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Spring sown camelina (*Camelina sativa*) contributes to the management of three summer weeds

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Highlights:

- Summer weeds have become problems in irrigated fields in semiarid regions.
- Camelina effectively reduces growth of dicotyledonous summer weeds.
- Drought tolerance of camelina enhances its suppressive ability.
- Severe water restrictions and dry conditions can reduce camelina's yield.
- Spring sowing of camelina helps manage summer weeds in irrigated systems.

Keywords:
Chenopodium album, crop rotation, integrated weed management, *Polygonum aviculare*, *Xanthium spinosum.*

ABSTRACT

Camelina (*Camelina sativa* (L.) Crantz) is an attractive drought-tolerant crop for Mediterranean regions due to its rapid growth and ability to out-compete many dicotyledonous winter annual weeds. In this experiment the weed suppression capacity of spring sown camelina against *Chenopodium album* L. (common lambsquarters), *Polygonum aviculare* L. (prostrate knotweed), and *Xanthium spinosum* L. (spiny cocklebur) was studied. The trial was conducted in Lleida (Spain) between 2019 and 2021, and camelina was sown in March each year. Experimental plots contained quadrats with each weed species as well as weed-free and crop-free quadrats. Height and aboveground biomass of weeds in competition with camelina decreased by over 50% compared to the controls. However, crop and weed growth had seasonal differences depending on the weather conditions: (1) a moderately dry spring promoted crop production (1573 kg ha^{-1}); (2) a rainy spring benefited weed development, negatively affecting crop growth and yield (739 kg ha^{-1}); and (3) a severe dry spring affected growth of both crop and weeds, reducing crop production by up to 80% (298 kg ha^{-1}). The summer weed suppression capacity of camelina is enhanced by drought conditions, which makes camelina useful for managing these weeds.

1. INTRODUCTION

Semiarid regions, which are characterized by low and unpredictable precipitation patterns, are expected to expand in the coming decades as a result of ongoing climate change (FAO, 2015). By 2050, the Mediterranean basin is projected to have a 20% decrease in precipitation between April and September (Woetzel *et al.*, 2020). Therefore, irrigation will be essential to mitigate the potential adverse effects of the expansion of semiarid climate regions and prevent declines in productivity (Barnett *et al.*, 2005; Dai *et al.*, 2018). In Spain, irrigated fields already account for 22.5% of the total arable land, and they have increased in area by 2.6% in the past ten years (MAPA, 2021). The use of irrigation enables three common cropping systems in Spain: (1) a single annual summer crop, mainly maize (*Zea mays* L.); (2) a perennial leguminous crop, alfalfa (*Medicago sativa* L.); and (3) an annual double crop rotation (winter cereal-annual summer crop). All these systems are simplified and specialized strategies that aim to increase crop yields (Barzman *et al.*, 2015). Mild winters in Mediterranean semiarid climates allow the third option (double cropping) by allowing the harvest of a winter and a summer crop in the same year. However, the current drought periods, and the increase of irrigated land and water demand, will result in a reduction of water availability for irrigating crops where cereal crops now predominate and water requirements are high. In these areas, short life cycle crops tolerant to drought, such as camelina (*Camelina sativa* (L.) Crantz), are appreciated for their fast development and early harvest, which generally occurs in early summer, thus allowing the establishment and growth of a summer crop (e.g., maize, soybean (*Glycine max* (L.) Merr.)) that can be harvested before the following winter (Borchers *et al.*, 2014; Berti *et al.*, 2015).

Over recent decades, the interest in oilseed crops, such as camelina, has increased because of their wide range of potential uses in industrial processes, cosmetic manufacturing, animal feed, or human diet; as well as for the potential agronomic benefits they provide, such as control of weeds and pests (Scott *et al.*, 2021). This has resulted in a 135% increase in the area sown to these oilseed crops between 2000 and 2014, reaching 302 million hectares worldwide (FAO, 2017). Camelina, despite not being a high-yielding crop (Liu *et al.*, 2019), has gained interest for its agronomic characteristics, since it is a very versatile crop regarding field management (Berti *et al.*, 2016), with a low water requirement, roughly half the level of evapotranspiration of winter grain crops (Hunsaker *et al.*, 2011). Moreover, camelina oil and its derivatives have a wide range of potential applications, both food uses and non-food uses (e.g., biofuels, hydraulic fluids and biopolymers, and cosmetics)(Zanetti *et al.*, 2021).

There are two groups of camelina varieties, spring and winter, the former with a shorter life cycle and the latter with a longer life cycle (Wittenberg *et al.*, 2019). This quality enables a wide range of sowing dates, from autumn to spring, and results in a crop cycle that can span between 59 and 298 days (Putnam *et al.*, 1993; Angelini *et al.*, 1997; Royo-Esnal and Valencia-Gredilla, 2018; Zanetti *et al.*, 2021). In dryland conditions, sowing is usually done in autumn, but delaying it until January or even spring, may allow better management of winter weeds (Royo-Esnal and Valencia-Gredilla, 2018). Also, the growth of the weeds that emerge after the sowing of the crop is reduced due to the competition exerted by camelina for light, nutrients and water, and the weed seed rain is lower due to an earlier harvest, compared to winter cereals (Codina-Pascual *et al.*, 2022). Despite this, delayed sowing also allows greater light penetration, as crop plants are smaller in late winter and early spring, and this can favour the germination of summer weeds. *Chenopodium album* L. (common lambsquarters, hereafter *C. album*), *Polygonum aviculare* L. (prostrate knotweed, hereafter *P. aviculare*), and *Xanthium spinosum* L. (spiny cocklebur, hereafter *X. spinosum*) are three important summer weeds that can cause significant losses to summer crops (Leblanc *et al.,* 2003; Holm *et al.,* 1997; Weber and Gut, 2005). In addition, these weeds might emerge earlier than usual in the coming years due to global warming. For example, *Echinochloa crus-galli* L. (barnyard grass), one of the most critical summer weeds worldwide, is known to be able to emerge even in winter if temperatures are high enough, as observed by Royo-Esnal *et al.* (2022) in Portugal and Turkey. Thus, the life cycle of summer weeds is likely to overlap with that of winter crops. Moreover, as summer weeds, these species may benefit more from irrigation than the crop itself and compete more strongly against the crop. Avoiding irrigation in spring, when summer weeds are in their early growth stages and the crop already maturing, might contribute to the management of summer weed populations, which would reduce their seed banks and, hence, lessen their pressure over the following crops (Gallagher *et al.*, 2013; Ali *et al.*, 2023).

The primary goal of this study was to examine the adaptability of camelina to spring sowing in northeastern Spain and assess its weed suppression capacity against summer weeds. Drought conditions in spring were hypothesized to benefit the crop against moisture-requiring summer weeds. Irrigation was used immediately after sowing solely to facilitate the establishment of the crop. Growth parameters of both the weeds and the crop were analyzed to validate the hypothesis.

2. MATERIAL & METHODS

2.1. Site Description

The trials were conducted during spring, from 2019 to 2021, on the experimental fields of the University of Lleida (41°37'N; 0°35'E, 180 m.a.s.l), in northeastern Spain. According to the Köppen classification, the climate is arid and semiarid (Bsk), with irregular precipitation concentrated during autumn and spring, with average annual total rainfall of 342 mm (AEMET, 2022). Climatic data were obtained from the meteorological station of the Botanical Garden of Lleida, 150 m from the experimental field. Soils were lithic xerorthents, well-drained clay loams (34% clay, 33% silt and 33% sand) (ICGC, 2019), with an organic matter content of 1.7% and a pH of 8.3. Furthermore, the soil contained 53, 11, and 450 ppm of $N\text{-}NO_3$, P, and K, respectively, which are considered sufficient for the growth of camelina (Obeng *et al.*, 2021).

2.2. Experimental design

Before sowing, the ground was tilled to a depth of 10 cm. Barley (*Hordeum vulgare* L.) was the previous crop. The experiment was maintained in the same area for three years. To ensure the emergence of both the crop and weeds, irrigation was provided two to three days after sowing in 2019 (22 mm) and 2021 (18 mm) due to dry soil conditions. In 2020 irrigation was not required due to high humidity and rain.

The experiment was set within a wider trial that followed a split-plot design, with three replicates arranged in a randomized complete block design (RCBD). Plots were 1.5 m wide x 15 m long, and were sown with a spring camelina variety ('*GP204*') provided by the Camelina Company Spain SL (Madrid, Spain) in 2014. The primary objective of the wider trial (Codina-Pascual *et al.*, 2022) was to study the effect of sowing dates (November and February) on the yield of camelina and its competitive ability against winter weeds. In the present trial, the principal focus was to investigate the adaptability and the development of camelina sown in spring (March) in Lleida, and the capacity of the crop to suppress three summer annual weeds (*C. album*, *P. aviculare* and *X. spinosum*). Sowing was performed with a Plotseeder TC (Wintersteiger AG, Ried im Innekreis, Austria) on March 13, 20 and 12 of 2019, 2020 and 2021, respectively. The sowing rate was 8 kg ha^{-1}, sowing depth was 1 cm, and no fertilizer was added. Three 0.25 m^2 quadrats were placed randomly in each plot for each weed species every season, and only five weed individuals were allowed to grow together with the crop in each quadrat. Control quadrats with weeds (five individuals per species and quadrat) but without camelina were established around the plots, in the same field and with the same conditions. All weed species came from the seed bank of the field. Plots were hand weeded throughout the crop cycle to maintain the target density of five weed individuals per quadrat.

On the date camelina was harvested, all five individuals of each weed species were hand-removed at soil level from the quadrats and taken to the laboratory. Furthermore, ten random camelina plants from each plot were collected at soil level to analyze growth and yield parameters. The rest of the camelina was harvested with a Wintersteiger plot combine.

2.3. Phenological development

Relevant phenological stages were monitored over all seasons to explain the life cycle of camelina and the weeds under study. The Biologische bundesanstalt, bundessortenamt and chemical industry scale (BBCH), based on Martinelli and Galasso (2010), was used to describe the growth of camelina. The considered stages were: emergence, shoot elongation, flowering (initial and 50%), and fruit maturation. The BBCH scale for dicotyledonous weeds (Hess *et al.*, 1997) was used to describe the growth of *C. album, P. aviculare* and *X. spinosum*. In this case, the studied stages were emergence, leaf development, lateral shoot formation, shoot elongation and flowering.

For all species the growing degree days (GDD) required to achieve each phenological stage during the crop cycle were calculated using the daily mean temperature and the base temperature (T_b), according to the following formula (Pruess, 1983):

$$GDD: \sum_{i}^{n}(T_m - T_b)$$

where T_m is the mean daily temperature, and T_b is the base temperature for the crop and each of the weed species. Also, for some species, like *P. aviculare*, germination is limited by a ceiling temperature (T_c) above which it stops. T_b values used were: 5°C for the 'GP204' camelina (Blackshaw *et al.*, 2011), 3.5°C for *C. album* (Leblanc *et al.*, 2003), -2.0°C for *P. aviculare* (Royo-Esnal *et al.*, 2015) with a T_c of 17°C (Batlla and Benech-Arnold, 2003), and, since there is no T_b value for *X. spinosum* in the literature, the value for *Xanthium strumarium* L. (common cocklebur) (9.5°C) was used (Dorado *et al.*, 2009).

2.4.Fitness parameters

Height and aboveground dry biomass of each weed were measured in the laboratory. The plants were placed in an oven at 65 °C for 48 hours to determine the dry biomass. Since these species had not developed their reproductive organs fully at the time of crop harvest, the BBCH scale was used to evaluate their phenology. The studied phenological parameters were the number of leaves, branches and nodes, and whether or not they had reached the blooming stage. For *X. spinosum*, the number and length of its thorns also were quantified. Also measured for camelina were vegetative parameters, such as total height and dry biomass, as well as reproductive parameters, such as the number of silicles per plant, the number of seeds per silicle, and the total seed number in each season.

2.5.Statistical analysis

Prior to conducting ANOVA, all parameters were tested for normality using the Shapiro-Wilks test ($P \leq 0.05$) and for homoscedasticity using the Levene test ($P \leq 0.05$). If necessary, appropriate transformations were applied (Ln(x) or Yeo-Johnson). Crop fitness parameters and yield were analyzed using a one-way ANOVA with year as a fixed factor. On the other hand, weed fitness parameters were analyzed using a two-way ANOVA with growing conditions (no crop control and camelina) and year as fixed factors. Year was established as a fixed factor due to the significant differences observed in the growth of camelina across each growing season. When treatment effects were significant at $P < 0.05$, comparisons were assessed using Tukey's significance test. When normality or homoscedasticity were not achieved, data were analyzed using a non-parametric one-way Kruskall-Wallis test to compare the results between growing conditions within each year and among years for each growing condition. Back transformed data are presented for clarity. All statistical analyses were done in JMP Pro 16.2 software (SAS Institute INC, Cary, USA, 2022).

3. RESULTS

3.1. Meteorological data

The air temperature during the growing season followed a similar trend across the three years (Fig. 1), with 2020 being the hottest year (average temperature 17.4 °C). However, there was less than one-degree of difference compared to 2019 (16.7 °C) and 2021 (16.8 °C). The precipitation pattern varied across years in both amount and distribution (Fig.

1). The driest year was 2019 with only 69 mm of rain from sowing to harvest. Sowing took place in arid conditions, and it was followed by a dry spring with irregular precipitation in April and May. The wettest year was 2020 with 269 mm of rain. Rain fell regularly from sowing through June. Drought reoccurred in 2021 with 81 mm of rain but, unlike the first year, seedbed conditions at sowing were much better due to adequate prior winter precipitation. However, precipitation was irregular during spring, with May being a very dry month.

3.2. Cycle of camelina

Camelina and the studied weeds showed slight seasonal differences in their respective life cycles. Camelina took 89, 80 and 96 days to complete its whole cycle in seasons 2019, 2020 and 2021, respectively. It was harvested on 10 June 2019, 8 June 2020 and 16 June 2021. Furthermore, the GDD needed to complete each developmental stage and cycle followed a similar pattern. The total GDD required to complete the life cycle of camelina were similar between seasons 2019 (931 GDD) and 2020 (969 GDD), but increased to 1115 GDD in 2021 (Fig. 2). These variations were consistent throughout all the growth stages, with yearly differences of approximately 10 GDD. The onset of the emergence occurred after 68 (2019 and 2021) and 78 (2020) GDD, while blooming began at 486, 491 and 501 GDD, in 2021, 2020 and 2019 respectively.

3.3. Fitness parameters of camelina

Most of the studied camelina fitness parameters were significantly different across the three years, except for the number of branches, and the number of silicles per plant in 2019 and 2020. However, both vegetative and reproductive parameters followed the same pattern, e.g., camelina plants were taller and produced more biomass in 2019 than in the following two years (Table 1). The reductions were of 21% and 47% in 2020, and 45% and 83% in 2021, for height and biomass, respectively.

Likewise, even if the average number of silicles per plant was similar in 2019 and 2020 (170), the number of seeds per silicles and the number of seeds per plant varied (Table 1). In 2020 plants produced, on average, 7.2 fewer seeds per silicle than in 2019, which was reflected in the quantity of seeds produced per plant, e.g., a 53% decrease. In 2021, the number of silicles and the number of seeds per silicle were both lower than in the previous seasons, with a reduction in seeds per plant of more than 80% compared to 2019 and 58% compared to 2020. This reduction was also reflected in the overall yield, which decreased by 53% from 2019 (1573 kg ha^{-1}) to 2020 (739 kg ha^{-1}), and by 81% from 2019 to 2021 (298 kg ha^{-1}). Comparable yields of autumn-sown camelina in adjacent plots were more stable and higher compared to those of the spring sown camelina (Table 1) (Codina-Pascual *et al.*, 2022).

3.4.Cycle of weeds

Weed growth over the seasons followed a pattern similar to camelina. However, at the time of weed harvest, these plants had not completed their life cycle; and as a result, the reported accumulated GDD are not sufficient for complete life cycles of these plants. In general, except for the GDD required to emerge, the plants growing without camelina were physiologically ahead of those that grew alongside camelina (Table 2). For example, to begin shoot elongation *P. aviculare* plants grown without the crop needed 425 and 142 additional GDD in 2019 and 2020, respectively. In contrast, *X. spinosum* was affected less by crop presence during the same phenological stage, with only a 22 GDD difference between plants grown with and without the camelina crop. However, the amount of GDD

required to reach the different phenological stages varied for each weed species under the different yearly growing conditions.
The beginning of the flowering stage of the weeds varied among years and growth conditions (Table 2). In 2019 and 2021, *C. album* individuals grown without the crop produced flowers, whereas those grown with camelina did not. In 2020, individuals from both treatments developed flowers, with a slight difference in the accumulated GDD. In contrast, *P. aviculare* and *X. spinosum* did not produce flowers in 2019 in either treatment, but did so in both treatments in 2020. In 2021, *X. spinosum* developed flowers only when growing without camelina, and *P. aviculare* was not present in the experimental field that year.

3.5.Fitness parameters of Chenopodium album, Polygonum aviculare and Xanthium spinosum

The presence of the crop significantly affected most fitness parameters of the weeds (Table 3 and 4). The few exceptions were: 1) the number of branches in 2019 and 2020 in *C. album*; 2) the number of nodes in 2020 in *P. aviculare*; and 3) the presence of flowers in 2019 in *P. aviculare* and in 2019 and 2020 in *X. spinosum*
The height and biomass of the weeds always were reduced significantly by the presence of camelina, regardless of differences in the biomass and height of camelina across years. However, absolute weed growth differed significantly each year. The smallest and lightest weed individuals, either with or without camelina, were observed in 2019. In 2020 and in 2021 weed plants were generally larger. *Chenopodium album* individuals grown without the crop were significantly taller in 2020 (86 cm) than in 2019 and 2021 (~60 cm both years) (Fig. 3). In *X. spinosum*, individuals grown without camelina were taller and heavier in 2021 (48 cm; 10.9 g) than in 2019 (24 cm; 2.6 g) and in 2020 (44 cm; 6.6 g). In contrast, individuals grown in the presence of the crop were bigger in 2020 (22 cm, 1 g) than in 2021 (13 cm, 0.7 g) and in 2019 (11 cm, 0.4 g) (Fig. 3).
Crop presence significantly delayed the development of branches, nodes, and flowers of weeds (Table 3). This reduction was significant and different for each weed in each year, following the same pattern of height and biomass. Nevertheless, in *P. aviculare* in 2020, the plants with crop presence produced more nodes (11) than plants without it (7). By the time camelina was harvested, some weed plants had already started flowering, but none of the three weed species developed fruits.
Finally, the presence of the crop significantly reduced the amount and the length of thorns of *X. spinosum* (Table 4). The average number of thorns per plant in this weed species ranged from 23 to 51 with camelina and between 166 and 368 without the crop. The length of the thorns was also shorter with (0.6 – 0.8 cm) than without (1.5 – 2.1 cm) the presence of camelina.

4. DISCUSSION

This study has demonstrated the feasibility of spring sowing camelina under moderate drought conditions in the northeast of Spain. Furthermore, the suppressive capacity of camelina against three problematic summer annual weeds (*C. album, P. aviculare* and *X. spinosum*) also was observed in this study. However, rainfall distribution and amount can lead to drastic changes in crop – weed interactions, ultimately impacting crop yields.

4.1.Spring camelina sowing

Semiarid regions are characterized by scarce and unpredictable precipitation patterns across seasons, although sometimes similar in amount from one year to another. Autumn and spring used to be the wettest seasons in northeastern Spain, but this distribution is becoming increasingly variable due to climate change, resulting in long and pronounced dry periods (García-Garizábal *et al.*, 2014). These alterations were reflected over the duration of this study, where the average spring precipitation (March-June) in the five years preceding the trial (138 mm) was nearly double the accumulated precipitation in 2019 and 2021 (75 mm), while it was half of the spring precipitation in 2020 (268 mm). Because of the unpredictable distribution of rain, late sowings are challenging without the support of an irrigation system during the crop's life cycle.

The life cycle and accumulated GDD needed by camelina were similar across the three years and aligned with previous studies conducted under similar climatic conditions, such as those reported by Righini *et al*. (2019).The results also agree with the cycle of spring sowing of camelina in continental and temperate regions (Czarnik *et al.*, 2017; Krzyżaniak *et al.*, 2019), with life cycles ranging between 80 and 100 days, and between 933 and 1411 GDD (Zanetti *et al.*, 2021).

Despite similarities in the length of the cycle and the number of cumulative GDD, the biomass production of camelina varied significantly among years, which was reflected in the measured vegetative and reproductive parameters. Height and biomass were reduced by more than 50% between the first and the second and third seasons. Reproductive parameters were also reduced. This decrease resulted in a decline in the yield of camelina. The yield decrease in 2020 could be attributed indirectly to excess of precipitation, which diminished any water limitation for summer weeds, and increased their competitive abilities against camelina. Although autotoxicity, demonstrated in other crops (Singh *et al.*, 1999), could not be discarded in camelina, the experiment was placed in a different area of the same field every year, thus reducing this possibility. On the contrary, differences between the first and the third year likely are explained by differences in temperature and the distribution of precipitation throughout the crop cycle (Gesch, 2014; Righini *et al.*, 2019; Wittenberg *et al.,* 2020). Higher temperatures, combined with a dry March (sowing date), followed by a lack of moisture during flowering and seed maturation, resulted in a significantly lower yield in 2021. The importance of rainfall distribution in camelina sown in March and April has been shown by Krzyżaniak *et al*. (2019), Obeng *et al.* (2019) and Righini *et al*. (2019), who obtained yields ranging from 317 to 2100 kg ha^{-1}, depending on rainfall. In the current work, irrigation in the third year may have been required to ensure acceptable yields.

4.2.Effect of water limitation and camelina on the growth of C. album, P. aviculare *and* X. spinosum

Sowing delay is an effective weed control tool (Kanatas, 2020). Delaying the sowing date of a winter crop to March can almost completely control some winter weeds (Codina-Pascual *et al.*, 2022), but summer weeds, such as *C. album* and *P. aviculare* may then become problematic (Recasens and Conesa, 2009). In these cases, the short life cycle of camelina can contribute to their control, even if low water supply in dry and semiarid climates also can decrease crop productivity.

The three selected summer weeds are species adapted to irrigated fields (summer crops). Seldom do they appear in non-irrigated fields, where survival is difficult after cereal harvest and scarce summer precipitation. Thus, limiting water availability is a first approach for successfully managing their populations.

The impact of limited water availability was evident in the mean height of the weeds grown without the crop (controls) in each year, as compared to their potential height documented in the literature. The height of all three studied weeds decreased by over 50% when compared to expected growth in areas without water restrictions (54% for *C. album*; 59% for *P. aviculare* and 52% for *X. spinosum* (Peralta, 2019)). Similar results were observed in this study where *C. album* and *P. aviculare* plants grown without camelina in the rainy spring of 2020 were taller than in 2019 and 2021, which had drier springs. Nevertheless, these reductions are similar to those obtained by Maganti *et al*. (2005) under extreme drought conditions (29% - 55% height reductions). However, certain species may exhibit distinct responses to reduced water availability. In this study, *X. spinosum* displayed a contrasting growth with larger individuals in 2021. This could be attributed to greater water availability in the soil before sowing, as compared to 2019, and the well-established root system that this species is known to develop, similar to *Xanthium italicum* Moretti (hunter burr) (Ma *et al.*, 2023).

The presence of a drought tolerant crop is an additional factor to water limitation that exerts competitive pressure over these weeds. Most fitness parameters, which were already affected by water limitation, were much lower in plants grown with camelina compared to the plants grown without the crop. In the three years, weed plants growing within the crop required more GDD for their development and, thus, more days to develop and complete their different growth stages. This delay at the beginning of the growth stages had a noticeable impact on the weed parameters assessed after harvest. In 2019, weed individuals grown with camelina exhibited a more pronounced reduction in height, biomass, and phenology compared to the controls, probably because the greater growth of camelina exerted stronger competition against weeds (Codina-Pascual *et al.*, 2022). In 2021, the crop also significantly suppressed weed growth, albeit with lower efficacy than in 2019 due to its own reduced growth. Conversely, the rainy spring in 2020 increased water availability and favoured the growth of weeds, increasing their competitive capacity against camelina. This could explain the lower growth and yield of camelina, despite having more water available than in the other two years, as similar negative impacts associated with competition from weeds occurs in other crops such as maize (Smith and Burns, 2022).

Most *C. album* control plants flowered in all three seasons, whereas control plants of *P. aviculare* only flowered in season 2020 and those of *X. spinosum* in 2020 and 2021. In contrast, weeds growing with camelina only flowered in 2020, during the unusually rainy season. The delay of the flowering stage in years with drought periods, together with the presence of the camelina crop, probably prevented *P. aviculare* and *X. spinosum* from flowering in 2019 and 2021. In contrast, a humid year (2020) allowed these weeds to flower, even with the presence of the camelina crop. *Chenopodium album* seems to be a more drought tolerant species, and it had a higher capacity to achieve the reproductive stage of the life cycle despite prolonged water stress. Nonetheless, none of the weeds reached the seed formation stage by the time camelina was harvested, which resulted in a complete absence of weed seed rain. This factor alone could affect long term weed management appreciably through the use of camelina as a spring-sown oilseed crop

Besides the growth parameters, thorns of *X. spinosum* also were studied. *Xanthium spinosum* plants grown within camelina developed significantly fewer and shorter thorns than control plants, and in some cases, none. This result might have two explanations: first, the competition exerted by the crop would have reduced the quantity and size of the thorns of the weed. Second, *X. spinosum* individuals grown with the crop could have sensed its presence because of a lower red/far red (R/FR) ratio of the received light (Ballaré *et al*., 1987), and allocated metabolites for vegetative growth rather than to reinforce their defense mechanisms (thorns). A low R/FR ratio caused by the presence of an adjacent plant (the crop) causes the shade avoidance syndrome, which can provoke stem elongation and reduce branching among other symptoms (Franklin and Whitelam, 2005). For example, the presence of perennial ryegrass changes the allocation pattern from shoots to roots and rhizomes in *Elymus repens* (L.) Gould (couchgrass) (Ringselle *et al.*, 2017). In the case of *X. spinosum*, a higher R/FR ratio may indicate a higher risk of predation by herbivores, and plants invest more energy for protection (bigger and stronger thorns); whereas the presence of other plants (in this case the crop) would reduce the R/FR ratio, and the weed would give preference to vegetative growth. Similar plasticity trends caused by shade have been observed in *Potentilla* species (Stuefer and Huber, 1998) and in *Trifolium repens* L. (white clover) (Weijschedé *et al.*, 2006). A combination of both explanations cannot be discarded. More research is needed to understand this issue.

4.3. Camelina sown in late winter/early spring

In Mediterranean annual double cropping systems, the sowing period of the winter crop may be influenced by the final use of the summer crop. That is, if the summer crop (maize) is sold for grain, the harvest will most likely be later (November-December, maybe even in January if rainfall and fog prevent it from drying) than if it is harvested for forage (usually in October). This situation can be beneficial to farmers. If a short-life cycle and drought tolerant crop, like camelina, is sown instead of leaving the soil bare, some advantages can be obtained for improving the field management, e.g.: 1) soil coverage and reduction of erosion (not measured in the current work); 2) better management of summer weeds, decreasing their number for the forthcoming summer crop, which is the aim of the present study; and 3) an economic oilseed income that fallow cannot provide, which requires further study. According to Codina-Pascual *et al.* (2022) and Royo-Esnal and Valencia-Gredilla (2018), a sowing delay of camelina from November to January in a semiarid Mediterranean climate is effective for weed management, though crop production can be reduced by up to 45%. Even later sowing dates (March) can decrease the yield by 10-80%, depending on the drought periods, as in 2021, and irrigation availability. But the results of the current study suggest that camelina could be worth sowing when the harvest of the previous crop is delayed to winter. This aspect must be verified in commercial field experiments to confirm our results.

5. CONCLUSIONS

In Mediterranean systems where camelina is usually sown in autumn, a pronounced delay of the sowing date to March generates unstable yields. The differences in the observed parameters in each season suggest that the climatic conditions determine the growth of camelina. In this regard, insufficient water availability during the flowering and ripening stages had a detrimental impact on the yield of camelina. These adverse climate conditions also affected the suppressive capacity of the crop against the three summer weeds under study. Extreme drought and irregular precipitation distribution resulted in reduced growth of camelina, thereby creating favourable conditions for the presence of weeds. In contrast, an excess of water availability can lead to the growth of summer weeds, allowing them to better compete with the crop. Despite these cautionary results, camelina effectively competed against the annual summer weeds *C. album, P. aviculare* and *X. spinosum*. It reduced not only their growth, but also prevented seed rain of these species, making it an excellent tool within integrated multi-year weed management strategy. While autumn sowing is generally preferred to spring sowing to achieve stable yields, certain circumstances, such as a late maize harvest in January or substantial weed infestation, may warrant a delay in camelina sowing until March.

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Table 1. Growth parameters of spring sown *Camelina sativa* in Lleida in 2019, 2020 and in 2021.
[a] Non-parametric Kruskall Wallis test; Different letters mean significant differences at $P<0.05$ (Tukey's test) within columns.
[b] Aboveground biomass.
[c] Data published in Codina-Pascual *et al*. (2022) for autumn-sown camelina.

	Height[a]		Biomass[b]		Branches		Infructescence		Silicles/ Plant		Seeds/ Silicle[a]		Seed/plant		Seed Yield		Yield (Autumn)[c]
	cm		g		number		number		number		number		number		kg ha^{-1}		kg ha^{-1}
2019	72.0	A	4.1	A	11.0	A	9.8	A	170.1	A	13.4	A	2249	A	1572	A	-
2020	56.7	B	2.2	B	10.1	A	8.2	AB	170.1	A	6.2	B	1060	B	739	B	1707
2021	39.4	C	0.7	C	7.8	A	6.6	B	99.8	B	4.5	C	445	C	299	C	1533
Year	<.0001		<.0001		ns		0.0321		0.0014		<.0001		<.0001		<.0001		

Table 2. Calendar dates and accumulated GDD at the onset of each of the phenological stages, specified for *Chenopodium album, Polygonum aviculare* and *Xhantium spinosum* in 2019, 2020 and 2021, without (con.) and with crop presence (cam.).

		C. album							
		Seedling emergence		Shoot elongation				Flowering	
		Date	GDD	Date	GDD			Date	GDD
2019	Con.	23 Mar.	83	08 May	555			03 Jun.	946
	Cam.	23 Mar.	83	17 May	686			-	-
2020	Con.	03 Apr.	99	29 Apr.	413			26 May	855
	Cam.	03 Apr.	99	29 Apr.	413			30 May	934
2021	Con.	24 Mar.	86	30 Apr.	461			31 May	925
	Cam.	24 Mar.	86	11 May	614			-	-
		P. aviculare							
		Seedling emergence		Shoot elongation				Flowering	
		Date	GDD	Date	GDD			Date	GDD
2019	Con.	31 Mar.	251	25 Apr.	587			-	-
	Cam.	31 Mar.	251	21 May	1012			-	-
2020	Con.	09 Apr.	269	29 Apr.	593			06 Jun.	1373
	Cam.	09 Apr.	269	06 May	735			06 Jun.	1373
2021[a]	Con.								
	Cam.								
		X. spinosum							
		Seedling emergence		Shoot elongation		First Thorns		Flowering	
		Date	GDD	Date	GDD	Date	GDD	Date	GDD
2019	Con.	23 Mar.	23	02 May	190	02 May	190	-	-
	Cam.	23 Mar.	23	08 May	220	17 May	298	-	-
2020	Con.	03 Apr.	24	24 Apr.	148	24 Apr.	148	26 May	462
	Cam.	03 Apr.	24	27 Apr.	170	27 Apr.	170	01 Jun.	542
2021	Con.	25 Mar.	18	30 Apr.	155	30 Apr.	155	06 Jun.	509
	Cam.	25 Mar.	18	03 May	169	03 May	169	-	-

[a] *P. aviculare* was not observed in 2021.

Table 3. Growth parameters of *Chenopodium album* and *Polygonum aviculare* in two growth conditions: control (without crop) and with camelina in 2019, 2020 and 2021 (Lleida, Spain). Flowering prop. is the proportion of plants with flowers.

		C. album						*P. aviculare*					
	Treatment	Branches number [a]		Nodes number		Flowering prop. [a]		Branches number [a]		Nodes number		Flowering prop [a]	
2019	Control	0.0	Ba	16.6	Ba	0.6	Aa	5.0	Aa	12.8	Aa	0.0	Ba
	Camelina	0.0	Ba	6.6	Bb	0.0	Ab	0.3	Bb	5.7	Bb	0.0	Aa
2020	Control	9.0	Aa	24.6	Aa	1.0	Aa	10.8	Aa	6.6	Aa	0.6	Aa
	Camelina	0.0	Bb	10.0	Ab	0.2	Ab	3.0	Ab	10.6	Aa	0.1	Ab
2021	Control	9.2	Aa	25.4	Aa	1.0	Aa	-		-		-	
	Camelina	4.4	Aa	11.0	Ab	0.0	Ab	-		-		-	
Season		0.0002		0.0006		ns		0.0009		ns		0.0183	
Treatment		<.0001		<.0001		<.0001		<.0001		ns		ns	
Season x Treatment				ns						<.0001			

[a] Non-parametric Kruskall Wallis test; Different letters mean significant differences at *P<0.05* (Tukey's test); upper case letters, among years for each treatment (without or with the crop); lower case letters, between treatments within years.

Table 4. Growth parameters of *Xanthium spinosum* in two growth conditions: control (without crop) and with camelina in years 2019, 2020 and 2021 (Lleida, Spain). Flowering prop. is the proportion of plants with flowers.

Year	Treatment	*X. spinosum*									
		Branches		Nodes		Flowering		Thorns		Thorn length	
		number [a]		number		prop. [a]		Number		cm	
2019	Control	3.2	Ba	12.0	Ca	0.0	Ba	166	Aa	1.5	Ba
	Camelina	0.0	Ab	5.2	Bb	0.0	Aa	23	Bb	0.4	Ab
2020	Control	9.0	Aa	20.0	Aa	0.6	Aa	268	Aa	2.1	Aa
	Camelina	0.5	Ab	9.3	Ab	0.2	Aa	51	Ab	0.8	Ab
2021	Control	9.4	Aa	16.0	Ba	0.8	Aa	376	Aa	1.6	Ba
	Camelina	1.0	Ab	7.6	ABb	0.0	Ab	48	ABb	0.6	Ab
Season		ns		<.0001		0.0297		ns		0.0266	
Treatment		<.0001		<.0001		0.0012		<.0001		<.0001	
Season x Treatment				ns				ns		ns	

[a] Non-parametric Kruskall Wallis test; Different letters mean significant differences at $P<0.05$ (Tukey's test); upper case letters, among years for each treatment (without or with the crop); lower case letters, between treatments within years.

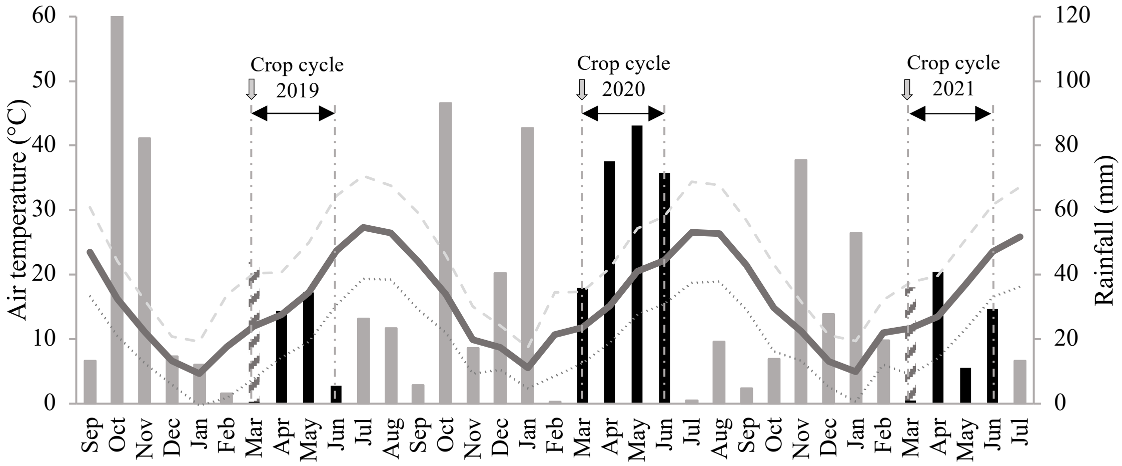

Figure 1 Mean monthly temperature (solid line), mean minimum temperatures (dotted line) and mean maximum temperatures (dashed line), total monthly precipitation (black bars: during crop cycle; gray bars: rest of the year) and irrigation (dashed bars) over the three years. Horizontal black arrows indicate the life cycle of camelina from sowing to harvest; vertical light-gray arrows indicate the sowing date.

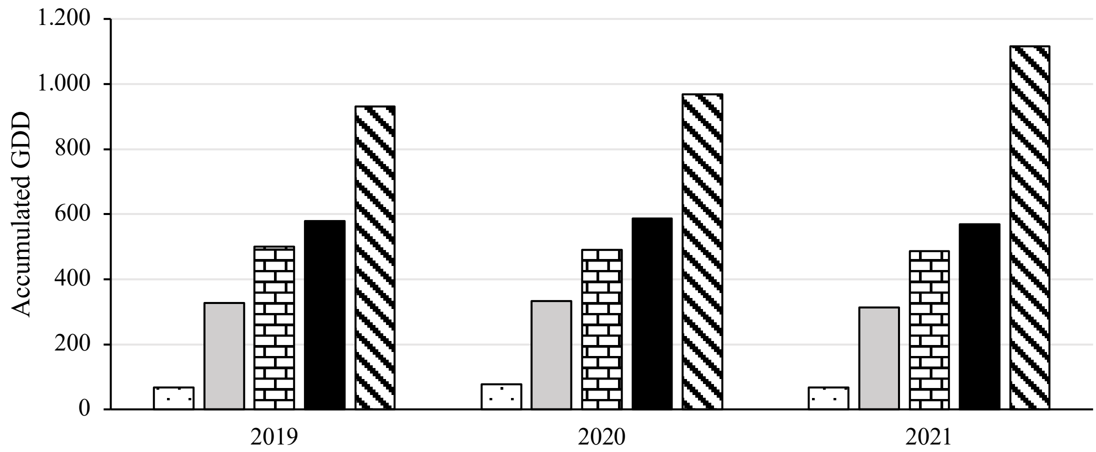

Figure 2. Accumulated GDD in camelina crop from sowing to: emergence (dotted bar); elongation (gray bar); flowering (brick bar); 50% of flowering (black bar) and harvest (striped bar).

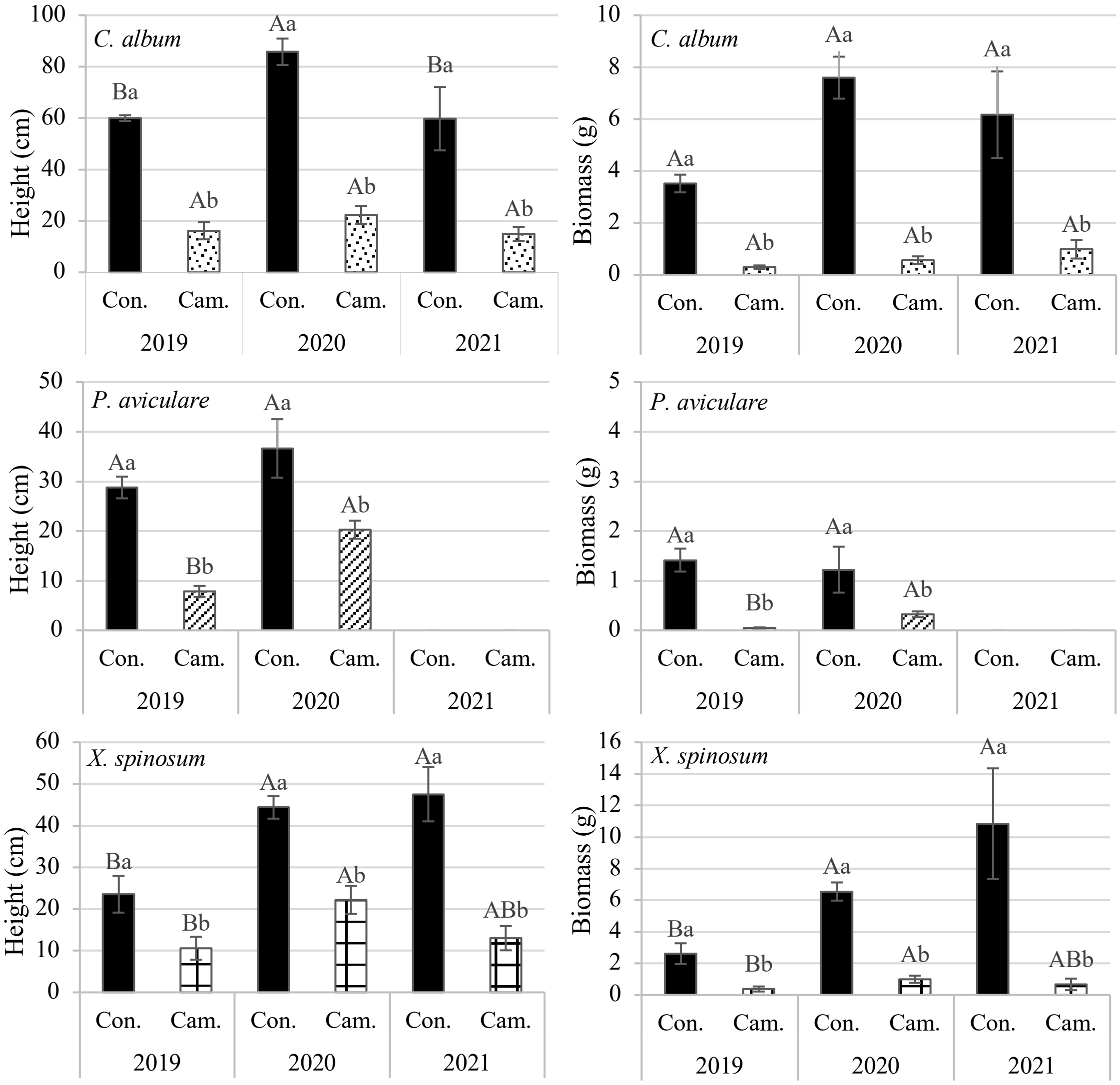

Figure 3. Height (cm) and aboveground dry biomass (g) of *Chenopodium album, Polygonum aviculare* and *Xanthium spinosum* growing without (con.) and with (cam.) crop presence. ANOVA results are provided. Different letters denote significant differences at $P<0.05$ (Tukey's test): upper case letters refer to differences among seasons within a treatment; lower case letters refer to differences between treatments within years. Due to the absence of *P. aviculare* in the trial, there are no data for this weed in 2021.