the consideration of crop rotations. As the farmer produces flour for breadmaking, instead of using durum wheat, he opted to use a self-produced wheat seed of a composite cross population of soft wheat SOLIBAM (Bocci *et al*., 2020) mixed with local varieties including Jervicella and Saragolla. The lentil variety used was Elsa, the same cultivar employed in the previous experiments, and it was provided by the researchers. Wheat and lentil were sown in autumn with a sowing machine composed of two hoppers, one for the cereal and the other for the lentil seeds, that allows sowing the two crops simultaneously, each at the desired seeding rate. The seeding machine was from 1990 and was initially composed of only one hopper (CIMAC, VITTORIA EXTRA M. 2.25 X 15). The machine was later modified by the farmer for intercropping by equipping it with an additional hopper for the contemporary sowing of the second crop. The setting for the seed dose was manually regulated by turning a lever around a graduated scale (0-14). Prior to the experiment, the machine was manually set up for wheat and lentil to associate the target seed density of the experiment with the corresponding point of the graduated scale of the machine (*Supplementary Figure 2*). The soil seed bed was prepared with a disk harrow and a rotary harrow combined with the seeding machine. No fertilizers were applied. In the first repetition of the experiment (2019-20) the farmer and scientists arranged the experiment in strip (strip area of 500 m^2) to study the effect of increasing seeding rates of lentil (respectively 0, 100 and 150 kg/ha) sown in a factorial combination with four target wheat seeding rates (0, 100, 150 and 200 kg/ha). The experiments were organised in a randomised strip-plot design (wheat density as strip factor and lentils density as splitting factors nested within each strip), with three replicates (blocks) for each wheat-lentil seed rate combination. Randomization and block orientation were performed considering the maximum gradient of variability in both experimental fields, which was the slope. The farmer agreed to use this approach because while he was driving the tractor for the seeding operation, an operator made real-time adjustments to the target seeding densities of wheat and lentils without the farmer needing to stop each time.

Re-design

The experiment was repeated for two consecutive years (2019/20 and 2020/21). In the second year, adjustments were made based on the critical points identified in the previous year's experiment. In accordance with the farmer, the seeding rate of lentil and wheat was increased to compensate for the lower efficiency of the seeding machine available on the farm. As suggested by Lechenet *et al.* (2017) and Simon *et al.* (2017), the use of an adaptive approach across the repetition of the on-farm experiment can be of high importance to fine-tune the experiment to the specific environment and the technological level of the farm.

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Field day with local stakeholders

The field experiment with wheat and lentil intercropping carried out at La Viola farm, was evaluated at near or full maturity of the crops by a total of 36 participants (52% male and 48% female) during the field day "Biodiversamente, la biodiversità dal campo alla tavola" organised on 8 July 2021 by the Scuola Superiore Sant'Anna and Rete Semi Rurali, with the collaboration of the host farmer. Participants included farmers, agronomists, scientists, students, millers, bakers and consumers. The field day was organised into two interactive sessions. The first session was carried out in the experimental field, and it was focused on the agronomic and technical viability of intercropping. The second session was carried out in the main building, and it was more focused on the point of view of post-harvest stakeholders such as millers, consumers and bakers.

Data collection

At wheat harvest (BBCH 92), wheat, lentil, and weed aboveground dry biomass (g/m^2) were measured. Biomass samples of 0.54 m^2 were hand harvested (one point per plot). Samples were transported to the CiRAA and processed. The three components, *i.e.*, wheat, lentil and weeds, were separated, fresh weighed and then oven-dried at 40°C. The wheat samples were further assessed for the number of spikes m^{-2}, spike biomass, and straw biomass. Threshing of wheat and lentil was carried out mechanically and separately to obtain clean grains, which were weighed to obtain grain yield. Land Equivalent Ratio (LER) was used to determine the yield advantages of intercropping over sole cropping for each of the seed dose combinations (Mead and Willey, 1980). In a wheat-lentil intercrop, LER is the sum of the partial LER of each species ($LER_L + LER_W$), as follows (Eqs. 2 and 3):

$$LER_L = (Y_{L\text{-}IC}) / (Y_{L\text{-}SC}) \quad (2)$$

$$LER_W = (Y_{W\text{-}IC}) / (Y_{W\text{-}SC}) \quad (3)$$

where Y is the grain yield for lentil in the intercrop ($Y_{L\text{-}IC}$), lentil in the sole crop ($Y_{L\text{-}SC}$), wheat in the intercrop ($Y_{W\text{-}IC}$) and wheat in the sole crop ($Y_{W\text{-}SC}$). Partial LER values were calculated per year for each of the wheat-lentil seed doses factorial combinations. LER values higher than 1 indicate higher land use efficiency for the intercropping treatments compared to sole crops.

Economic assessment

Gross income analysis was used to determine the economic sustainability of wheat-lentil intercrops adapting the approach applied by Antichi *et al*. (2022) and Vasileiadis *et al.* (2015). Gross income (GI) was calculated as follows (Eq. 4):

$$GI = (GPV_w + GPV_L) - C \quad (4)$$

where GPV_w and GPV_L are respectively the gross production value (GPV, €/ha) for wheat and lentil minus the variable costs (C, €/ha) incurred in achieving that income. For the scope of this study GI does not include the common agricultural policy (CAP) payment. gross production value (GPV) is the value of production at the point of sale. In case of intercropping GPV was calculated as follows (Eq. 5):

$$GPV = (Y_L \times Q_L) + (Y_w \times Q_w) \quad (5)$$

where Y_L and Y_w are lentil and wheat grain yield (t ha^{-1}), respectively, and Q is the quotation for that specific crop (€ t^{-1}). For the current experiment, the price quotations were determined by the farmer because all the production is marketed by direct sale. At the time of the experiment prices for soft wheat were set at 400 €/t and 3,500 €/t for lentils. The variable production costs used in the economic analysis included seed purchases, mechanical operations (tillage, seeding, harvest) and post-harvest grain separation. Regarding the seed cost, for soft wheat it was self-produced and therefore assessed as opportunity cost at 400 €/t whereas lentil seed was sourced at 2000 €/t. The quotations for agriculture operations and services were obtained from the Regional Agricultural Mechanic Entrepreneurs' Association Price List (F.R.I.M.A.T, 2019), which is the reference source for these data (Raffaelli *et al*., 2013) and include downtime, insurance, depreciation, labor, machinery servicing and maintenance. According to the agricultural operations performed by the farmer we included in the cost: i) disk harrow (66 €/ha), ii) rotary harrow combined with seeding machine (90 €/ha), iii) mechanical harvest (130 €/ha). In case of intercropping, a company provided the service for grain cleaning and separation at €/t of grain.

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Statistical analysis

For the small scale (plot) experiment, detailed methods for statistical analysis are reported in Koskey *et al.* (2022). For the medium scale (field) experiment the normality of data on the potential wheat and lentil yield at harvest stage and the homoscedasticity of its variance were tested using Shapiro-Wilk and Brown-Forsythe tests, respectively. When treatment differences were significant, from ANOVA analysis, post-hoc comparison analysis was performed, using Tukey's honestly significantly differenced test implemented in the Python library 'statsmodels'. All results are presented in the graphs as bars indicating the mean and error bars representing the standard error of the mean. For the large (on-farm) experiment, data analysis was performed using R environment for statistical computing (R Core Team, 2020). Statistical models were performed using the R/'Lme4' package (Bates *et al*., 2015). For significant explanatory variables, Sidak post-hoc test was performed to separate means ($p<0.1$) using the R/'emmeans' package (Lenth, 2023). Normality and homogeneity of residuals variance have been graphically studied for the validation of each model using R/'DHARMa' package (Hartig, 2020). Lentil, wheat grain yield and gross income (GI) have been analysed by a linear mixed model assuming Gaussian distribution and identity link function with lentil seeding rate (0, 100, 150 and 200 kg/ha), wheat seeding rate (0, 100, 150 and 200 kg/ha), year (2019/20 and 2020/21) and their interaction as fixed factors and replicates (3 blocks) as random factor. We performed a regression analysis to test the effect of the total grain yield on total weed biomass at harvest stage in the two years of trial: 2019/20 (year 1), 2020/21 (year 2).

Results and Discussion

First stage: plot experiment on-station

The first of the three experiments was carried out over three years in the experimental station of the University of Pisa (CiRAA). According to the Food and Agriculture Organization of the United Nations (FAO), small-scale experiments are an efficient way to test a large number of innovations that have the potential to enhance productivity and sustainability in local farming systems (FAO, 1999). However, one of the limitations of these experiments

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is the small plot size associated with the experimental diversity of crop types, which may affect ecological dynamics compared to actual agricultural landscapes (Holland *et al*., 1994). For this reason, such experiments should be considered as preliminary studies and without the implementation of further experiments at a larger scale they are often no longer considered sufficient to support transitions towards sustainable farming (Lacoste *et al.*, 2022). Therefore, from a set of tested factors only the most promising solutions should be implemented on a larger scale for further investigation.

Small scale plot experiments such as that carried out by Koskey *et al*. (2022) have specific characteristics. The plot size is relatively small to facilitate plot management and data collection (Husson *et al*., 2016; Laurent *et al*., 2022). The small plot size allows testing of several levels of factors and their interactions in a restricted and uniform area with the support of specific experimental designs (Laurent *et al*., 2022). Environmental factors, such as soil type, climate, light exposure, and irrigation, are taken into account and controlled as much as possible (Carton *et al*., 2021). In a plot experiment, the level of failure of treatments or treatment combinations can be high. However, considering the small scale of the experiment the impact of failure is relatively low. Furthermore, plot experiments are labor-intensive. Researchers collect data on agronomic parameters, such as plant height, biomass, yield components, nutrient content, weeds, soil microbial community, and other relevant variables. These measurements are often conducted at multiple time points throughout the experiment to capture the growth stages and evaluate treatment effects over time. At crop harvest time samples are often collected by hand or with the appropriate machinery designed for small field trials. For this reason, the results from plot experiments are representative of the potential yield of the studied agroecological practices but overestimate the actual yield (Loïc *et al*., 2018). In the current case study, Koskey *et al*. (2022) reported a significant yield advantage in relay intercropping of wheat with lentil and improved weed control. Moreover, in the same study, it was shown that wheat and lentil interactions could significantly affect the microbial community in the rhizosphere with a positive effect on nutrient availability and uptake.

The interaction with farmers in this trial took place during open-farm field days that were organised in 2018 and 2019. The first question addressed weed control, and farmers were asked if they were satisfied with weed control in the case of intercropping between wheat and lentils. Overall, farmers found weed control to be satisfactory, especially regarding lentils. Moreover, farmers appreciated the role of wheat in preventing lodging issues in lentils, which is one of the main limiting factors determining the low uptake of lentil cultivation in the Pisa area. The second question focused on whether farmers were willing to adopt this type of intercropping on their farms, and if not, what were the obstacles preventing the use of intercropping. In this case, farmers highlighted several critical aspects regarding the implementation of this agronomic practice on their farms. One issue is the lack of a double-hopper seeder for intercropping, able to sow two or more crops together in the same field. Another practical issue that emerged was the harvesting of wheat together with lentils and the adjustment of the combine harvester to preserve the integrity of the lentils. In the discussion also agronomic challenges concerning potential water competition between the two crops during the grain filling stage of wheat with negative consequences on grain quality. An important issue discussed was the post-harvest separation of the two grains, and farmers suggested trying different cereal crops, such as oat (*Avena sativa* L.) and lentil or emmer (*Triticum dicoccum* Schrank) and lentil intercropping. Lastly, doubts were raised about the synchronisation of lentil harvest time that is later than wheat. One organic farmer who had already tried wheat-lentil intercropping, experienced difficulties with the harvest of lentils in the intercrops because the presence of green lentil biomass increased wheat grain moisture, leading to grain post-harvest issues. Feedback obtained from open discussions with farmers was used to design the following field-scale experiment. This experiment assessed the technical viability of relay intercropping with the use of commercial machinery such as a mechanical seeder and combine harvester. Additionally, an ongoing experiment focusing on post-harvest seed separation is being conducted using specially adapted sieves for wheat and lentils. Furthermore, based on the feedback received from farmers, we have identified the next research objectives; namely, to select wheat and lentil cultivars with more synchronised harvest time.

The owner of the "La Viola" farm in the Marche region (Italy) participated in this event and, thanks to his interest, the research group started a collaboration with him (stage 3) to improve the wheat-lentil intercropping system on his farm. The main question he was struggling with was to find the optimal sowing density and spatial arrangement for both intercrops.

Second stage: field-scale experiment on-station

The intermediate step was based on the research question of whether the most promising solutions tested at plot scale can be successfully implemented at a larger scale using the machinery and technological inputs available to farmers. For this reason, specific experiments at larger scale need to be conducted in experimental stations or directly on-farm with the support of researchers such as in the study carried out by Antichi *et al.* (2022). At this stage, the experiments are conducted with a reduced number of treatments and the experimental design is simplified to reproduce as much as possible the farm condition (Lawes and Bramley, 2012). Moreover, the research questions can be more focused on the evaluation of the overall sustainability and the technical viability of the tested innovations (Debaeke *et al*., 2009). In our case study, relay intercropping of wheat with lentil has been implemented in a field-scale trial using machinery and technological inputs commonly available to farmers. The large strip plots were set to allow the harvest of wheat-lentil intercrops with a commercial combine harvester. During the experiment, the sum of daily mean temperatures over the wheat growing period was above the 30-year mean of the experimental site (2982 *versus* 2711°C). The total rainfall during the growing period (571 mm) was in line with the 30-year mean (531 mm). However, there was a peak in precipitation in December (169 mm) and this preceded a long dry period between early January and late March. The results obtained from the mechanical harvest of crops showed that, in high-density intercropping, low-density intercropping and sole crops, respectively, the wheat grain yield was 2.0, 1.7 and 1.8 t/ha, whereas for lentil the dry grain yield was respectively 0.38, 0.56 and 1.3 t/ha (Figure 2). Results on lentil grain yield obtained in this experiment contrast with what has been observed by Koskey *et al.* (2022) in the plot experiment, reporting a significant yield loss in sole lentil treatments compared to that of the intercrops due to high weed competition, as shown by weed dry biomass at harvest (603 g/m^2). Instead, during this experiment, drought conditions occurred in spring and lowered weed dry biomass (140 g/m^2), reducing the impact of weeds on lentil production. This highlights the low yield stability of lentil which is strongly influenced by specific weather and field conditions (Akanksha *et al.*, 2021). The lentil dry grain yield determined by hand-harvested samples was lower for both high-density and low-

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density intercrop than in the sole crop (0.50±0.05 and 1.06±0.1 *versus* 1.89±0.1 t/ha, respectively) (Figure 2), which agrees with the findings of Loïc *et al.* (2018) who assessed the performance of wheat-lentil under contemporary intercropping. No significant effect of intercropping was observed for the wheat yield (Figure 2). Finally, we compared the potential crop yield (hand-harvested samples) with the actual yield obtained by using a commercial mechanical harvester (Figure 2). For lentil, a general trend highlighted that actual grain yield obtained from a mechanical combine harvester was systematically lower compared with hand-harvested samples. The mechanical harvest efficiency of lentils in high-density intercrops (81%) was higher compared with sole lentil (71%); however, this was not observed for low-density intercrops that had the lowest mechanical harvest efficiency (57%). Therefore, these results partially agree with what has been reported by Loïc *et al.* (2018) who observed a higher mechanical harvest efficiency for lentil in intercrops compared with that of the sole crops. For wheat, the mechanical harvest efficiency was not significantly affected by intercropping regardless of the seeding rates.

The impact of the commercial combine harvester has been evaluated on wheat and lentil grain integrity (Figure 3). The high-density intercrops contained a significantly lower percentage of broken lentils compared with low-density intercrops and sole lentil (2.1% *versus* 3.5% and 4.0% respectively). Instead, intercropping resulted in a higher percentage of broken wheat kernels compared with sole wheat (1.2% *vs* 1.5% *vs* 0.2%, respectively for high-density intercropping, low-density intercropping and lentil sole crop). The non-marketable components of yield including stones, weed seeds, insects, *etc*. ranged from 2.6% of the total grain yield in the case of sole wheat to 12.5% in the case of sole lentil crop (Figure 3).

Third stage: on-farm field experiment

The experiment aimed to investigate the most suitable seeding rate of wheat-lentil intercrops that maximises the gross income of the system and improves weed control. It is obvious that the presented results should be contextualised considering the farm characteristics such as the low technology availability, the organic low-input crop management and the reference market that relies mainly on the on-farm transformation and direct selling of the products in the local shops. Notably, the external input level and crop yield in the farm are very low and not representative of the local production level. Nevertheless, the agronomic and economic sustainability of the farm is guaranteed thanks to the large use of legumes as intercrops with cereals and the high added value of these products in the

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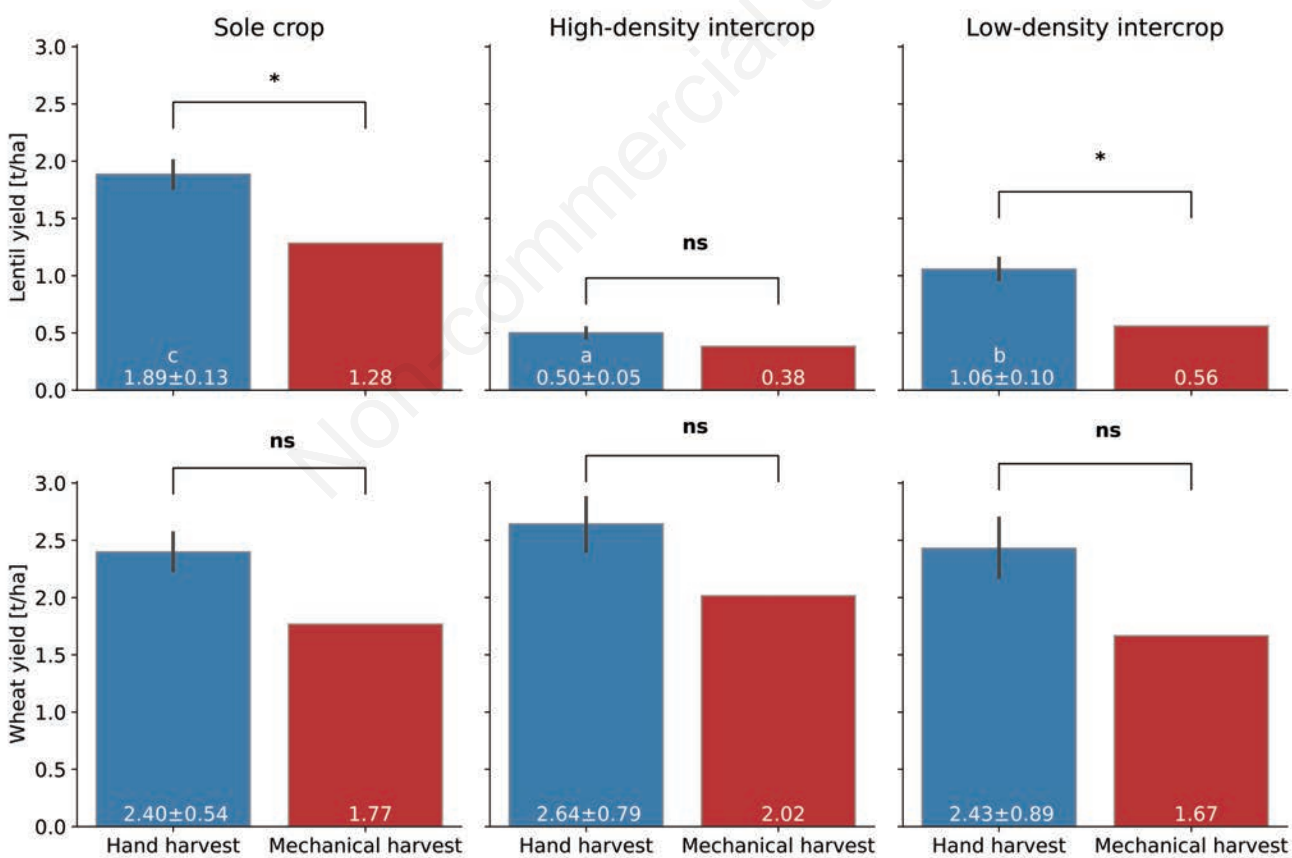

Figure 2. Mean yield of hand-harvested and mechanical harvested lentil (upper charts) and wheat (bottom charts) in intercropping and sole crop treatments. The significance of the difference between hand harvest and mechanical harvest within each sole crops and intercropping treatments, is indicated as "ns" when p>0.05 or as "*" when p≤0.05 (*t*-test). Lowercase letters within bars indicate statistically significant differences at p≤0.001 level (Tukey's honestly significant difference test) across sole crops and intercropping treatments for hand-harvest data.

short and direct value chain set up by the farmer. In this experiment, the mechanical seeder used for intercropping determined a low plant emergence compared to the target wheat-lentil density. For wheat and lentil, the actual emergence was on average 74% and 60%, respectively, in comparison to the target crop density. For the adaptation of the seeding machine for intercropping, the seed tubes were removed, and seeds were spread on the soil surface directly from the two hoppers resulting in a blended seeding technique mixing drill and broadcast sowing characteristics. Seeds were subsequently covered with soil by passing a light harrow. In this way, seeds were incorporated into the soil only superficially thus decreasing seed contact with the soil and increasing their susceptibility to unfavourable environmental conditions and seed predation (Brennan and Leap, 2014). During the first repetition of the experiment, the lentils sown at 100 and 150 kg/ha had an average dry grain yield of 55 and 245 kg/ha, respectively, regardless of the wheat seeding rate (Table 1), while the wheat grain production was on average 1.66 t/ha. During the second repetition of the experiment, lentil sown at 100, 150 and 200 kg/ha yielded respectively 250, 290 and 409 kg/ha whereas the production level of wheat was on average 0.68 t/ha (Table 1).

To evaluate the grain yield advantage in intercropping *versus* in sole crop, the partial LER was calculated separately for wheat and lentil for each of the seeding rate factorial combinations (Figure 4). LER is defined as the relative land area of sole crops required to produce the same yield achieved by intercropping, and with the same species proportion in total grain (Willey and Rao, 1980). Plotting the partial LER for lentil *versus* the partial LER for wheat, we obtained four different LER combinations (+/+, -/+, +/- and -/-). The best combination (+/+) was achieved when both lentil and wheat had LER>1 such as in the case of wheat and lentil both sown at 150 kg/ha (W150-L150). The wheat sown at 200 kg/ha combined with lentil sown at 150 kg/ha had LER higher than 1 for both wheat and lentil, but only during the first repetition of the experiment (Figure 4). The intermediate situation (-/+ and +/-) was achieved when only one of the two components of the intercropping had LER>1. For example, W100-L150 had an LER higher than 1 for lentil but not for the wheat in both repetitions (Figure 4). On the contrary, W200-L100 and W200-L150 showed a favourable LER for wheat but not for lentil. During the second repetition of the experiment, wheat sown at 100 combined with lentil sown at 200 kg/ha had LER<1 for both wheat and lentil (-/-) (Figure 4).

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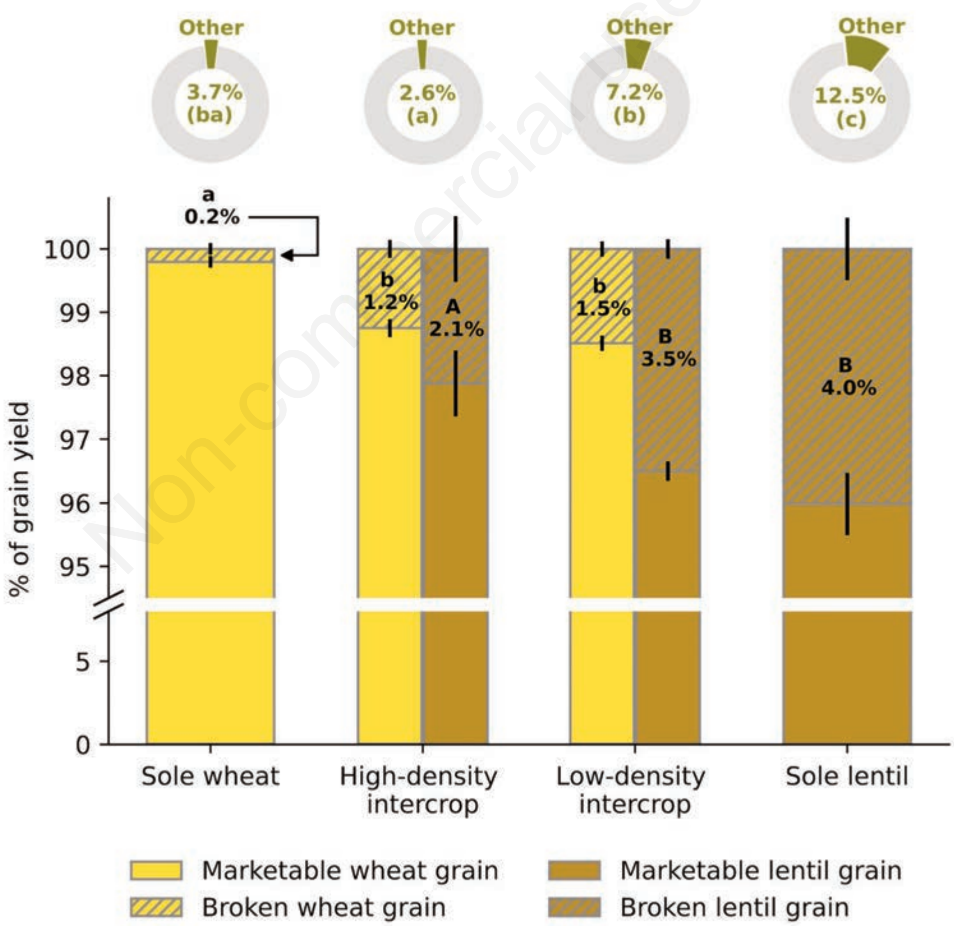

Figure 3. Mechanically harvested grain yield composition: percentage of the total mass of marketable wheat kernels, broken wheat kernels, marketable lentil seeds, broken lentil grain, and others (including stones, weeds seeds, insects, etc.). The percentage of the bars is calculated over the total dry weight of marketable plus broken grain. The donut chart percentage refers instead to the dry weight of the total yield in each treatment. For each of the yield components, different letters indicate statistically significant differences at p≤0.001 level (Tukey's honestly significant difference test) between treatments.

The economic value of lentil is almost nine-fold higher than that of wheat; therefore, the seeding rate that maximises the total grain yield (wheat + lentil) can be different from the combination that maximises the gross income of the intercropping system. Results obtained during the first replication of the experiment showed that sole lentil and sole wheat cultivation at low density (100 kg/ha) resulted in economic losses (Figure 5a). Meanwhile, for each of the wheat seeding rates, an increase in lentil seeding rate in the intercropping system resulted in an increasing trend in the gross income. During the second repetition of the experiment,

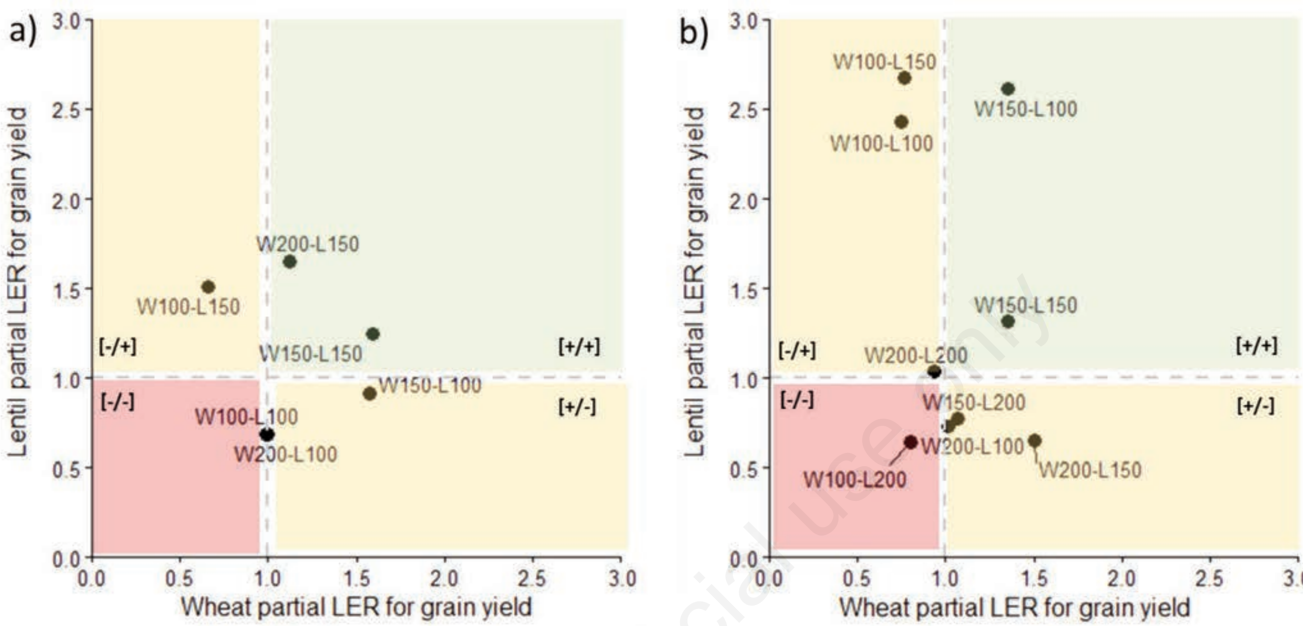

Figure 4. Partial land equivalent ratio (LER) of lentil grain yield versus the partial LER of wheat grain yield for 2019/20 (**a**) and 2020/21 (**b**). The green area (+/+) indicates a partial LER>1 for both lentil and wheat, the orange area (+/- and -/+) indicates partial LER>1 only for one of the intercropping components and the red area (-/-) indicate LER<1 for both wheat and lentil.

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Table 1. Wheat and lentil grain yield (mean ± standard error) during the two replications of the experiment (2019/20 and 2020/21) for different combinations of wheat and lentil seeding density. The significance of the differences was calculated within each wheat seeding dose (0, 100, 150 and 200 kg/ha).

Wheat-lentil seed dose combination	Wheat grain yield (dt ha^{-1}) 2019/20	Lentil grain yield (kg ha^{-1}) 2019/20	Wheat grain yield (dt ha^{-1}) 2020/21	Lentil grain yield (kg ha^{-1}) 2020/21
W0-L0	-	-	-	-
W0-L100	-	69.8±10.2^{a}	-	137.4±21.1^{b}
W0-L150	-	173.8±32.2^{a}	-	185.1±16.2^{b}
W0-L200	-	-	-	568.2±58.1^{a}
W100-L0	14.9±0.2^{a}	-	6.2±0.5^{a}	-
W100-L100	17.2±2.4^{a}	43.3±4.5^{b}	4.3±1.7^{a}	316.3±31.2^{a}
W100-L150	8.5±1.2^{b}	249.6±73.6^{a}	4.8±0.9^{a}	466.2±101.1^{a}
W100-L200	-	-	4.8±0.7^{a}	339.8±82.5^{a}
W150-L0	8.1±1.9^{a}	-	5.8±1.5^{a}	-
W150-L100	13.5±2.4^{a}	58.1±7.3^{b}	6.7±1.7^{a}	320.3±108.2^{b}
W150-L150	12.4±1.1^{a}	211.5±30.3^{a}	8.7±0.9^{a}	230.1±78.1^{ab}
W150-L200	-	-	5.9±1.3^{a}	434.8±74.4^{a}
W200-L0	15.9±1.6^{a}	-	8.9±2.1^{a}	-
W200-L100	17.4±3.9^{a}	49.5±2.8^{b}	7.3±1.3^{a}	226.4±47.6^{a}
W200-L150	17.6±8.1^{a}	347.1±20.1^{a}	11.3±1.1^{a}	281.4±3.5^{a}
W200-L200	-	-	7.9±0.9^{a}	297.5±16.1^{a}

[a,b]Different letters indicate statistical differences at 0.05 level (Sidak *post hoc* test).

the high weed competition may have led to the negative or neutral gross income obtained in sole lentil seeded at 100 and 150 kg/ha (Figure 5b). On the contrary, sole lentil seeded at 200 kg/ha had a positive gross income (Figure 5b). In this case, the higher plant density reduced the negative effects of weeds on the grain yield. The intercropping of wheat at 100 and 150 kg/ha with lentil guaranteed a positive gross margin and the increase in lentil seeding rate may have led to a positive trend on the gross income of the intercropping system (Figure 5b). Since the gross income increased proportionally with the wheat and lentil seeding dose, the saturation limit of the available resources was not reached, and neither was the peak of productivity of the two crops. For this reason, it was not possible to identify the optimal yield ratio of lentil and wheat. However, despite the high plant density in lentil and wheat sown both at 200 kg/ha (W200-L200), gross income and crop yield increment rate differed (Figure 5).

The results of this experiment confirmed that agronomic practices that support crop diversification in agro-ecosystems such as in the case of wheat-lentil intercropping systems can be valuable tools for integrated management of weeds (Liebman and Dyck, 1993; Silberg *et al*., 2019; Leoni *et al*., 2022). In particular, low competitive but valuable crops such as lentils can enormously benefit from the ecological and agronomic advantages of intercropping. During the first repetition of the experiment, the weed dry biomass in fallow plots (541 g/m^2) was not statistically different from that of the plots with sole lentil (436 g/m^2), regardless of the lentil density. In the plots where lentil was cultivated with wheat, the weed dry biomass correlated negatively with the total grain yield of the intercropping system ($y=413.11-1.65x$, $R^2=0.70$), and the same trend was observed for the second year ($y=166.60-0.55x$, $R^2=0.15$) (Figure 6). The mean weed dry biomass in wheat-lentil intercrops was 158 g/m^2, almost three-fold lower than that of the sole lentil. For the sole wheat, the increasing seeding dose (100, 150 and 200 kg/ha) led to a proportionally lower weed dry biomass (432, 242 and 161 g/m^2, respectively).

The co-design experience in the intercropping experiment provided valuable insights from both the researchers and the host farmer. During the experiment, researchers experienced a significant knowledge exchange with the farmer. Indeed, conducting the experiment on a real commercial farm increased the reliability of the results because the farm setting provided a realistic environment, giving researchers a better understanding of the challenges and opportunities associated with intercropping in practical farming scenarios. However, the valorisation of scientific results obtained from the on-farm experiment may not always fit the traditional format of scientific research and be innovative enough for academic publications. However, this drawback was overcome by the first stage research in plots managed on the experimental farm. From the researcher's perspective, the limited project duration and funding posed limitations for creating and consolidating farmer clusters. Indeed, the establishment of collaborations and the continuous development of on-farm experiments and the building of farmer clusters require a long-term funding programme and support. From the host farmer's perspective, there were several advantages to participating in the co-design process with researchers. Firstly, the experience allowed the farmers to become familiar with the scientific approach of designing new experiments and implementing on-farm innovations such as the comparison between standard and innovative management practices under comparable environmental and soil conditions. Measurements and observa-

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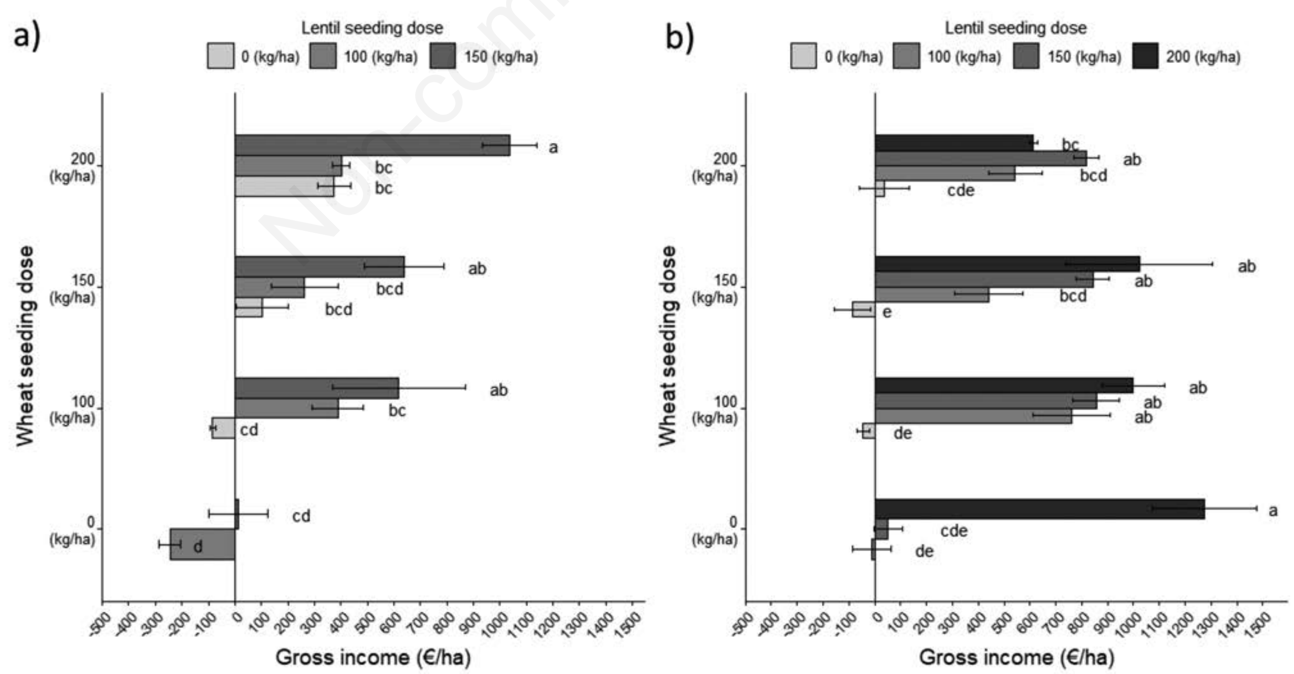

Figure 5. Gross Income for wheat-lentil intercrops with different seeding doses combination for the 2019/20 growing season (**a**) and 2020/21 growing season (**b**). Different letters (a-e) indicate significant differences at the 0.05 level (Sidak *post-hoc* test). Error bars represent standard error. Gross income does not include the common agricultural policy payment.

tions made by researchers offered useful information to the farmers, helping them gain a deeper understanding of their own farming systems and identify areas for improvement. However, there were also constraints faced by the host farmer. One limitation was that researchers were more focused on the agronomic part of the process and less on the market value of the crop production, which is a crucial element for the sustainability of the farm. For example, researchers selected a lentil variety with a large grain size that is not appreciated by the farm consumers. Another constraint was the difficulty in accessing funding for acquiring specific machinery at the farmer consortium level. This constraint made it necessary to adapt and modify existing machinery or develop alternative techniques to suit the specific requirements of intercropping but with sub-optimal results. For instance, machinery required for grain separation in intercropping systems may not be readily available or affordable for individual farmers, hindering the implementation of certain practices. This highlights the need for more intensive cooperation among farmers in the same area.

The open field day organised in the La Viola farm has led to a consolidation of local farmer clusters. Falconnier *et al*. (2017) highlight the importance of involving other local farmers in on-farm demonstration days. This involvement may support the implementation of agronomic practices at the landscape level based on crop diversification thanks to a peer-to-peer knowledge exchange (Garforth *et al*., 2003; Marraccini *et al*., 2020, Sutherland and Marchand, 2021). Despite the general success of the open field day in promoting innovations for sustainable agriculture, only those farmers directly involved benefitted. For this reason, Chowdhury *et al*. (2015) proposed the publication of videos as a fundamental tool for participatory agricultural and rural research for the broadest dissemination of information. Therefore, an interview with the host farmer Gilberto Croceri was published (https://www.youtube.com/watch?v=rszca3WBGUE&t=15s). The video at the date of 3 August 2023 reached 2188 views.

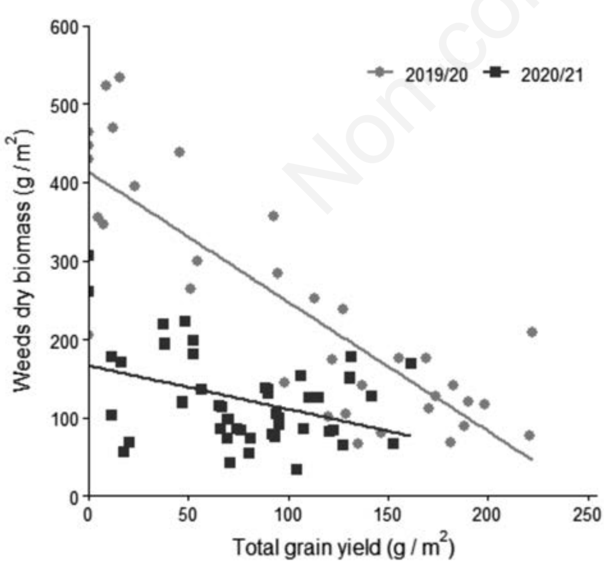

Figure 6. Relationship between total grain yield (wheat+lentil) of the wheat-lentil intercropping system and weeds dry biomass in the two years of on-farm trial (2019/20 and 2020/21). The slope of the regression line was significantly different from 0 in 2019/20: y=413.11–1.65×(R^2=0.70; F=77.78; df=33; p<0.001) and 2020/21: y=166.60−0.55×(R^2=0.15; F=7.67; df=43; p<0.0082).

Conclusions

A three-stage participatory approach was successfully applied to the wheat-lentil intercropping case study. It supported the uptake of wheat-lentil intercropping and the efficacy of this agroecological practice, and its success proved interesting for researchers and farmers. Carrying out experiments at different scales (plot, field and farm) around a specific question, is a strategy we can recommend for making the participatory research approach successful for farmers and researchers. It allows mitigation of the risk of crop yield losses for farmers while enabling them to evaluate innovative farming practices. At the same time, researchers manage to publish scientific data, while in parallel evaluating the feasibility of the innovations at the farm level. In particular, the controlled plot experiments at the experimental station allowed all interested farmers to observe and comment on the various treatments that were demonstrated during dedicated events. Based on the results obtained from the first stage and the feedback of local farmers, a second experiment was carried out using commercial agriculture machines to test the technical viability of intercropping at a larger scale. In the last and third stages, one interested farmer proposed an on-farm experiment to optimise the sowing density of his lentil-wheat intercrops adapted to the farm conditions. This trial allowed us to test the agronomical and financial benefits alongside the technical feasibility of wheat-lentil intercropping. In particular, the wheat-lentil intercrops sown at 150 kg/ha guaranteed a higher production than sole crops and significantly improved weed control. The proposed three-stage approach, applied to the case study of wheat-lentil intercropping emphasizes the importance of involving farmers from the initial phases of the experimental process. This involvement includes a peer evaluation of the most promising solutions tested on the station and the active engagement of farmers in co-designing on-farm experiments tailored to meet the actual needs of the farmers. This approach facilitates the co-creation of knowledge relevant to farmers and researchers and effectively supports the agroecological transition of farms towards more sustainable agricultural systems.

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Online supplementary material:
Supplementary Figure 1. Experimental layout for the medium scale experiment.
Supplementary Figure 2. a) The seeding machine was modified for intercropping and equipped with two independent hoppers respectively for wheat and lentil; b,c) the machine was manually set up for wheat and lentil to associate the target seed density of the experiment with the respective point of graduated scale of the machine.

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