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# Optimizing grain legume intercropping with buckwheat to improve weed management and reduce yield loss

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## Abstract

Increasing grain legume cultivation is key to Europe's protein autonomy and agroecological transition goals. Weeds represent a major issue for grain legumes, commonly managed mechanically in organic farming, although intercropping (IC) is emerging as an agronomic alternative. Alternate row IC can replace mechanical weeding but often reduces legume yields, while mixed row IC in addition to mechanical weeding may provide more effective results. This study examined soybean, chickpea, and lentil intercropped with buckwheat, comparing additive alternate and mixed row IC for weed suppression and crop performance and different IC ratios (2:1, 4:1). Buckwheat (*Fagopyrum esculentum* Moench.) is a pseudocereal known for its weed suppressive abilities but is seldom considered in intercropping studies. Three randomized trials took place in 2023–2024 in the plains of northeastern Italy. Crop and weed aboveground biomass and crop grain yield were measured, and the land equivalent ratio and weed performance ratio were calculated. Intercropping at the 4:1 ratio with buckwheat in mixed IC (where MIX25 is within row intercropping with buckwheat at 25% of its pure stand seed rate) was the only case where legume yield was maintained across species. The MIX25 also provided satisfactory weed suppression. Combining agronomical and mechanical weed control methods could facilitate the spread of agroecological practices in arable crops by reducing redesign risks while increasing agro-biodiversity. This study is among the few to propose buckwheat as a suitable companion crop for three grain legumes in a Mediterranean rainfed environment, showing promising results for weed control and legume performance.

## Plain Language Summary

Europe needs to grow more grain legumes to reduce food import and the impact of agriculture. Weeds are a major issue for legumes and are mainly controlled with herbicides, but intercropping (IC)—growing two or more crops together—might help

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**Abbreviations:** AGDM, aboveground dry matter; BW, pure buckwheat plots; IC, intercropping; LER, land equivalent ratio; WPR, weed performance ratio.

manage weeds naturally. Despite this, the success of IC varies depending on the climate and the crops involved. We tested growing soybean, chickpea, and lentil together with buckwheat to control weeds and assess yield effects in northern Italy. We compared alternate rows (one row of buckwheat is planted between legume rows, no mechanical weeding) and mixed rows (legumes and buckwheat seeds are mixed together in the same row with mechanical weeding), at 50% and 25% of buckwheat sole crop seed rate. Mixing legumes with buckwheat at 25% of its dose maintained yields similar to the ones of the pure legumes while controlling weeds. Combining IC with mechanical weeding could improve weed control and support more sustainable farming.

## 1 | INTRODUCTION

Two major goals of the EU agricultural policy are related to reducing the protein import and to enhancing the transition from animal- to plant-based proteins, requiring a forecasted increase of 14% of domestic EU human grain legume consumption by 2031 (European Commission. Directorate General for Agriculture & Rural Development, 2021). To date, pulses cover 2.01 M ha of European agricultural land, which equates to just less than 3% (van Loon et al., 2023). Grain legume production faces several challenges that stem from a lack of varieties adapted to organic farming and from biotic stresses (Cernay et al., 2015; Watson et al., 2017), which cause unstable yields (Antichi et al., 2023; Reckling et al., 2018). These issues lead to inadequate profit margins for farmers (Antichi et al., 2023), hindering a larger adoption of pulses over high-yielding crops, such as corn, sunflower, or soybean, despite the EU subsidies for crop diversification (Benini et al., 2023; Magrini et al., 2016).

Mechanical or physical weed control practices (e.g., hoeing, inter-row cultivation, false seed beds) are regarded as the most reliable solutions in organic farming (Gallandt, 2014), but the best results in the long run are obtained by combining diverse crop management practices (i.e., crop rotations, cover crops, intercropping [IC], fertilizer timing/placement; Bàrberi, 2002; Cordeau, 2022; Dhakal et al., 2024), otherwise known as the "many little hammers" approach (Liebman & Davis, 2009; Tidemann et al., 2023). Recent meta-analyses support the central role of IC to maximize land use efficiency (Gu et al., 2021; Martin-Guay et al., 2018) while providing important agro-ecosystem services such as ameliorating soil health, increasing pest biological control, and suppressing weeds (Gu et al., 2021; Yousefi et al., 2024). Legumes are known to have a slow growth rate in the initial vegetative phases and reach full cover around the flowering phase, allowing weeds to develop in the inter- and intra-row niches (Avola et al., 2008; Pannacci et al., 2018), but recent research supports that legumes can also benefit from IC with regard to weed and pest suppression and yield stability (Jensen et al., 2020; Tosti et al., 2023; Zhou et al., 2023).

Legume–cereal intercrops represent 68% of IC combinations worldwide (Martin-Guay et al., 2018) and are a key example of the use of trait complementarity in intercrops, though legumes are often the service crop. In a meta-analysis, Brooker, Pakeman, Adam, et al. (2024) report a 30% increase in yield per unit area (expressed as crop performance ratio) of IC in different climatic zones of Europe, although the benefit was linearly related to average daily rainfall. Under conditions of reduced rainfall in the Mediterranean, Monti et al. (2019) showed that the advantages of cereal–legume IC cannot be unequivocally confirmed and often benefit cereal yields to the detriment of legumes (Blanc et al., 2024; Tosti et al., 2023). Therefore, it is necessary to explore other non-cereal companion species that are better suited to support grain legumes with limited trade-offs in Mediterranean areas (Blanc et al., 2024; Cheriere et al., 2023; Pagani et al., 2024).

Minor crops (e.g., buckwheat, camelina, flax) require less irrigation and fertilization (Izydorczyk et al., 2014; Manners et al., 2020), which makes them well-suited as companion crops for legumes. Devi et al. (2014) found an increased water use efficiency and the highest monetary index in a 6:2 lentil–mustard IC trial, while Pagani et al. (2024) investigated camelina-field pea and camelina–lentil IC to increase land use efficiency of food and oilseed crops. Buckwheat (*Fagopyrum esculentum* Moench.; *Polygonaceae*) is also emerging as a companion crop in alternative IC combinations (Biszczak et al., 2020; Cheriere et al., 2020; Virili et al., 2024). Buckwheat has been identified as a potentially suitable candidate for IC, as its growth cycle is compatible with many spring/summer crops (Virili et al., 2024). Buckwheat has documented weed suppressive abilities due to its rapid establishment and through allelochemicals stored in the stem and leaves, released in the soil after termination mainly when used as a cover crop (Falquet et al., 2015; Vieites-Álvarez et al., 2024). Few studies however investigated the use in IC of buckwheat with grain legumes (Virili et al., 2024); furthermore, most studies focus on comparing different seeding ratios in additive or replacement designs (Raseduzzaman & Jensen, 2017), while few also compare the spatial arrangement of the crops. In a systematic review by Virili et al. (2024), examples of different IC arrangements were reported (e.g., mixed, row, strip), but only one out of the 17 studies compared alternate rows to mixed row arrangements (Cheriere et al., 2020).

The present study investigated the performance of IC of soybean, chickpea, and lentil with buckwheat in the lowland plains of northeastern Italy. This area is characterized by 2- or 3-year rotations of maize and soybean as dominant summer crops following winter cereals (typically wheat or barley; Benini et al., 2023); crop diversification urges to strengthen the resilience of these cropping systems to the impacts of climate change and to limit threats (e.g., evolution of herbicide-resistant weeds) favored by an increasing frequency of soybean in the crop rotation (Milani et al., 2023). IC was hypothesized to be a good diversification practice for soybean to reduce chemical-based inputs and for chickpea and lentil (which are being introduced in the area to diversify crop rotations) to stabilize yields and provide an additional tool for weed control.

The main objectives of the study were to determine which IC arrangement and management practices best maximized weed suppression, land-use efficiency, and legume yield. The grain legumes were intercropped with buckwheat in two different additive IC arrangements and managements: within row + hoeing (2:1 and 4:1 ratios, legumes and buckwheat sown together in the same row with buckwheat sown at half or a quarter of its sole crop dose) and alternate rows without hoeing (2:1 ratio, one row of buckwheat sown at half its sole crop dose in the legume inter-row). The two IC arrangements were chosen to investigate weed control efficacy in the row and between rows; the two buckwheat densities in the within row arrangement were chosen to investigate the minimum seed investment of the companion crop to obtain acceptable weed control in combination with hoeing, without compromising legume grain yields. The 2:1 ratio in the additive design was hypothesized to give enough competitive advantage to the legume (Kraska et al., 2019) and because of the rapid establishment of buckwheat, alternate row IC was hypothesized to guarantee the best legume yields by allowing a better exploitation of resources from the two crops and removing the need for hoeing in the inter-rows (Koskey et al., 2023; Reid et al., 2024). On the other hand, mixed row IC at a 4:1 ratio was hypothesized to maximize the trade-off between weed control and legume yield, due to buckwheat's exploitation of ecological niches in the intra-row spaces and the most favorable ratio for the legume (Wang et al., 2012).

**Core Ideas**

- Three grain legumes were intercropped with buckwheat in a Mediterranean lowland plain.
- Buckwheat significantly reduced legume yield at the 2:1 ratio.
- Mixed row intercropping (IC) improved weed control versus alternate row IC.
- 4:1 mixed row IC resulted in the best trade-off between improved weed control and yield loss.

## 2 | MATERIALS AND METHODS

### 2.1 | Experimental site and details

#### 2.1.1 | Experimental site

The trials were carried out at the experimental farm of the University of Udine (NE Italy; 91 m above the sea level; 46.03 N, 13.22 E) in 2023 and 2024 in two adjacent fields. The area is characterized by a Mediterranean North climate (European Environment Agency). The long-term (1993–2013) average annual rainfall and average air temperature of the area were 1427 mm and 13.2°C, respectively. The weather conditions were recorded by a local meteorological station (ARPA FVG – OSMER) situated within the experimental farm. The soil from the experimental area was silty (36.5% sand, 41% silt, 22.5% clay) and well-draining with 7.2 pH, 0.15% total N (C/N ratio 13.6), and 3.52% soil organic matter (other soil properties were total limestone: 2%, organic C: 1.9%, available P: 96 mg kg$^{-1}$, exchangeable K: 258 mg kg$^{-1}$, exchangeable Mg: 523 mg kg$^{-1}$, exchangeable Ca: 2782 mg kg$^{-1}$).

#### 2.1.2 | Experimental design

Lentil (*Lens culinaris* Moench, cv Itaca), chickpea (*Cicer arietinum* L., cv Sultano) and soybean (*Glycine max* (L.) Merr., cv Ascasubi) were grown in pure stands and intercropped with buckwheat (*F. esculentum* Moench, cv Panda) in two spatial arrangements: within row (where MIX is within row intercropping) and alternate row (ALT; where ALT is alternate row intercropping with buckwheat at 50% of its pure stand seed rate) IC. The sowing rate in the pure plots was as follows: 240 seeds m$^{-2}$ for buckwheat, 120 seeds m$^{-2}$ for lentil, 55 seeds m$^{-2}$ for chickpea, and 45 seeds m$^{-2}$ for soybean. The seed rate of the legumes was kept constant across all treatments. In addition, two buckwheat plant densities were considered for the MIX plots, resulting in plots with 25% of the pure buckwheat seed rate (where MIX25 is within row intercropping with buckwheat at 25% of its pure stand seed rate, 4:1 ratio)

**TABLE 1** Main events during the chickpea, lentil, and soybean trials in 2023 and 2024.

| | Chickpea | | Lentil | | Soybean | |
|---|---|---|---|---|---|---|
| **Operation** | **2023** | **2024** | **2023** | **2024** | **2023** | **2024** |
| Harrowing | March 20 | April 2 | March 20 | April 2 | May 29 | June 13 |
| Sowing | March 29 | April 9 | March 29 | April 9 | June 1 | June 20 |
| Hand hoeing | May 2 | May 27 | May 2 | May 27 | July 9 | July 21 |
| Legume flowering | June 3 | June 11 | May 29 | June 6 | July 21 | August 5 |
| Legume harvest | July 31 | July 31 | July 15 | July 22 | October 11 | October 30 |

and 50% of the pure buckwheat seed rate (where MIX50 is within row intercropping with buckwheat at 50% of its pure stand seed rate, 2:1 ratio). In the ALT plots (2:1 ratio), buckwheat seed rate was also halved compared to the control plots. Plots were 8 m long and 1.02 m wide with four rows spaced 34 cm apart in the pure legume and MIX plots, while the ALT and pure buckwheat plots had eight rows spaced 17 cm apart. Plots were spaced 1 m apart on the short side and 0.5 m apart on the long side. The legumes and buckwheat were sown on the same date using a plot seeder with four sowing elements spaced 34 cm apart, shifted relative to the center of the seeder. This allowed to seed the four rows of the pure legume and MIX treatments at the established inter-row distance in one pass, and to seed the pure buckwheat and ALT treatments in two passes (four rows on the first pass and the other four rows on the return pass) on the same wheel guides. The MIX50 treatment was included for lentil in 2024 but not in 2023 due to a priori assumptions regarding lentil competitiveness. Since soybean had to be seeded after chickpea and lentil, the investigated cropping systems were separated by legume type. Within each legume trial, the plots were completely randomized with four replicates per treatment, and four pure buckwheat plots were included for each legume. No irrigation or fertilization was provided, and weeding was performed once by hand hoeing the inter-row (keeping a 10-cm distance from the row to avoid damaging the crops) at the fifth leaf stage of the legumes, only in pure legumes and in the MIX plots (i.e., all plots with row distance of 34 cm). One hoeing pass is the common weed management followed by organic farmers in the region, usually in combination with a false seed bed. In both years, the preceding crop was corn (for grain). The details on the main field events for the three trials are presented in Table 1. Buckwheat was harvested on the same day with chickpea and lentil, but the buckwheat cultivar used for the trial had a shorter growing cycle compared to soybean, which did not allow for a double harvest.

## 2.2 | Data collection

An assessment of the weed community was conducted prior to and after hoeing in two quadrats of 0.35 m$^2$ (0.50 m × 0.7 m), which were randomly placed in each plot. For each quadrat, the percentage of plant cover was estimated visually for each weed species. The dominant weeds were classified as those species with an average of more than 10% cover and which were present in more than 30% of the sampling areas in both years. At legume flowering aboveground biomass of the legume, buckwheat and weeds (total) were collected in one quadrat per plot of 0.35 m$^2$. The samples were then oven-dried at 70˚C for 72 h.

The aboveground biomass of the legume, buckwheat, and weeds (total) was collected again at harvest in a 0.35-m$^2$ quadrat per plot. Samples were oven-dried at 70˚C for 72 h, after which the total aboveground dry biomass (AGDM) was assessed (stem + leaves + seeds), and the crops were then threshed to separate the seeds. Weed biomass data were used to calculate the weed performance ratio (WPR; Brooker, Pakeman, Hewison, et al., 2024) and the “weed control index” (W_index; Cheriere et al., 2020), as follows (Equations 1 and 2):

$$\mathrm{WPR} = \ln(\mathrm{WBic}/(\mathrm{Zlegbw} \cdot \mathrm{WBleg} + \mathrm{Zbwleg} \cdot \mathrm{WBbw})), \tag{1}$$

where WBic is the weed biomass in the intercrop, Zlegbw is the sown ratio of legume to buckwheat (the legume sown ratio is always = 1), WBleg is the weed biomass in the sole legume, Zbwleg is the sown ratio of buckwheat to legume (for 2:1 ratio = 0.5, for 4:1 ratio = 0.25), and WBbw is the weed biomass in the sole buckwheat plots, Where values of WPR <0 indicate that weed biomass was reduced in the intercrop.

$$\mathrm{W\_index} = 1 - (WBic/WBleg)\,. \tag{2}$$

The W_index is proportional to the effect of the intercrop on weed biomass.

The growth cycle of buckwheat coincided with the ones of lentil and chickpea, allowing for a double harvest. In the soybean trial, buckwheat completed its cycle 3 weeks before soybean, so its achenes had already fallen by the time of soybean harvest.

Crop grain yield was measured by manually collecting a larger area of 1.36 m$^2$ (0.70 m × 2 m) in each plot; in this case, crops were left to air-dry for 1 week and threshed. The seed moisture at threshing time was 12% for chickpea, 10% for lentil and soybean, and 12% for buckwheat.

Crop grain yield data were used to calculate the land equivalent ratio (LER) (Equation 5) for lentil and chickpea, as follows (Equations 3 and 4):

$$\text{pLER (legume)} = \text{Ylegic}/\text{Yleg}, \tag{3}$$

$$\text{pLER (buckwheat)} = \text{Ybwic}/\text{Ybw}, \tag{4}$$

$$\text{LER} = \text{pLER (legume)} + \text{pLER (buckwheat)}, \tag{5}$$

where Ylegic is the legume grain yield in the IC, Yleg is the legume grain yield in the pure legume, Ybwic is the buckwheat grain yield in the IC, and Ybw is the buckwheat grain yield in the pure buckwheat.

For soybean, LER was calculated using the AGDM of soybean and buckwheat (replacing Y).

## 2.3 | Data analysis

All data analyses were carried out using R (version 4.3.3; R Core Team, 2021). For each response variable, a linear mixed effect model was adopted with the interaction between cropping system and legume type in the fixed part, while the random structure included year and legume type (1|year:legume type) to account for the experimental design structure and for the unbalanced design (Zuur et al., 2009). Models were validated using the Kolmorov-Smirnov test, and residuals were checked for homogeneity (function "simulateResiduals," package "DHARMa"; Hartig, 2018). The models that did not meet the Kolmorov–Smirnov criteria were fitted with a glmer model with a gaussian (link = "log") distribution. Response variables were then analyzed with the Anova function. Differences between means were assessed with a Tukey honestly significant difference test (function "emmeans," package "emmeans"; Lenth, 2017) after which the letters were extracted with the "cld" function in the "lsmeans" package (Lenth, 2018).

# 3 | RESULTS AND DISCUSSION

## 3.1 | Weather

Cumulative rainfall and average daily temperatures during the two growing seasons were 852 mm and 19.7°C in 2023 (March–October) and 1210 mm and 20.1°C in 2024 (April–October). Daily rainfall together with the average daily air temperatures for the 2 experimental years are illustrated in Figure 1.

## 3.2 | Crop biomass, grain yield, and LER

The aboveground biomass of all three legumes was reduced in the IC systems (Tables 2 and 3). The different precipitation pattern and the warmer spring in 2024 (Figure 1) produced generally higher yields in 2024 compared to 2023 (data not shown). It is well known that seasonal weather events can impact agricultural practices, but overanalyzing yearly performances can be counterproductive when the objective is the assessment of the practice per se (Moore & Dixon, 2015). Brooker, Pakeman, Adam, et al. (2024) reported higher benefits from IC in areas with higher daily mean rainfall, but these effects are only discernible in the same site using long-term data or by comparing areas with different climates.

The yield of the three legumes was significantly reduced in the alternate row and MIX50 layouts (in both cases buckwheat was sown at half of its sole crop dose) compared to the MIX25 arrangement (Table 3), confuting the original hypothesis based on findings from Kraska et al. (2019). In a sunflower–soybean trial, Saudy and El-Metwally (2009) found that hoeing promoted the highest grain yields, regardless of the IC combination. This was the case only when the legumes were intercropped at the 4:1 ratio with buckwheat, producing comparable yields to the sole legumes. Chickpea and lentil are often defined as weak competitors in IC studies (Banik et al., 2006; Radicetti et al., 2012; Raza et al., 2024) even at higher ratios compared to the companion crop (Tosti et al., 2023; Wang et al., 2012). Pagani et al. (2024) recorded halved lentil yields (~0.16 Mg ha$^{-1}$) in a 1:1 ratio with broadcast-sown camelina, compared to the sole lentil crop (~0.30 Mg ha$^{-1}$). Zhou et al. (2023) also reported significant chickpea yield losses both when intercropped at a 70:30 ratio and at a 50:50 ratio with flax but in a replacement design. Contrary to expectations, soybean was also negatively affected by buckwheat IC at the 2:1 ratio, confirming the findings from Cheriere et al. (2020) who reported a significant soybean yield loss with buckwheat in both alternate (−50%) and mixed row (−75%) arrangements at a 1:1 ratio in a replacement design. Contrary to the aforementioned replacement designs, our additive design was purposefully selected to facilitate the legume. Our results show that this was not the case. However, we can attribute the yield losses of legumes solely to the plant density of pure buckwheat plots (BW), rather than to a reduced plant density of the legume crop, and this helps us to understand how to better optimize legume-based IC. Measurements on the trait plasticity (e.g., first pod height, leaf angle, root depth) of the intercropped species would provide valuable information on how to mitigate the underlying mechanisms related to inter-specific competition, which negatively affect

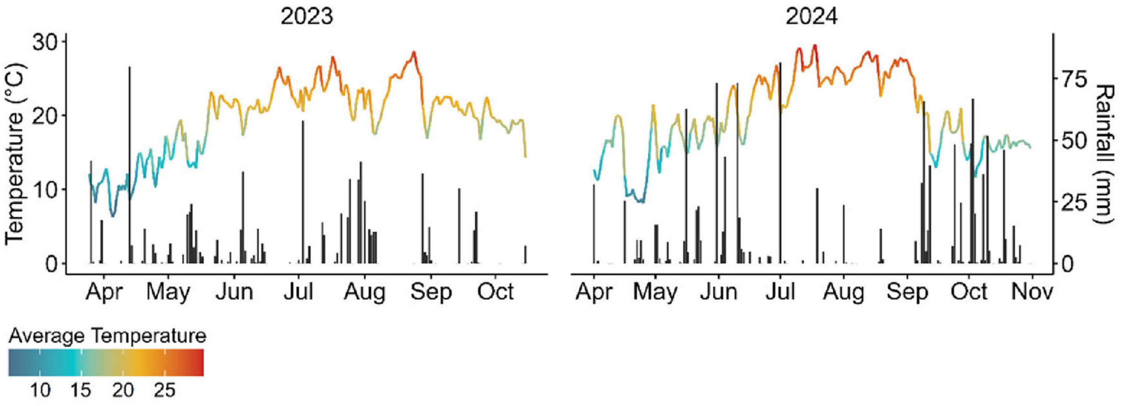

**FIGURE 1** Daily rainfall (mm, gray bars) and average daily temperature (˚C) in 2023 and 2024 during the months in which the field trials took place (Udine, Italy).

**TABLE 2** Effect of legume type (L) and cropping system (CS) on legume (_l) and buckwheat (_bw) above ground dry matter (AGDM; Mg DM ha$^{-1}$), grain yield (Y; Mg DM ha$^{-1}$), partial land equivalent ratio (pLER), and total LER at harvest.

| | AGDM_l (Mg DM ha$^{-1}$) | AGDM_bw (Mg DM ha$^{-1}$) | Y_l (Mg DM ha$^{-1}$) | Y_bw (Mg DM ha$^{-1}$) | pLER_l (–) | pLER_bw (–) | LER (–) |
|---|---|---|---|---|---|---|---|
| L | 21.66<br>*** | 0.07<br>ns | 10.67<br>*** | 0.04<br>ns | 0.34<br>ns | 2.61<br>ns | 1.06<br>ns |
| CS | 6.12<br>** | 34.73<br>*** | 6.48<br>** | 18.10<br>*** | 0.90<br>ns | 7.41<br>** | 4.83<br>** |
| L × CS | 0.94<br>ns | 3.64<br>** | 0.72<br>ns | 1.01<br>ns | 2.00<br>ns | 3.60<br>** | 4.01<br>** |

*Note*: Numbers represent *F*-values. Effect was considered significant at the $p < 0.05$ level.
Abbreviations: DM, dry matter; ns, not significant.
**0.0001 < $p$ < 0.01; ***$p$ < 0.0001.

**TABLE 3** Significant arithmetic differences in legume (_l) above ground dry matter (AGDM; Mg DM ha$^{-1}$), and in legume and buckwheat (_bw) grain yield (Y; Mg DM ha$^{-1}$) between legume types and cropping systems from the Tukey honestly significant difference post hoc test.

| | AGDM_l (Mg DM ha$^{-1}$) | Y_l (Mg DM ha$^{-1}$) | Y_bw (Mg DM ha$^{-1}$) |
|---|---|---|---|
| Chickpea | 3.81 ± 0.31ab | 1.26 ± 0.11b | 0.38 ± 0.04 ns |
| Lentil | 3.55 ± 0.17 b | 1.57 ± 0.12b | 0.46 ± 0.05 ns |
| Soybean | 7.33 ± 0.41a | 3.54 ± 0.15 a | — |
| LEG | 6.04 ± 0.52 a | 2.56 ± 0.26 a | — |
| ALT | 4.39 ± 0.49 b | 1.88 ± 0.25b | 0.31 ± 0.05 c |
| MIX50 | 4.86 ± 0.61b | 1.96 ± 0.29 b | 0.51 ± 0.06 b |
| MIX25 | 4.51 ± 0.42 b | 2.18 ± 0.24 ab | 0.31 ± 0.06 c |
| BW | — | — | 0.58 ± 0.07 a |

*Note*: Effect was considered significant at the $p < 0.05$ level. The table displays treatment means ± standard error. Different letters represent significant differences ($p < 0.05$) between means.
Abbreviations: ALT, alternate row arrangement with buckwheat sown at 50% of its sole crop sowing density; BW, sole buckwheat; DM, dry matter; LEG, sole legume; MIX50, within row mixed arrangement with buckwheat sown at 50% of its sole crop sowing density; MIX25, within row mixed arrangement with buckwheat sown at 25% of its sole crop sowing density; ns, not significant.

the legume crop and allow for more effective plant breeding specifically for IC (Ajal et al., 2022; Schell et al., 2025).

Accepting some yield loss (like in MIX25) could be compensated by obtaining better legume grain quality, as also mentioned by Zhou et al. (2023) who report a reduction of 50% Ascochyta blight severity in 1:1 chickpea flax IC. It is well documented that buckwheat provides important services related to biological pest control (Virili et al., 2024),

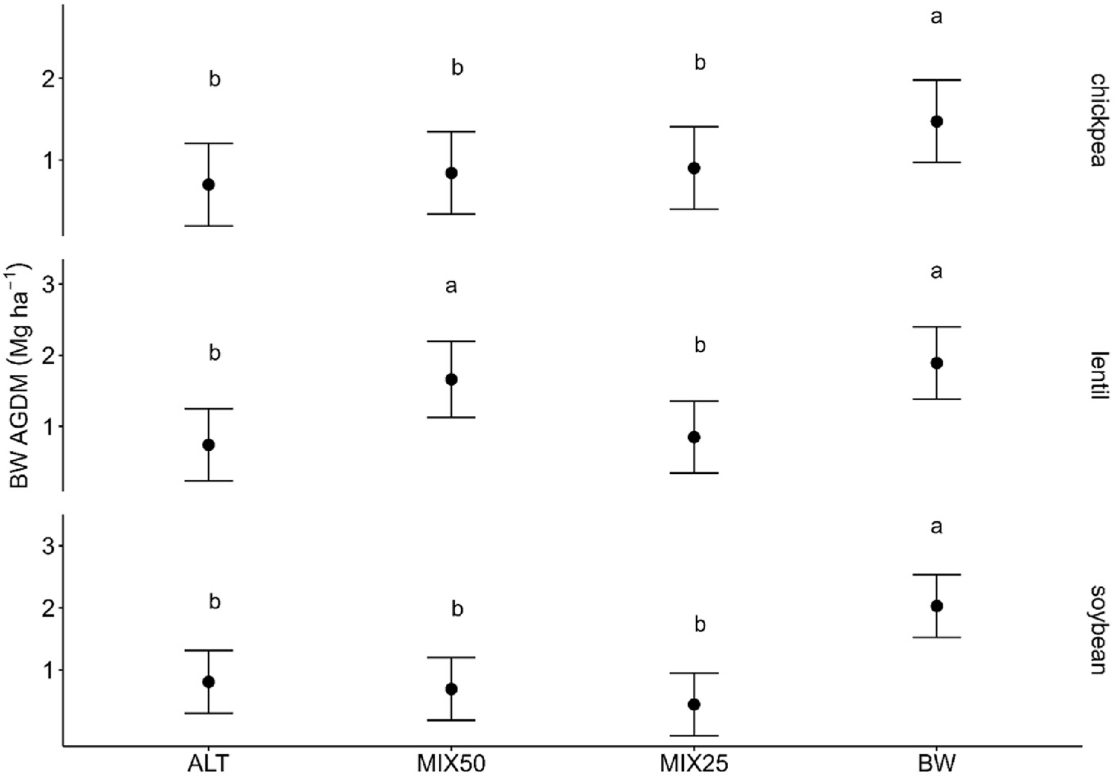

**FIGURE 2** Effect of the interaction between cropping system and legume type on buckwheat above ground dry matter (AGDM, Mg DM ha$^{-1}$). The data are averaged across years. Bars represent the standard error of the mean. ALT, alternate row arrangement with buckwheat sown at 50% of its sole crop sowing density; BW, sole buckwheat; MIX50, within row mixed arrangement with buckwheat sown at 50% of its sole crop sowing density; MIX25, within row mixed arrangement with buckwheat sown at 25% of its sole crop sowing density. Different letters represent significant differences ($p < 0.05$) between means from the Tukey honestly significant difference post hoc test (treatments are compared within each legume type). DM, dry matter.

but whether yield loss can be compensated by better grain quality linked to reduced pest incidence needs to be further understood (Alarcón-Segura et al., 2022; Labrie et al., 2016).

Buckwheat aboveground biomass and yield did not respond proportionately to the buckwheat plant density in the IC arrangements compared to the sole crop (Figure 2). Buckwheat biomass at 25% of its sowing density was never significantly lower than the 2:1 ratio (50% stand density), while buckwheat outperformed the sole cropping system when intercropped with lentil in the MIX50 arrangement.

In both chickpea and lentil trials, buckwheat could be harvested simultaneously as a secondary cash crop. When buckwheat was intercropped with chickpea and lentil in the MIX50 arrangement, it produced comparable yields to those of the sole crop, despite being sown at half the dose. Companion crops of legumes usually benefit from IC more than the legumes (Cheriere et al., 2020; Hauggaard-Nielsen et al., 2008; Pinto et al., 2024; Wang et al., 2012), which could be partially confirmed in the present study.

IC with buckwheat had no significant effect on the pLER of the three legumes, only on the pLER of buckwheat (Table 2), which was the highest in the MIX50 arrangement with chickpea, whereas no differences were recorded in lentil and soybean (Figure 3A). Regardless, the partial LER of all legumes was >0.5, indicating that a net benefit was obtained through IC compared to the sole legume crop at the same sowing density. A net benefit from IC was also observed for the total LER, with the highest overall values recorded for lentil and the lowest for soybean (Figure 3B). Brooker, Pakeman, Adam, et al. (2024) found that the net benefit of IC is lower with higher yields; average soybean yields in the area are around 3.5 Mg ha$^{-1}$ (compared to the 1–2 Mg ha$^{-1}$ of chickpea and lentil; Table 3), so the low LER values for soybean could reflect these findings. In a 1:1 lentil–camelina IC trial, despite an LER of 1.51, camelina pLER was 0.99 while the benefit for lentil was minimal (lentil pLER = 0.52) (Pagani et al., 2024). On the other hand, Devi et al. (2014) intercropped lentil and mustard in 1:1 (25 cm inter-row) and 2:1 rows (13 cm inter-row), and lentil benefitted from the IC in both systems (0.65 in 1:1 and 0.88 in 2:1). Das et al. (2017) recorded the highest LER (1.42) when chickpea was sown at a 3:1 ratio with rapeseed. Dowling et al. (2023) investigated the performance of chickpea–canola and chickpea–flax IC in 2:2 alternate rows and registered a higher LER in the

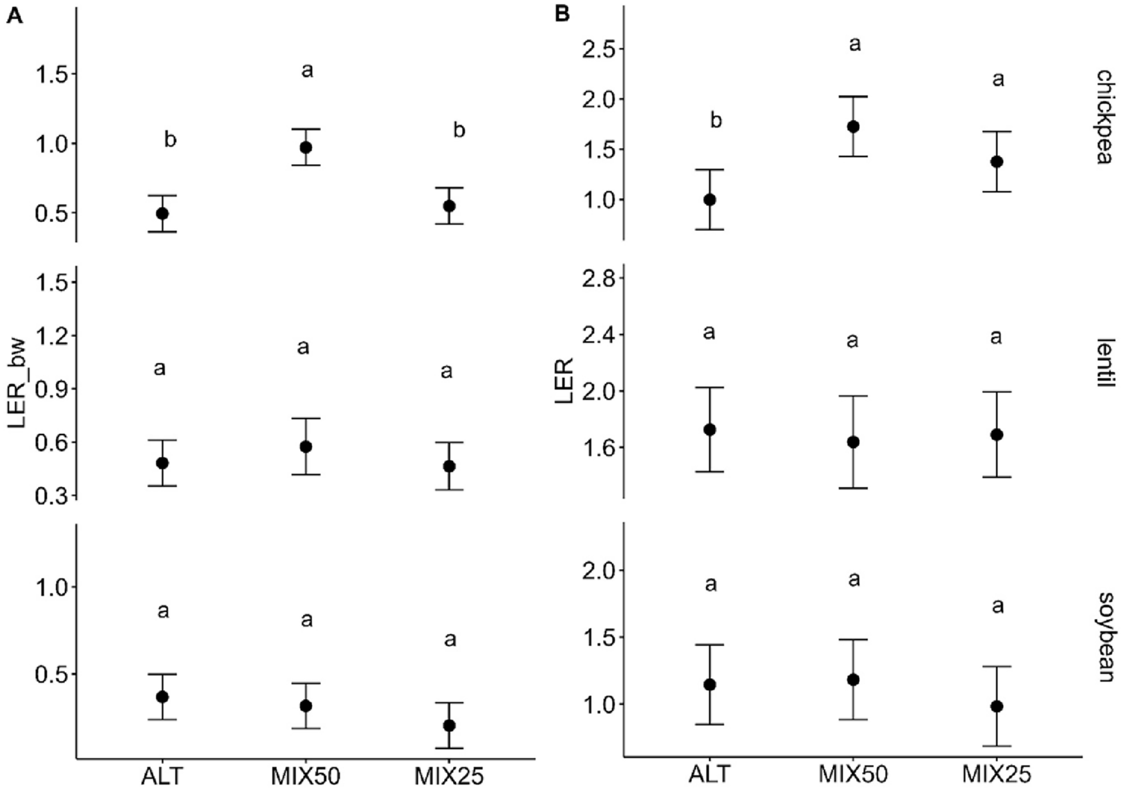

**FIGURE 3** Effect of the interaction between cropping system and legume type on (A) buckwheat LER (LER_bw) and (B) system LER. The data are averaged across years. LER values in the soybean trial were calculated based on biomass, since buckwheat yield was not available. Bars represent the standard error of the mean. Different letters represent significant differences ($p < 0.05$) between means from the Tukey honestly significant difference post hoc test (treatments are compared within each legume type). ALT, alternate row arrangement with buckwheat sown at 50% of its sole crop sowing density; MIX50: within row mixed arrangement with buckwheat sown at 50% of its sole crop sowing density; MIX25: within row mixed arrangement with buckwheat sown at 25% of its sole crop sowing density

chickpea–canola intercrop (1.77) compared to the chickpea–flax intercrop (1.03). The literature shows great variability, although there is also a plethora of different IC systems that have been studied (Martin-Guay et al., 2018), making comparisons difficult. In our study, a difference between IC arrangements was evident only for chickpea–buckwheat in which LER was higher in the MIX arrangements.

Buckwheat and chickpea seeds could be easily separated using a 6mm sieve, which was not possible for buckwheat with lentil due to their similar size and thousand seed weight. Separation could be possible through optic selection but may not be available to farmers. Despite this, lentil and buckwheat have similar cooking times, and since there are no contamination issues from allergens, they may be sold as one product (e.g., as an ingredient for soups). This could transform a limitation into an opportunity for food chains but calls for a re-design of agri-food systems to break current technical and socio-economical lock-ins (Magrini et al., 2016; Meynard et al., 2017).

The buckwheat cultivar (“Panda”) was not compatible with the growth cycle of soybean. Other commercial buckwheat cultivars with longer cycles and lower seed shattering could be considered for IC with soybean to guarantee a double yield. For example, the buckwheat cultivar “Kora” has a growth cycle of around 90 days and can retain its achenes even after reaching full maturity (observations from an ongoing trial, unpublished). Soybean varieties with shorter growth cycles can also be considered to obtain a simultaneous harvest. The seeds can be easily separated with a 6mm sieve (personal experience). Despite this, soybean is a primary allergen and may cause contamination in buckwheat seeds (Wiederstein et al., 2023), so this aspect should be further investigated to ensure that soybean allergens are not present in buckwheat, even after dehulling, to guarantee a revenue from both crops for the food industry.

### 3.3 | Weed control

The dominant weeds in the chickpea and lentil trials were *Chenopodium album* L. (lambsquarters) and *Galinsoga parviflora* L. (gallant soldier), followed by *Artemisia vulgaris* L. (common mugwort) in 2023 and by *Mentha arvensis* L. (common mint) in 2024. *Portulaca oleracea* L. (purslane) and *C. album* were the dominant weeds in the soybean trial

**TABLE 4** Effect of legume type (L) and cropping system (CS) on weed (_W) above ground dry matter (AGDM, g DM $m^{-2}$), weed performance ratio (WPR), and weed control index (W_index) at legume flowering and harvest.

| | **AGDM_W (g DM $m^{-2}$)** | | **WPR (–)** | | **W_Index (–)** | |
|---|---|---|---|---|---|---|
| | Flowering | Harvest | Flowering | Harvest | Flowering | Harvest |
| L | 0.0006 | 0.0002 | 0.57 | 2.81 | 0.21 | 1.71 |
| | ns | *** | ns | ns | ns | ns |
| CS | 25.16 | 12.62 | 2.65 | 3.94 | 1.59 | 1.03 |
| | *** | *** | ns | * | ns | Ns |
| L × CS | 3.35 | 2.40 | 0.19 | 0.02 | 0.18 | 0.48 |
| | *** | *** | ns | ns | ns | ns |

*Note*: Numbers represent *F*-values. Effect was considered significant at the $p < 0.05$ level.
Abbreviations: DM, dry matter; ns, not significant.
*$0.01 < p < 0.05$; ***$p < 0.0001$.

in both years. Cropping system had a significant effect on total weed biomass for all legumes at flowering and harvest but varied between the three legumes (Table 4, Figure 4). WPR was affected only by cropping system at legume harvest (Table 4), whereas no effect of cropping system was found on the W_index. The lowest weed control was provided by the alternate row layout (−0.74 ± 0.17), followed by MIX25 (−1.60 ± 0.38), and the highest weed control was provided by MIX50 (−2.14 ± 0.54).

Buckwheat was considered the most weed suppressive crop, but contrary to the results from Gu et al. (2021), weed biomass was higher in the sole buckwheat plots compared to the IC plots (Figure 4A,B). The mixed arrangements in the present study received one hoeing pass, which contributed to the higher weed control by removing plants in the inter-row, while the higher vegetation density in the row was controlled by the IC. Despite this, the present findings are partially in line with Gu et al. (2021), who stated that the spatial arrangement did not matter in additive designs with respect to weed suppression. At legume flowering (which occurred between 1 month and 2 weeks after hoeing, see Table 1), comparable weed biomass values were registered in the IC plots, but at harvest, the effect of hoeing in addition to the increased plant density in the rows was able to contain weed biomass compared to the ALT plots and to the pure legume plots (Figure 4B).

The results from weed biomass were confirmed by the WPR values. The results are partially in line with Cheriere et al. (2020) who reported significant weed suppression in soybean in both alternate and mixed row arrangements. Brooker, Pakeman, Hewison, et al. (2024) report that WPR was only affected by ploughing and not IC. Although the effect of soil management was apparent in our case as well, IC also contributed to weed suppression in the row. Even though all three systems produced WPR values <0 (indicating better weed control compared to the sole crops), the combination of hoeing and the highest row density of the 2:1 ratio led to the highest weed suppression for all three legumes. At harvest, comparable WPR values could be observed in both MIX arrangements compared to ALT IC for all three legumes. Larger plots would have allowed to sow the crops as farmers would (40–50 cm) and use a hoeing machine, which would have been more correct. This was not possible because a 34cm inter-row distance was the best compromise to shift the seeding elements and seed the rows for the pure buckwheat and ALT arrangement on a return pass so as to stay on the same tractor lines while having a minimum amount of rows for the samplings. Hand-hoeing could have resulted in a more meticulous weed control but was comparable for all cropping systems. Larger scale trials in on-farm experimentations, for example, would allow to overcome on-station trial constraints while also fostering co-design with farmers and accelerating the agroecological transition (Giannini & Marraccini, 2023).

## 4 | CONCLUSIONS

This study is the first to assess the performance of three IC grain legumes with buckwheat in an area, which is highly representative of inner Mediterranean plains and where the simplified cropping systems based on intensive maize-soybean rotations are threatened by longer drought periods and increased incidence of herbicide-resistant weeds. As hypothesized, the mixed row IC layout with 25% of buckwheat seed rate resulted in the best trade-off between legume yield and weed control. Contrary to our hypothesis, the alternate row arrangement was not able to replace hoeing with regard to weed control efficiency, and halving the buckwheat seed rate was still not enough to reduce its pressure on the legume. The present 2-year study produced encouraging preliminary results, although the authors acknowledge limitations in the experimentation and methodology, including the missing MIX50 treatment in the lentil trial in 2023, plot size, and manual harvesting. Larger plots would have allowed to collect more representative yield and weed biomass data, though this was not possible to implement with the available

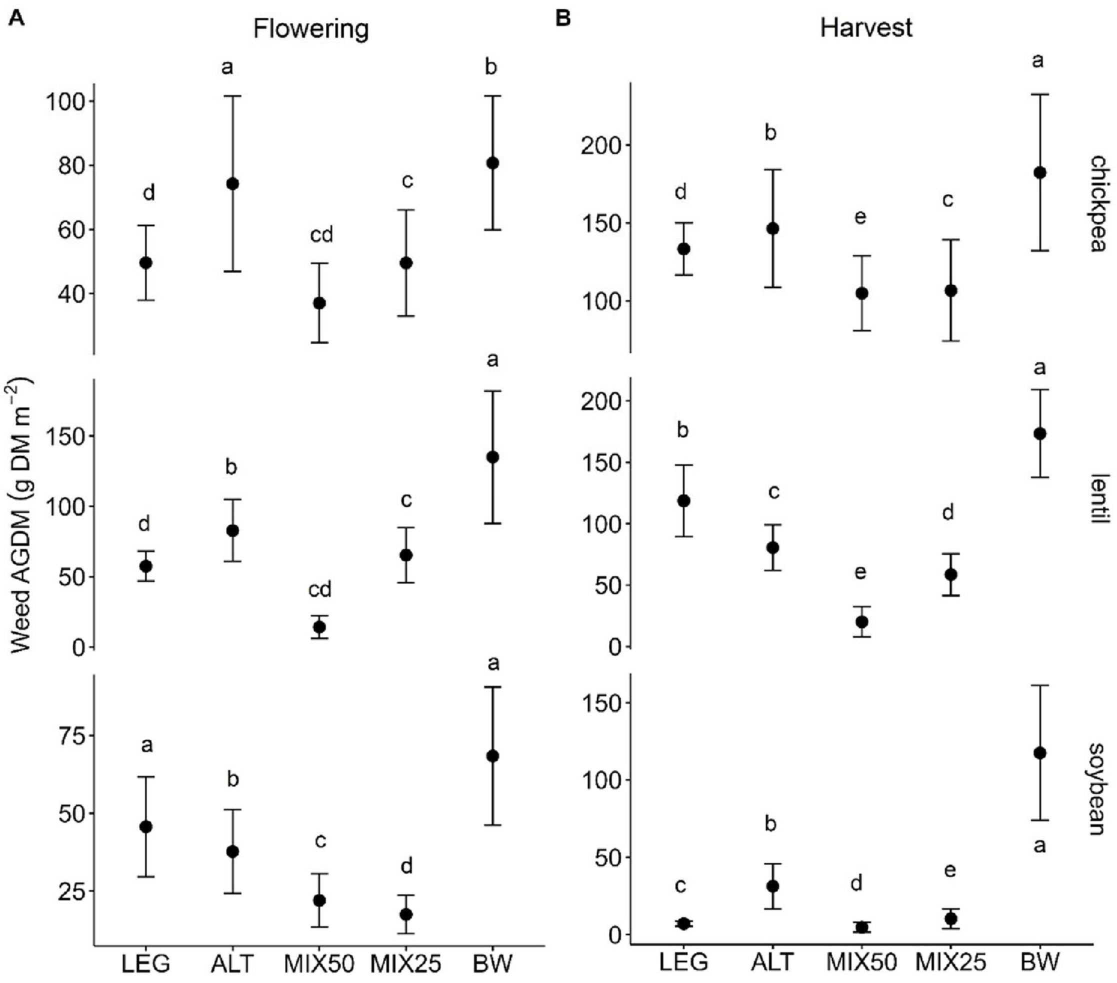

**FIGURE 4** Effect of cropping system and legume type on weed above ground dry matter (AGDM, g DM m$^{-2}$) at legume (A) flowering and (B) harvest. The data are averaged across years. Bars represent the standard error of the mean. Different letters represent significant differences ($p < 0.05$) between means (treatments compared within each legume type). BW, sole buckwheat; ALT, alternate row arrangement with buckwheat sown at 50% of its sole crop sowing density; LEG, sole legume; MIX50, within row mixed arrangement with buckwheat sown at 50% of its sole crop sowing density; MIX25, within row mixed arrangement with buckwheat sown at 25% of its sole crop sowing density.

machinery in the experimental farm, and additional years are necessary to investigate the effect on yield stability. Despite this, the present study lays the groundwork for future systematic studies on grain legume IC in Mediterranean lowlands. Research prospects include testing the on-farm scalability of the proposed solutions, assessing different companion species in alternate and mixed row arrangements, but also test different buckwheat cultivars with the three grain legumes and post-harvest seed separation.

## AUTHOR CONTRIBUTIONS

**Alessandra Virili**: Data curation; formal analysis; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Daniel Marusig**: Investigation; writing—review and editing. **Gemini Delle Vedove**: Conceptualization; funding acquisition; methodology; supervision; writing—review and editing. **Elisa Marraccini**: Conceptualization; methodology; supervision; writing—review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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