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Alternatives for sustainable weed control in single- and double-cropped soybean: A case study for Mediterranean irrigated conditions

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Abstract

The irrigated cropping systems in South Europe could benefit from soybean [*Glycine max* (L.) Merr.] introduction in their maize (*Zea mays* L.)-based crop rotations. However, sustainable weed management strategies are needed for soybean growers under Mediterranean irrigated conditions. This work aimed to assess the weed control efficacy, and the soybean performance, of alternative management practices for single- and double-cropped soybean. Two field experiments were carried out in northeast Spain in the period 2019–2021. Row width narrowing (75–37.5 cm), herbicide application (yes/no), and roller-crimped rye [*Secale cereal* (L.) M.Bieb.] cover crop (yes/no) were assessed in the single cropping system experiment (SCS). In the barley-soybean double cropping system experiment (DCS), row width narrowing and herbicide application were assessed. In the SCS, the presence of rye cover crop reduced weed biomass up to 92% compared to the controls without herbicide and cover crop in 2020. In 2021, no effect of the cover crop on weed pressure was found due to the low amount of rye biomass accumulated (11.8 and 3.4 ton DM ha^{-1} in 2020 and 2021, respectively). In the DCS, herbicide application attained the expected weed control. Row width narrowing to 37.5 cm did not have an impact on weed pressure nor on soybean yield in either experiment. We concluded that herbicide reduction for single-cropped soybean under Mediterranean irrigated conditions can be achieved by roller-crimping a rye cover crop, provided enough rye biomass is accumulated. In the DCS, our results indicated that further research is needed to find alternatives to chemical weed control.

Abbreviations: DCS, double cropping system; SCS, single cropping system.

1 | INTRODUCTION

Europe is a net exporter of cereals, milk, pork, and poultry meat (FAOSTAT, 2021). However, livestock production depends on 58 Mt year^{-1} of soybean [*Glycine max* (L.) Merr.] imported from overseas (Guilpart et al., 2022). From an agronomic point of view, the European dominance of intensive cereal cropping led to some environmental and agronomic problems (Brisson et al., 2010; Cavero et al., 2003). In northeastern Spain, winter cereals and maize (*Zea mays* L.) (MAPA, 2020) cropping systems are highly dependent on irrigation, due to the dry conditions during this period of the year. Crop diversification with soybean might be a strategy to increase the successive cereal yields due to the preceding crop effects of grain legumes (Preissel et al., 2015), to reduce the negative environmental impacts from intensive use of nitrogen fertilizers (Notz et al., 2023), and to increase European soybean self-sufficiency. While soybean production is currently moving toward the northern parts of Europe (Karges et al., 2022), little research has addressed its potential to move toward southern regions. Under Mediterranean semiarid conditions, soybean production is restricted to irrigated areas (Gonzalez-Bernal & Rubiales, 2016). In this context, water availability, high temperatures, and often high soil mineral N contents (Isidoro et al., 2006; Maresma et al., 2019) can trigger dense weed infestations leading to severe yield and quality losses. This situation is particularly important in soybean, given its low competitiveness against weeds (Carton et al., 2018; Place et al., 2011; Reckling et al., 2020).

Despite its broad use in livestock feed, soybean is an uncommon crop in Spain (1166 ha in 2020)(MAPA, 2020). Therefore, little knowledge exists regarding weed species infesting soybean and alternative control methods to chemical control. It can be expected that the weeds infesting soybean will be similar to those infesting other annual summer crops (maize, sunflower [*Helianthus annuus* L.], etc.) such as *Chenopodium album* L., *Datura stramonium* L., *Amaranthus* spp., and so forth (Meissle et al., 2010). The use of herbicides in soybean can have a cost of up to 276 USD ha^{-1} in the study area (excluding application costs), and an environmental cost associated with their production and use (Audsley et al., 2009). Moreover, the current European Union (EU) agricultural policies are promoting a reduction in pesticide use in European agriculture (European Commission, 2021). Therefore, there is a need to explore alternative management practices for chemical-free weed control in soybean adapted to different cropping systems (MacLaren et al., 2020). For instance, the use of narrow rows (e.g., 38 cm) leads to an earlier full canopy closure compared to wide rows (76 cm) in soybean (Hock et al., 2006). The earlier the canopy closes, the more competitive the crop is against weeds, with yield increases associated with narrow rows in some cases (Andrade et al., 2002; Bullock et al., 1998; Jha et al., 2017; Steckel & Sprague, 2004).

In Mediterranean irrigated cropping systems, soybean can be grown in a single or a double cropping system (Gutiérrez López, 2020). In the single cropping system (SCS), only one cash crop is grown over the year. Maize is usually preferred given the greater profitability and water availability through irrigation. This situation opens the possibility of including a cover crop during wintertime. The use of cover crops can bring different benefits such as nitrate leaching reduction, soil and water conservation, and improved weed control (Osipitan et al., 2019; Plaza-Bonilla et al., 2016; Quemada et al., 2013). A rye [*Secale cereale* (L) M.Bieb.] cover crop terminated with a roller-crimper has been reported as a suitable strategy for weed control in soybean in cooler environments in the EU (Halwani et al., 2019; Weber et al., 2017), the United States (Forcella, 2013), and Brazil (Branco et al., 2022). However, information is lacking on roller-crimped cover crops' potential for weed control in soybean under Mediterranean irrigated conditions.

In the double cropping system (DCS), a winter cereal (often barley (*Hordeum vulgare* L.) is followed by a late sown summer crop (e.g., maize and soybean) that is planted right after the cereal harvest. This system implies a significant delay in the summer crop planting date, from late March in the SCS to mid-June to late June in the DCS. With a much later soybean planting date, the germination peak of some weed species might also be avoided in the DCS (Stoller & Wax, 1973). Moreover, in intensive cropping systems, such as the DCS, the increased soil resource and radiation capture by the crops can help suppress weed growth by competition (Poggio & Ghersa, 2011). In that regard, Andrade et al. (2017) found a reduced frequency of the most common weed species in wheat (*Triticum aestivum* L.)-soybean DCS compared to the single-cropped soybean. In the DCS scenario, the possibility of a volunteer infestation from the previous crop can also be problematic (Kraehmer & Bell, 2019).

The efficacy of the described alternative methods can be difficult to predict and might depend on the local pedoclimatic conditions (Nichols et al., 2020). Given the need for diversification in these Mediterranean irrigated cropping systems and the potential suitability of soybean as an alternative, this work aimed to (i) assess the weed control efficacy of alternative crop management practices in soybean, both under a single and a double cropping system and, (ii) quantify their impact on soybean emergence and yield. We hypothesized that the use of a rye cover crop terminated with a roller-crimper in the SCS and narrow rows in both systems would reduce soybean weed pressure without a major impact on soybean performance compared to chemical weed control.

Core Ideas

- Roller-crimped rye cover crop controlled weeds in soybean when enough biomass was accumulated.
- Roller-crimped rye effectively controlled most weed species, especially *Datura stramonium* L. and *Setaria adhaerens* (Forssk) Chiov.
- Narrowing the row width from 75 to 37.5 cm did not improve weed control or soybean yield.

2 | MATERIALS AND METHODS

2.1 | Experimental site and design

The experimental site was based near Lleida (Spain, 41°41′51.16″N, 0°25′57.08″E, 287 masl) from 2019 to 2021. The area is located in the east of the Ebro Valley, a semiarid flat area with an average annual precipitation of 364 mm distributed mainly in autumn and spring (Figure 1). Annual mean air temperature is 14.4°C and potential evapotranspiration is 1073 mm. During the experimental period, no temperature extreme events (untimely freezing or heat waves) were recorded. Precipitation differed remarkably between 2020 and 2021. In 2020, total annual precipitation was 500 mm (137-mm higher than the 30-year average), while in 2021 the rainfall was 364 mm (coinciding with the historical average). In 2020, 70% of the total precipitation was concentrated in the January–June period (winter cropping period), contrasting with the long-term average where 50% of the precipitation falls during these months. In 2021, the distribution was similar to the average for the area, with a slightly dryer spring than the average (Figure 1). Climate data were obtained from a public meteorological station (Raimat) located 1.9 km from the experimental field. To compensate for the summer water deficit typical in the semiarid Mediterranean climate, irrigation was applied through a solid set of sprinklers set up in an 18-by-16-m spacing. Irrigation was applied according to crop needs and on average, in both seasons, 660 and 530 mm were applied to the single- and double-cropped soybean, respectively.

The soil of the field was classified as a Typic Calcixerept (Soil Survey Staff, 2014) with the following main characteristics in the top 30 cm: clay loam texture (29% clay, 37% silt, and 34% sand), 17.3 g organic carbon (C) kg^{-1}, 2.3 g organic nitrogen (N) kg^{-1} (Kjeldahl), 44.1 mg phosphorus (P) kg^{-1} (Olsen), 434 mg potassium (K) kg^{-1} (ammonium acetate), and pH 8.1 (ext. 1:2.5 H_2O).

Two field experiments were carried out, SCS and DCS, in the same location. In the second year, the plots were moved to a contiguous area within the same field to have the same preceding crop each year, conventionally managed grain maize in the SCS and winter barley in the DCS. In the SCS experiment, three factors were studied in a split-split-plot design with four replications. The main plot was row width (75 vs. 37.5 cm) and the sub-plot was herbicides use (henceforth: no herbicide application [NoH]; herbicide application [H]). Finally, planting green with the use of a rye cover crop terminated with a roller-crimper was investigated (henceforth: no cover crop [NoCC]; cover crop [CC]) in the sub-sub-plots.

In the DCS experiment, two factors were studied in a split-plot design with four replications. As in the SCS, row width (75 vs. 37.5 cm) was placed in the main plots. In the sub-plots, herbicide application was studied (NoH/H). The preceding cash crop was winter barley harvested for grain a few days before the soybean sowing. In both experiments, main plots consisted of 9-by-9-m strips (tractor turnaround areas included in these) where row width treatments where randomized. The sub-plots, herbicide application, were defined using exclusions areas (using impermeable plastic cover), thus eliminating any possibility of herbicide contamination in NoH plots. In the sub-sub-plots, cover crop (only in the SCS experiment), rye was sown all over the field except in the NoCC areas. Within each sub-sub-plot, 1.5-by-3-m areas were delimited to carry out the measurements.

2.2 | Crop management

2.2.1 | Single cropping system experiment

Rye cover crop ('Amber') in the SCS was sown on November 29, 2019 and December 15, 2020 at 100 kg ha^{-1}. No top-dressing fertilization was applied either year. The rye cover crop (SCS) was terminated with a roller-crimper simultaneously to the soybean planting (May 3, 2020 and May 7, 2021) using a combined equipment consisting of individual roller crimpers attached to each unit of a no-till planting machine (ZRX Plus—with integral row cleaner from Dawn—coupled with a John Deere 1705 MaxEmerge, row width of 75 cm). The 37.5-cm row width was done by two passes with the planting machine with a GPS-equipped tractor. ES Isidor (maturity group I) cultivar was used and the seed rate was kept constant at 50 seeds m^{-2} for both row width treatments (75 and 37.5 cm). In the following days after soybean planting, metaldehyde slug pellets (metaldehyde 50 g kg^{-1}) at 5 kg ha^{-1} were applied to control slug attacks in soybean. A total herbicide (glyphosate 360 g a.i. ha^{-1}) was applied 2 days before soybean planting. Preemergence herbicides were applied on May 5, 2020 and May 10, 2021. The preemergence herbicide consisted of pendimethaline (688 g ha^{-1}) plus clomazone (138 g ha^{-1}) plus metribuzin (210 g ha^{-1}). Postemergence herbicides were applied on May 27, 2020 and June 27, 2021

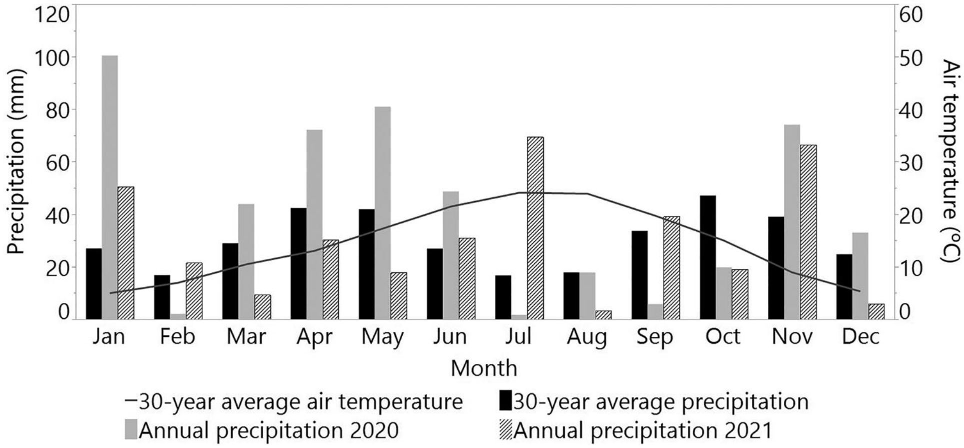

FIGURE 1 Monthly average precipitation and air temperature for the long-term average and the two experimental seasons.

and consisted of imazamox (46 g ha^{-1}) plus bentazon (912 g ha^{-1}) plus propaquizafop (150 g ha^{-1}).

2.2.2 | Double cropping system experiment

Winter barley ('Hyvido Zoo') was sown on November 29, 2019 and December 5, 2020 at 90 kg ha^{-1}. Considering the pre-sowing soil analysis, no fertilizer was applied as top-dressing in the 2019–2020 season, while 75 kg N ha^{-1} were applied on February 3, 2021 as urea-ammonium nitrate (ammonia N [N-NH_4]-8%, nitrate N [N-NO_3]-8%, and amide N [N-NH_2]-16%). Barley was harvested for grain using a commercial combine harvester on June 16, 2020 and June 26, 2021. Barley grain yield was 8.4 ton ha^{-1} (average of 2020 and 2021 at 14% moisture) and barley straw was chopped during the harvest and kept on the soil surface. Soybean was planted 6 (2020) and 2 (2021) days after barley harvesting using the same machinery (with the roller-crimper units lifted) and method as in the SCS. The seed rate was also 50 seeds m^{-2} and ES Isidor (maturity group I) cultivar was used. No tillage was performed either year between the barley harvest and soybean planting. A total herbicide (glyphosate 360 g a.i. ha^{-1}) was applied 2 days before soybean planting. Postemergence herbicides were applied on July 1, 2020 and July 15, 2021. The formulation applied consisted of imazamox (46 g ha^{-1}) plus bentazon (912 g h^{-1}) plus propaquizafop (150 g ha^{-1}).

2.3 | Data collection

Before soybean planting, 0.1 m^2 of cover crop biomass was cut at ground level in three observations per plot in both years, dried for 48 h at 65°C and weighted (only in the SCS experiment). Soybean emergence was measured by counting all plants within a 1 lineal m along the planting row with two observations per plot when soybean was in stage V2 (Fehr et al., 1971). The emergence rate was calculated by dividing the number of plants m^{-2} measured in the sampling by the planting density and expressed as a percentage of emergence. To determine the grain yield, soybean aboveground biomass samples were taken at physiological maturity of 1 lineal m along the planting row from each plot, dried, and threshed with a laboratory legume thresher.

Weed density was determined for each weed species using a 0.33-by-0.33-m quadrat randomly placed in each plot, with four observations per plot at each sampling date. These measurements were made on June 1 and 18, 2020 for the SCS experiment and on July 16, 2020, July 28, 2020, and July 30, 2021 for the DCS (V3 to R1 soybean stages, respectively). As the weed plants grew, the variable was changed to the percentage of ground covered by weeds (henceforth, weed ground coverage) to better represent the weed pressure in the soybean crop (Nkoa et al., 2015). Weed ground coverage was visually estimated for each weed species in each plot. In 2020, weed ground coverage was assessed on June 30, July 16 and 28, and August 11 for the SCS experiment (R1 to R6 soybean stages) and on August 11 and 25, and September 8 and 25 for the DCS experiment (R2 to R6 soybean stages). In 2021, weed ground coverage was measured on July 13th and 26th, August 24th, and September 7th for the SCS experiment (V4 to R7 soybean stages), and on August 24th and September 7th and 24th for the DCS experiment (R3 to R6 soybean stages). Finally, before soybean physiological maturity and before the weed seed rain began, all the weed biomass was cut from all the plots (1.5 by 3 m) and weighed. A subsample was taken from each plot to determine the dry matter content of the whole sample. In 2020, this measurement was done on August 18 and September 25 and in 2021 it was done on September 25 and October 22 for the SCS and DCS, respectively.

2.4 | Statistical analyses

All the analyses were performed with JMP 14 Pro (SAS Institute, 2019). Statistical analyses were performed separately for each experiment and year. In the SCS, mixed-model analyses of variance (ANOVA) for a split-split-plot design with four replications (blocks) were performed. The factors included in each analysis depended on the variable. For the emergence rate, row width, herbicide application, and cover crop were included in the model as fixed effects. For the weed density data and the soil weed ground coverage, row width, herbicide application, cover crop, and sampling date were included in the model as fixed effects. For weed biomass data, the same factors as the soybean emergence were included in the model. Weed density, weed ground coverage, and weed biomass data were square root transformed to meet the normality assumption. The soybean yield mixed-model included the same factors as the emergence rate plus the weed biomass measured at the end of the crop cycle as a co-variable.

In the DCS, mixed-model ANOVA for a split-plot design with four replications (blocks) was performed. For the emergence rate, row width and herbicide application were included in the model as fixed effects. For the weed density data in 2020 and weed ground coverage data in 2020 and 2021, row width, herbicide application and sampling date were included in the model as fixed effects. For the weed density in 2021, the sampling date was dropped from the model since this variable was measured once that year. For weed biomass data, the same factors as the soybean emergence were included in the model. As in the SCS, weed density and weed ground coverage data were square root transformed to normalize the data. The soybean yield mixed-model included the row width and the herbicide application as fixed effects and the weed biomass measured at the end of the crop cycle as a co-variable. When significant effects were found, the treatment means were compared using honest significant difference (HSD) Tukey at $p < 0.05$. In all the analyses, the block was considered a random effect. Untransformed data are presented in tables and figures. All figures were built with the JMP 14 Pro Graph builder tool.

3 | RESULTS

3.1 | Weed control in soybean in the single cropping system

Rye cover crop biomass at the termination moment of anthesis (early May) was 11.8 ton DM ha^{-1} (SD ± 3.4 ton DM ha^{-1}) and 3.4 ton DM ha^{-1} (SD ± 2.7 ton DM ha^{-1}) in 2020 and 2021, respectively. In 2020, row width by cover crop interaction significantly affected soybean emergence (Table 1). Under the CC treatments, 75-cm row width pre-

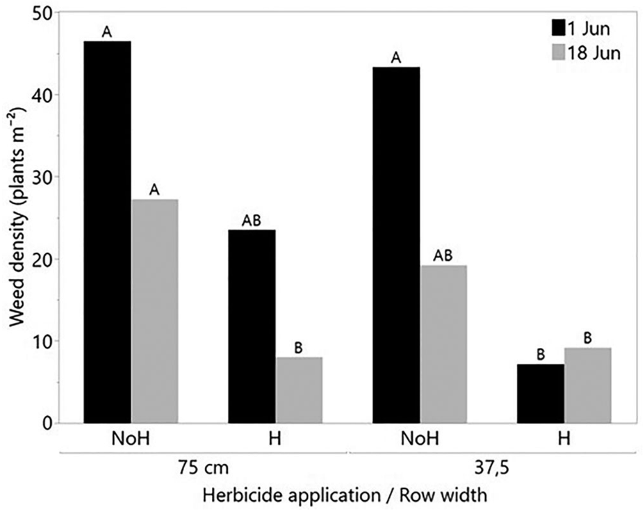

FIGURE 2 Weed density in the two sampling dates in 2020 for the combination of row width (75 vs. 37.5 cm) and herbicide application (H, herbicide application; NoH, no herbicide application) in the single cropping system (SCS) experiment. Levels not represented by the same letter are significantly different at $\alpha = 0.05$.

sented a higher emergence rate compared to the 37.5 cm (75% vs. 47%, respectively). In the NoCC treatments, emergence was in the range of 56%–68% and no differences were found between the row widths. In 2021, soybean emergence was not affected by the studied factors (Table 1) and the average soybean emergence was 40% (SD ± 17%). Severe slug attacks were observed in 2021, despite the metaldehyde application, which could have reduced overall emergence.

The sampling date by row width by herbicide interaction affected weed density in 2020, as well as the cover crop single effect (Table 1). Regarding the three-way interaction, in the first sampling date (June 1st), no differences were found between the NoH and H treatments in the 75-cm row width, while in the 37.5-cm row width, weed density was significantly higher in the NoH than in the H treatment (Figure 2). On June 18th, however, differences between NoH and H treatments were significant in the 75-cm row width whereas they were not in the 37.5-cm row width (Figure 2). For each specific treatment, no differences between the two sampling dates were found, although there was a trend to lower weed densities on June 18th compared to June 1st (Figure 2). On the other hand, the cover crop single effect reduced weed density from 32 to 14 plants m^{-2} in the NoCC and the CC treatments, respectively. Weed species composition on June 1 and 18 was largely dominated by *Euphorbia prostrata* Aiton and *Veronica persica* Poir. (Figure 3).

In 2020, the herbicide by cover crop interaction affected weed ground coverage and weed biomass (Table 1). Both the cover crop and the herbicide application reduced weed ground coverage and biomass compared to the NoH–NoCC

TABLE 1 Effects (p values) of sampling date (when applicable), row width, herbicide application, cover crop, their interactions, and weed biomass as co-variable for yield on soybean emergence, weed density, weed coverage, weed biomass, and soybean yield for the two experimental seasons (2020 and 2021) in the single cropping system experiment.

	2020					2021			
Factors/variables	**Soybean emergence**	**Weed density**	**Weed coverage**	**Weed biomass**	**Grain yield**	**Soybean emergence**	**Weed coverage**	**Weed biomass**	**Grain yield**
Sampling date (SD)		0.001*	0.001*				0.192		
Row width (RW)	0.107	0.110	0.999	0.309	0.919	0.721	0.915	0.43	0.092
Herbicide application (H)	0.465	0.001*	0.001*	0.142	0.424	0.72	0.002*	0.204	0.591
Cover crop (CC)	0.617	0.005*	0.004*	0.046*	0.442	0.582	0.172	0.127	0.985
SD × RW		0.285	0.045*				0.466		
SD × H		0.317	0.468				0.015*		
RW × H	0.058	0.728	0.324	0.309	0.278	0.191	0.891	0.717	0.031*
RW × CC	0.004*	0.449	0.949	0.324	0.791	0.656	0.442	0.519	0.664
H × CC	0.359	0.064	0.046*	0.046*	0.575	0.759	0.527	0.205	0.938
SD × CC		0.271	0.51				0.683		
SD × H × CC		0.343	0.553				0.959		
SD × RW × CC		0.071	0.943				0.915		
RW × H × CC	0.071	0.208	0.162	0.323	0.219	0.671	0.678	0.726	0.965
SD × RW × H		0.014*	0.461				0.674		
SD × RW × H × CC		0.088	0.32				0.878		
Weed biomass					0.002*				0.144

*Significant at $p < 0.05$.

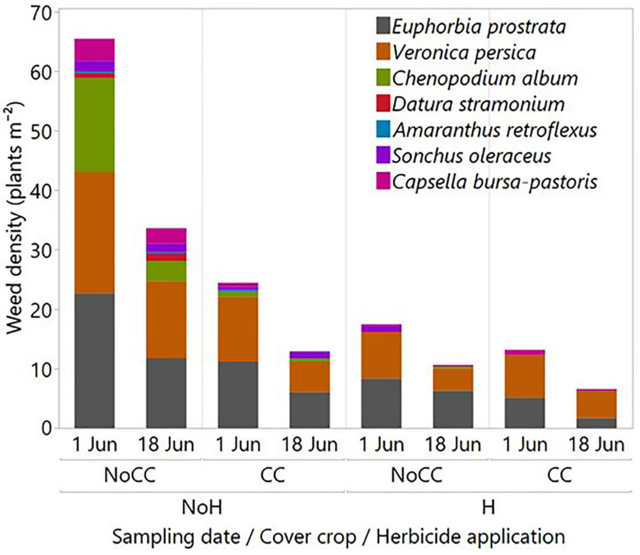

FIGURE 3 Weed composition in the two weed density sampling dates (June 1 and 18, 2020) for the combination of herbicide application (H, herbicide application; NoH, no herbicide application) and cover crop (CC, cover crop; NoCC, no cover crop) in the single cropping system (SCS) experiment.

treatment (Figure 4a,c). The combination of both management practices (herbicide and cover crop) reduced weed ground coverage compared to using cover crop alone (Figure 4a), while no differences were found in the weed biomass between the NoH–CC and the H treatments (Figure 4c). In 2021, only herbicide application significantly affected weed ground coverage (Table 1), resulting in 17% and 5% of weed ground coverage in the NoH and H treatments, respectively. No impact of the cover crop on the weed ground coverage or weed biomass was found (Figure 4b,c).

Weed ground coverage species composition differed per year, except for *E. prostrata* (Figure 5). This species appeared in both years and followed a similar pattern, being present at the first stages of the crop and disappeared as the soybean canopy closed. In 2020, the most frequent species were *C. album* and *D. stramonium* (Figure 5). In 2021, the weed composition was more diverse. In the NoH-NoCC treatment, *Setaria adhaerens* (Forssk.) Chiov., *Sonchus oleraceus* L. and *Digitaria sanguinalis* L. played a major role, while in the NoH–CC treatment there was no infestation with *S. adhaerens* (Figure 5). In the H treatments, *E. prostrata* remained present throughout the season, as opposed to 2020 where it was not found toward the last sampling dates.

Average soybean grain yield was 4.55 and 3.05 ton ha^{-1} (14% moisture) for 2020 and 2021, respectively, and was not affected by the studied factors (Table 1). However, weed biomass at the end of the crop cycle affected the yield in 2020 ($p < 0.01$, Table 1). This effect was studied through regression analysis between weed biomass (X-axis) and soybean yield (Y-axis), showing a negative relationship between them ($Y = 4190–0.1453X$, $R^2 = 0.77$, p-value < 0.01). In 2021, row width by herbicide application interaction significantly affected yield ($p < 0.05$), but no differences were found according to the means separation test (HSD Tukey).

3.2 | Weed control in soybean in the double cropping system

Soybean emergence was not affected by any of the studied factors (Table 2). The average emergence rate was 50% (SD ± 18%) and 70% (SD ± 17%) in 2020 and 2021, respectively. Weed density in 2020 was influenced by the herbicide application (Table 2). The NoH and the H treatments presented 260 and 99 plants m^{-2}, respectively. In 2021, weed density was affected by the row width and the herbicide application (Table 2). Weed density was higher in the 37.5 cm than in the 75 cm row width treatment, with 126 and 49 plants m^{-2}, respectively. Herbicide application highly reduced weed density, from 164 to 11 plants m^{-2} in the NoH and the H treatments, respectively. Weed density species composition was largely dominated by barley volunteers in 2020 (from the previous barley crop), representing 84% and 94% of the individuals in the NoH and H treatments on July 16th, respectively (Figure 6). In 2021, barley volunteers only represented 31% and 37% of the individuals in the NoH and H treatments, respectively. As in the single cropping system, *E. prostrata* was present in all the treatments. Other weed species such as *C. album, D. stramonium* or *Amaranthus retroflexus* L. were also present in the NoH treatment in both years (Figure 6).

On August 11, 2020, barley volunteers represented 33% of the weed coverage in the NoH treatment (Figure 7). Throughout the season, this species reduced its presence until it disappeared (no barley volunteers were detected after September 8). In parallel, *C. album* and *D. stramonium* replaced the former space occupied by the barley volunteers (Figure 7). In 2021, barley volunteers were only detected in the weed density counts. As for the weed ground coverage, the composition did not change across the sampling dates, with *C. album, A. retroflexus*, and *Echinochloa crus-galli* L. Beauv. being the most predominant species in the NoH treatment (Figure 7). As in the SCS, none of the studied factors affected soybean grain yield significantly. However, weed biomass (added in the model as a covariable) was significant in 2021, indicating that weed presence influenced soybean yield. The average grain yield of the experiment was 3.3 and 3.4 tons ha^{-1} (14% moisture) in 2020 and 2021, respectively.

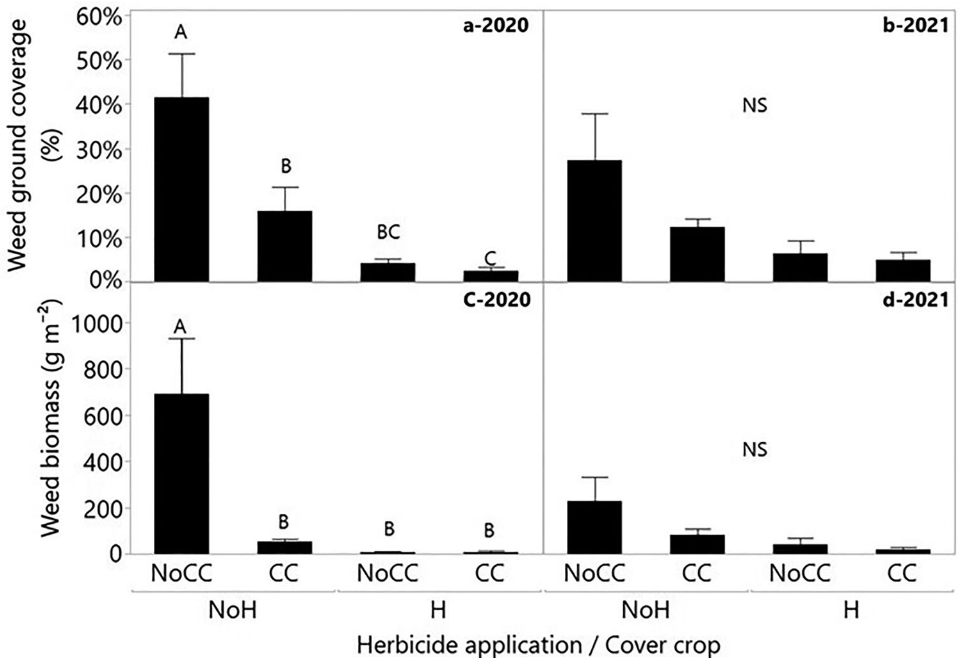

FIGURE 4 Weed coverage (a and b) and weed biomass (c and d) affected by the herbicide application (H, herbicide application; NoH, no herbicide application;) and the cover crop (CC, cover crop; NoCC, no cover crop) in the single cropping system experiment in 2020 (a and c) and 2021 (b and d). For each sub-figure, levels not represented by the same letter are significantly different at $\alpha = 0.05$. Error bars refer to standard error.

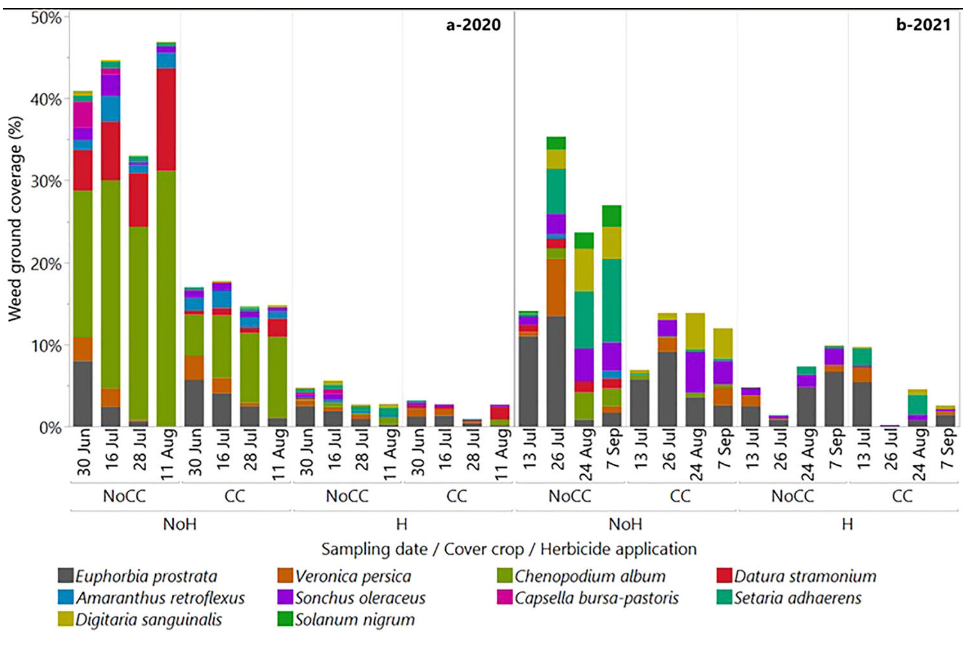

FIGURE 5 Weed species composition at four weed ground coverage sampling dates for the herbicide (H, herbicide application; NoH, no herbicide application;) and cover crop (CC, cover crop; NoCC, no cover crop) treatments combination in 2020 and 2021 for the single cropping system (SCS) experiment.

4 | DISCUSSION

4.1 | Alternative methods for weed control in soybean single cropping systems

The contrasting amounts of cover crop biomass each year can be attributed to the different climatic conditions in 2020 and 2021. In 2020, the total precipitation in the January to April period was 218 mm, while in 2021 this value was 111 mm. The amount of cover crop biomass is directly related to its potential to provide weed control (Osipitan et al., 2019). The cover crop effect alone (NoH–CC) in 2020 (11.2 ton DM ha^{-1}) reduced weed ground coverage by 67% compared to the NoH-NoCC treatment. These results are consistent with

TABLE 2 Effects (p values) of sampling date (when applicable), row width, herbicide application, their interactions and weed biomass as co-variable for yield on soybean emergence, weed density, weed coverage, weed biomass, and soybean yield for the two experimental seasons (2020 and 2021) in the double cropping system experiment.

Factors/variables	2020					2021				
	Soybean emergence	Weed density	Weed coverage	Weed biomass	Grain yield	Soybean emergence	Weed density	Weed coverage	Weed biomass	Grain yield
Sampling date (SD)		0.778	0.001*					0.317		
Row width (RW)	0.980	0.299	0.772	0.471	0.234	0.443	0.044*	0.992	0.386	0.133
Herbicide application (H)	0.377	0.001*	0.004*	0.085	0.474	0.922	0.001*	0.001*	0.072	0.237
SD × RW		0.016*	0.040*					0.184		
SD × H		0.086	0.967					0.024*		
RW × H	0.747	0.109	0.421	0.374	0.790	0.583	0.412	0.963	0.290	0.243
SD × RW × H		0.118	0.759					0.998		
Weed biomass					0.243					0.01*

*Significant at $p < 0.05$.

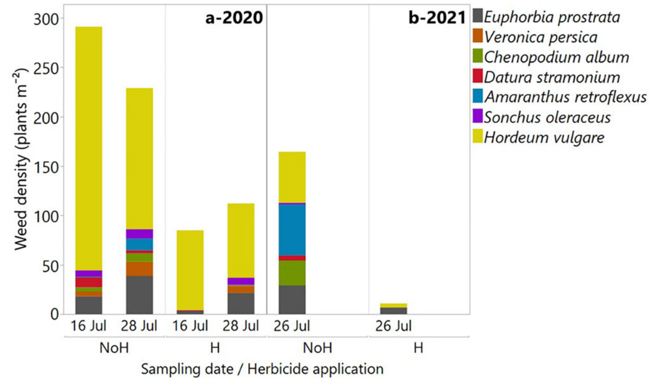

FIGURE 6 Weed species composition at two (2020) and one (2021) weed density sampling dates for the two herbicide treatments (H, herbicide application; NoH, no herbicide application) in the double cropping system (DCS) experiment.

the findings of Wayman et al. (2015) who reported a 19% weed coverage on a 9 tons DM ha^{-1} of a roller-crimped rye cover crop, compared to an 81% weed coverage observed in their weediest control. In 2021 the cover crop (3.4 ton DM ha^{-1}) effect on the weed ground coverage was less evident. Previous studies carried out in North Carolina under organic agriculture, found no weed control by the rolled rye when its biomass was below 7 ton DM ha^{-1} and adequate weed control (weed ground coverage of 5%–10%) when the cover crop exceeded 9 ton DM ha^{-1} (Smith et al., 2011). Thus, from our research and the literature it can be suggested that around 9–10 tons DM ha^{-1} of rolled rye would be necessary to achieve adequate weed control under Mediterranean irrigated cropping systems. Under these conditions, cover crop biomass accumulation during winter is feasible due to the mild winters but limited due to water availability. Although irrigation could offset this limitation, winter cover crops are not likely to be irrigated in areas where the irrigation water is expensive compared to the final profit (Plaza-Bonilla et al., 2017).

Herbicide application led to a lower weed ground coverage than cover crop alone. This finding is consistent with the results of a meta-analysis that reported significantly increased weed control whenever the cover crop was complemented with a herbicide application (Osipitan et al., 2019). In our experiment, CC and NoCC treatments received the same herbicides, which could have hindered the effectiveness of the cover crop in the H-CC treatments. If the rolled cover crop can partially control weed infestation, the postemergence herbicide application could be more targeted, complementing the cover crop effect aiming to control only the weeds that the cover crop could not. Such a strategy would help achieve the pesticide reduction target proposed by the EU Green Deal (Jacquet et al., 2022). Further research should focus on the weed pressure threshold that can be tolerated in a soybean grown under a rolled cover crop system before a postemergence herbicide is applied. Such a threshold would highly

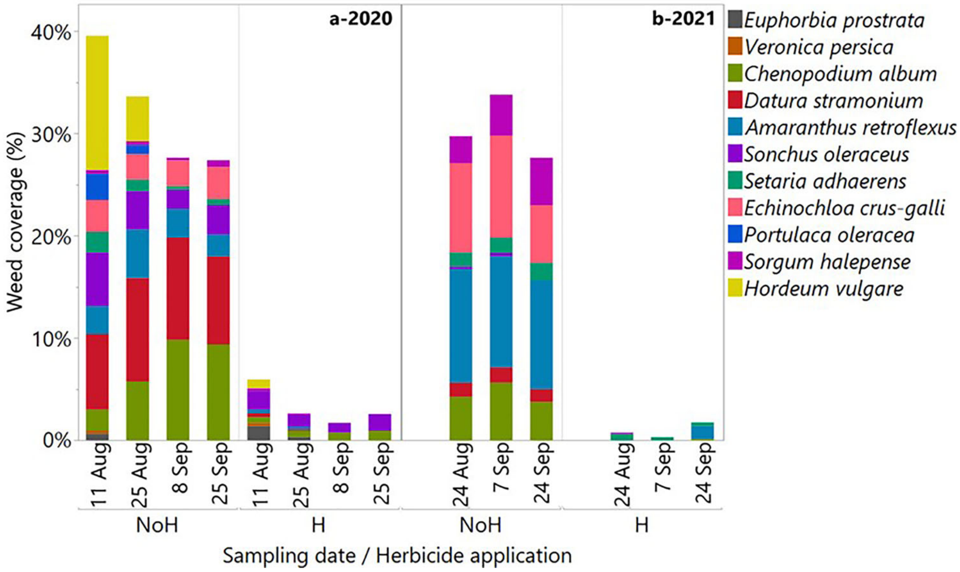

FIGURE 7 Weed ground coverage species composition at four (2020) and three (2021) weed ground coverage sampling dates for the herbicide treatment (H, herbicide application; NoH: no herbicide application) in the double cropping system (DCS) experiment.

depend on the intended grade of the produced soybean (feed or food) and the buyer requirements (see, for example, Snobelen Farms, 2020) and the potential build-up of the soil seedbank due to the remaining weeds (Bernstein et al., 2014; Knezevic et al., 2003), especially in no-till systems (Mazzoncini et al., 2008). In 2020, we observed that *D. stramonium* cover in the roller-crimped rye cover crop was reduced from 8% to 1% (treatments with herbicide application reduced *D. stramonium* to 0.5%). This finding is supported by other research carried out on soybean, where the rye cover crop terminated with herbicide and left in the soil surface effectively controlled *D. stramonium* (Zhang et al., 1999). While *D. stramonium* can be highly competitive with the crop, its toxicity jeopardizes also the quality of the harvested grain (Adamse & Egmond, 2010), especially in food-grade soybean.

There was no consistent effect of the row width on weed pressure. The main driver of increased weed control in narrow rows is the earlier resource capture (especially light) by the crop (Gunsolus, 1990), thus leaving fewer available resources for the weeds to thrive. However, in the presence of a thick cover crop on the soil surface, the space between soybean rows is already covered, so that the light cannot be captured by the emerging weeds (Osipitan et al., 2018). Although soybean yield was not affected by the study factors, weed biomass was significant in 2020 when added as a co-variable. The regression analysis showed a negative impact of weed biomass on soybean yield, indicating that weed biomass was large enough (at least in 2020) to cause yield reduction. However, these results make it challenging to disentangle whether the weed control achieved by the cover crop in the absence of herbicides is enough to prevent significant yield losses.

4.2 | Alternatives for weed control in the cereal-soybean double cropping system

The available time between the winter cereal harvest and the following crop's sowing in cereal-soybean double cropping systems is short, especially for soybean (Battisti et al., 2020). For instance, Calviño et al. (2003) quantified, in the Argentinean Pampa, a soybean grain yield loss of 56 kg ha^{-1} per day of planting delay. Their research stresses the importance of shortening the time between the barley harvest and soybean planting. To do that, no-till double cropping systems are popular so that the soil preparation time can be saved up, along with different benefits regarding soil quality (Pareja-Sánchez et al., 2017) and C footprint reduction associated with the tillage operations (Plaza-Bonilla et al., 2018). In this scenario, weeds are one of the main problems for double-cropped soybean in an irrigated Mediterranean region (Arslan et al., 2006). In our experiment in 2020, there was also an early infestation of barley volunteers. This infestation could have been caused by a severe barley lodging, which led to a sub-optimal barley harvest thus leaving several grains in the field. Even though the barley volunteer densities were high (>200 plants m^{-2}), they decreased as the soybean developed (even in the absence of herbicide application), thus causing very little competition for the soybean. In both years, herbicide application led to effective weed control, as expected (Colbach & Cordeau, 2018). As in the SCS, narrowing the row width to 37.5 cm did not consistently improve weed control throughout the season. This result can imply a simplification of the planting task as described for the SCS. Not needing specific machinery or additional machinery costs for soybean cropping lifts one of the many constraints for the farmers to grow local soybean.

On the downside, our research shows that alternatives for weed control in double-cropped soybean are limited if herbicide use is to be reduced (Sooby et al., 2007). For instance, hoeing is not feasible in a no-till cropping system and, in addition, it can have a detrimental effect on the soil surface quality (Ball & Crawford, 2009). The use of cover crops is not an option in these double cropping systems and, although the barley straw can be chopped and distributed over the field, its degree of soil cover is not enough to control weeds. Other cultural nonchemical alternatives such as the use of a false seedbed (Kanatas et al., 2020) would lead to an even later planting date, which would directly affect the soybean yield potential.

5 | CONCLUSIONS

Weed control in single-cropped soybean under Mediterranean irrigated conditions using a roller-crimped rye cover crop was dependent on the rye biomass accumulated. Whenever the cover crop cannot reach sufficient cover and homogeneity over the field, the cover crop capacity to control weeds will be inconsistent. We conclude that further research with multiple site-years and different levels of weed pressure would be useful to support our findings. Combining the use of cover crops with herbicides can improve weed control and the decision to do so might depend on the intended soybean grade and the buyer's requirements. The lack of an effect of row width narrowing on the weed pressure or the soybean performance implies that soybean can be planted with the same machinery as maize, with row width around 70–75 cm, under these Mediterranean irrigated conditions.

Our research demonstrates that soybean can be grown with adequate levels of weed control as a second crop after a winter cereal under a no-till system provided that herbicide use is available. Barley volunteer infestations can occur in these double-cropping systems. Nonetheless, its control with herbicide eliminates it or it is naturally substituted by more competitive weed species when no herbicides are applied. The weed composition in this system was similar to the one in the single cropping system, indicating a long emergence period for these weed species and the need to seek sustainable weed control strategies to mitigate them. Further research in the winter cereal-soybean double cropping system under Mediterranean irrigated conditions could focus on nonchemical alternatives for weed control while maintaining no-till soybean planting.

AUTHOR CONTRIBUTIONS

Genís Simon-Miquel: Conceptualization; data curation; formal analysis; writing—original draft. **Moritz Reckling**: Formal analysis; supervision; writing—review and editing. **Jordi Recasens**: Methodology; writing—review and editing. **Daniel Plaza-Bonilla**: Conceptualization; methodology; supervision; project administration; funding acquisition; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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