Weed Science

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Responses of soil seedbank and aboveground weed communities to globe artichoke–cropping systems: an on-farm analysis

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Research Article

Cite this article: Scavo A, Restuccia A, Di Martino A, Mauromicale G (2024). Responses of soil seedbank and aboveground weed communities to globe artichoke–cropping systems: an on-farm analysis. Weed Sci. doi: 10.1017/wsc.2024.5

Received: 3 September 2023
Revised: 2 December 2023
Accepted: 30 January 2024

Associate Editor:
Nicholas Basinger, University of Georgia

Keywords:
Crop rotation; *Cynara cardunculus*; weed management; weed abundance; weed diversity; species composition

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Abstract

Globe artichoke [*Cynara cardunculus* L. var. *scolymus* (L.) Fiori] is one of the most important crops across the Mediterranean basin, where weeds are an important biotic constraint limiting crop yields. However, the effects of globe artichoke–cropping systems on weeds have been rarely tested. Following the demand for eco-friendly weed management practices, a multi-location trial (13 farms) was carried out, measuring weed seedbanks and aboveground communities within four globe artichoke–cropping systems: globe artichoke monoculture (ART), past cultivation of globe artichoke (8 to 10 yr ago) (past-ART), a globe artichoke–durum wheat (*Triticum durum* Desf.) rotation (ART-WHEAT), and a control where globe artichoke was never grown. Both below- and aboveground weed communities were dominated by annual therophytes, but a low correspondence was found between both types of communities. Averaged over farms, ART highly reduced both the weed soil seedbank (1,600 seeds m^{-2} on average) and the aboveground weed biomass (only 3.4 g dry weight m^{-2}) compared with the control, with a decrease of 72% in the soil seedbank and 99% in the aboveground flora. Moreover, on the farms where globe artichoke was previously grown, a very low aboveground weed biomass (77% less than control) was found. In addition, ART contributed to the preservation of high levels of weed diversity (except for aboveground communities) and therefore avoided the creation of a specialized weed flora. In conclusion, we suggest the inclusion of globe artichoke into crop rotation schemes in Mediterranean agroecosystems as a sustainable tool for reducing both the soil weed seedbank and aboveground weeds, thus reducing the requirement of direct weed control methods and preserving the environment.

Introduction

Modern agriculture, driven by public opinion and governmental institutions, is increasingly looking for agronomic practices able to reduce weed pressure effectively without impacting the environment and causing damage to living organisms. For instance, in agreement with the European Green Deal and particularly with the Farm to Fork strategy, the European Commission (EC) aims to reduce by 50% the use and risk of chemical pesticides by 2030 (EC 2020). Moreover, the Sustainable Development Goals developed by the United Nations promote the sustainability of agricultural systems through an agroecological and multifunctional approach toward agroecosystems (UN 2015). Several agronomic techniques and strategies, including the exploitation of allelopathic mechanisms (Scavo and Mauromicale 2021), can be used for effective and eco-friendly weed management in agroecosystems, especially integrated approaches (Scavo and Mauromicale 2020). In recent years, we have witnessed an increasingly return toward crop rotation, one of the oldest agricultural practices in history (Hufnagel et al. 2020). Much scientific evidence demonstrates that it is associated, over different cropping systems, with a reduction of pests and lower soil seedbank and weed densities (Bullock 2008; Cardina et al 2002; Tanveer et al. 2019). Introducing allelopathic crops, such as sunflower (*Helianthus annuus* L.) or wheat (*Triticum aestivum* L.), into crop sequences for one or more years may offer a valid weed-suppressive ability, on the soil seedbank density and diversity, especially in conservation agriculture, thanks to the release of allelochemicals into the soil through root exudation, decomposition of plant residues, and leaching from plant foliage (Farooq et al. 2011; Scavo and Mauromicale 2021). However, harmful effects from allelopathic crops on the subsequent cash crop are sometimes reported (Karkanis et al. 2109).

Globe artichoke [*Cynara cardunculus* L. var. *scolymus* (L.) Fiori, Asteraceae] is a herbaceous C_3 perennial crop that originated in the Mediterranean basin, where it is appreciated for the

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immature inflorescence (*capitulum* or head) (Mazzeo et al. 2020; Portis et al. 2012). Italy is the leading world producer with 376,280,000 kg ha^{-1} obtained from 38,450 ha, followed by Spain and Egypt, although other South American and Asian countries are increasing their harvest areas (FAOSTAT 2021). Its allelopathic activity against seed germination and seedling growth of a number of weed species has been demonstrated under laboratory conditions (Scavo et al. 2018, 2019c, 2020), whereas no strong evidence has been demonstrated in the field. In Mediterranean agroecosystems, the globe artichoke is traditionally cultivated as a perennial crop by renewing the aboveground plant part after summer dormancy, but its cultivation as an annual crop through gamic propagation is increasing. Previous research found that the repeated cultivation for three consecutive years of globe artichoke halved the soil seedbank size over two different areas, compared with a wheat/fava bean (*Vicia faba* L.) rotation and an olive (*Olea europaea* L.) grove (Scavo et al. 2019b). According to Hossain and Begum (2015), introducing perennial crops into annual cropping systems helps to decrease the soil seedbank size. Also, MacLaren et al. (2019) indicated that the integration of perennial forage crops with livestock grazing in crop rotations limits the replenishment of the weed seedbank for several years and consequently reduces weed abundance for the following annual cash crop. Given that the seedbank size reflects the present and past field operations, its reduction is of key importance to reduce the emerged weed flora and the disturbance level of control practices (Sjursen 2001).

In this context, we hypothesized that the inclusion of a perennial crop (i.e., globe artichoke) in crop rotation sequences in the studied area could decrease weed pressure. Hence, we performed a multi-location on-farm analysis across 13 farms to evaluate different globe artichoke inclusion rates into cropping systems on density and diversity of below- and aboveground weed communities.

Materials and Methods

Locations, Climate, and Soils

This research was carried out during the 2021/2022 growing season across 13 farms located in central-eastern Sicily within the territory of Niscemi, Gela Plain (Caltanissetta, Italy), an area with a long tradition of globe artichoke cultivation. The zone is subjected to a Mediterranean semiarid climate, with mild wet winters and hot arid summers. Rainfall is primarily concentrated in the autumn–winter period and is generally below 500 mm yr^{-1}. In accordance with the typical trend of the zone, the experimental growing season experienced a dry summer with only 7 mm of rainfall in June, 1 mm in July, and 4 mm in August, whereas the sum of rainfall in November, December, January, and February accounted for 59% of the total annual rainfall (308 mm) (Supplementary Figure S1). September and October rainfall (49 mm) allowed a good establishment and emergence of weeds before the aboveground harvest. Minimum air temperatures never fall below 0 C and were in an optimal range for globe artichoke growth (Pesce and Mauromicale 2019). Based on the USDA soil classification (USDA-NRCS 1999), the soils of the zone are Regosoils (typic Xerorthensis or Xerochrepts) with medium-clayey to loamy-sandy texture, subalkaline reaction, low soil organic matter, medium cation exchangeable capacity, and high exchangeable K_2O levels.

Experimental Setup and Field Operations

In order to study the effect of globe artichoke inclusion rate into cropping systems on weed flora, a multi-location trial involving 13 on-farm locations that either did or did not include globe artichoke in their crop rotations was performed. Following this criterion, four groups of farms were selected: (1) repeated globe artichoke cultivation for 10 to 15 yr (ART); (2) past cultivation of globe artichoke (8 to 10 yr ago) (past-ART); (3) globe artichoke–durum wheat (*Triticum durum* Desf.) annual rotation (ART-WHEAT); and (4) farms that have never cultivated globe artichoke (control). For each of these criteria, three farms were considered, except for ART-WHEAT, which involved four farms. For aboveground weed evaluation, 11 farms were selected, because the excluded farms (Blanco 2 and Lo Iacono) performed tillage operations before aboveground weed sampling.

The geographic coordinates and the agronomic management of the 13 farms under study are shown in Supplementary Table S1. Overall, field operations followed the standard practices of southern Italy, as recommended by the Sicily Department of Agriculture (www.regione.sicilia.it). Control and past-ART farms have been managed with very low inputs (no mineral fertilization and chemical weed control). Tillage was similar among all farms, as well as the fertilization program, where adopted. In ART farms, plant residues were plowed every year. ART-WHEAT consists of an annual rotation between the two crops with similar varieties, timing of biological cycle (from November to June for durum wheat, and from August to June for globe artichoke), and plant density of ART. The former, they have been subjected to chemical weed control over the last 10 years with the typical active ingredients used in the zone for globe artichoke: pyraflufen-ethyl, fluazifop-*p*-butyl, and oxyfluorfen, applied at the dosages recommended by producers (0.35, 1.5, and 1.2 L ha^{-1}, respectively). Table 1 shows the crop rotation sequences of the farms under study over the last 10 yr. Control farms involve various arboreal crops (orchards) managed with low input and no weed chemical control.

Analysis of the Weed Flora and Data Collection

All farms under study were initially monitored through field scouting to obtain an adequate visualization of the weed spatial distribution and to locate the sampling units. In accordance with Nkoa et al. (2015) and Scavo et al. (2022), a stratified random sample was collected by dividing each sampling zone into homogeneous strata due to high variability within and between the study sites. In each farm, a 1,000-m^2 area was chosen (Nkoa et al. 2015). Then, three sampling zones within these areas were selected by excluding the nonhomogeneous areas and the outer 3-m borders. The weed flora has been analyzed in terms of soil seedbank (potential flora) and aboveground communities (actual flora), considering both the abundance and diversity (Scavo et al. 2022). The collection of soil cores was performed from July 13 to 31, 2021, while aboveground weed samples were taken from November 4 to 10, 2021. The choice of these two different sampling periods was due to the fact that, in semiarid zones, all therophytes are the end of their biological cycles and present mature seeds in July, while the aboveground weed flora is already well established after early autumn rainfall in November.

In each farm, soil samples were collected with a 4-cm-diameter steel probe from the top 0- to 15-cm soil layer along the diagonals of the central part of each sampling zone. A soil sample was composed of five 0.75-L subsamples (3.75 L per replicate), giving a total of 195 soil cores (13 farms × 3 replicates × 5 subsamples). In the laboratory, the inert components (i.e., stones, pebbles, and dead debris) were removed by hand, and then seeds were extracted

https://doi.org/10.1017/wsc.2024.5 Published online by Cambridge University Press

Table 1. Crop sequence of all farms under study, excluding control, in the last 10 yr.

Farm[a]	Crop sequence
1. ART	
Buccheri 1	Monoculture of globe artichoke 'Violetto di Sicilia'
Pepi	Monoculture of globe artichoke 'Violetto di Sicilia' and 'Romanesco' and 1-yr fallow
Blanco 1	Monoculture of globe artichoke 'Madrigal', 'Apollo', and 'Romanesco'
2. Past-ART	
Di Modica	Strawberry (*Fragaria* L.) in 2021 and fallow for 9 yr
Buccheri 2	Fallow for 10 yr
Blanco 2	Durum wheat in the last 2 yr, apricot (*Prunus armeniaca* L.) in the previous 8 yr
3. ART-WHEAT	
Minardi 1	Globe artichoke 'Violetto di Sicilia'–durum wheat 'Core'
Minardi 2	Globe artichoke 'Romanesco'–durum wheat 'Antalis'
Alessandrello	Globe artichoke 'Violetto di Sicilia'–durum wheat 'Antalis'
Lo Iacono	Globe artichoke 'Violetto di Sicilia'–durum wheat 'Rusticano'

[a]ART, repeated cultivation of globe artichoke; past-ART, past cultivation of globe artichoke; ART-WHEAT, globe artichoke–durum wheat rotation.

through a metal tube using pressurized water (Karcher, K 3500 model, Winnenden, Germany) with a removable cap fit with 250-µm steel mesh (Scavo et al. 2021). The extracted fraction was placed inside petri dishes and air-dried for 24 h. An MS5 Leica stereomicroscope (Leica Microsystems, Wetzlar, Germany) was used for seed identification and count, thus obtaining the seedbank size, expressed as the number of seeds per square meter for each replicate.

For aboveground weed communities, following Restuccia et al. (2020), three 1.0-m^2 quadrats (with subquadrats kept separate) were randomly positioned within each sampling zone of all farms, for a total of 33 quadrats (11 farms × 3 replicates). After weed identification and count, the aboveground weed biomass at the quadrat level was obtained by clipping weeds at the soil surface and drying them at 55 C in an oven up to constant weight.

Weed abundance in the seedbank and aboveground samples was assessed by calculating the seedbank size, aboveground biomass, relative density (RD), relative frequency (RF), and relative abundance index (RAI), as suggested by Derksen (1993):

$$\mathrm{RD}\ (\%) = \left(\frac{\sum Y_i}{S}\right) \times 100 \qquad [1]$$

$$\mathrm{RF}\ (\%) = \left(\frac{F_i}{\sum F}\right) \times 100 \qquad [2]$$

$$\mathrm{RAI}\ (\%) = \frac{\mathrm{RD} + \mathrm{RF}}{2} \qquad [3]$$

where $\sum Y_i$ is the sum of the number of seeds or individuals for a given weed; S is the species richness; F_i is the absolute frequency of a species; and $\sum F$ is the sum of the absolute frequencies of all species.

Weed diversity was described in terms of weed community structure, species composition, and three α-diversity (within-community) and one β-diversity (between-communities) indices (Nkoa et al. 2105; Travlos et al. 2018). Based on Conti et al. (2005), weeds were grouped by botanical family, life cycle (annuals, biennials, or perennials), and biological group (life-form category considering the Raunkiaer system). Diversity indices were derived from the five soil cores for each soil sample or from four 0.25-m^2 subplots per quadrat (Adeux et al. 2019). The α-diversity indices taken into account were Margalef's (D_{MG}), Shannon-Wiener (H), and Pielou's (J), while Whittaker's (W) was considered for β-diversity:

$$D_{MG} = \frac{(S - 1)}{\ln(N)} \qquad [4]$$

$$H = \sum[-p_i\ (\ln p_i)] \qquad [5]$$

$$J = \frac{H}{H'_{\max}} \qquad [6]$$

$$W = \frac{\Upsilon}{S} \qquad [7]$$

where N is the total number of seeds or individuals of all species in the community; p_i is the proportional abundance of the ith species; $H'_{\max}$ is the logarithm of species richness; and Υ is the total number of all species in the entire study area.

Statistical Analysis

All data were analyzed using one-way analysis of variance (ANOVA) with the Fisher's protected least significant difference (LSD) test for paired multiple comparisons, fixing $\alpha = 0.05$. Residuals were checked for homoscedasticity by Bartlett's test and for normal distribution by graphical inspections. To ensure data normality, soil seedbank and aboveground biomass data were $\log_{(x+1)}$ transformed, H data were square-root transformed, and J data were logit transformed (Adeux et al. 2019; Scavo et al. 2021). To study the effect of cropping systems, data from farms belonging to the same group were pooled using farms as replicates. For one-way ANOVAs to all farms, the replicates within each farm were used.

Species composition was analyzed by multivariate statistics. In particular, the interactions between cropping system treatments (ART, past-ART, ART-WHEAT, control) and weed communities were tested through principal component analysis (PCA) on the correlation matrix of density data, one for the soil seedbank and one for aboveground weeds. Before PCA, the seven major weeds ($\mathrm{RD} \geq 6\%$) for the soil seedbank and the six major weeds for aboveground weeds were standardized by $\log_{(x+1)}$ transformation (Scavo et al. 2022). In accordance with Legendre and Legendre (2012), PCA results were displayed on "distance" biplots derived from the first two principal components (PCs) explaining the maximum variance. The CoStat® 6.003 software (CoHort Software, Monterey, CA, USA) was used for ANOVAs, while PCAs were performed in Minitab® 16 (Minitab, State College, PA, USA).

Results and Discussion

This study concerns an on-farm analysis performed in central-eastern Sicily, an important area devoted to globe artichoke cultivation, aiming at evaluating the effects of different globe artichoke inclusion rates into cropping systems on the abundance and diversity of the soil seedbank and aboveground weed communities. Although some results were farm specific, we think that conducting such weed science experiments at the farm scale

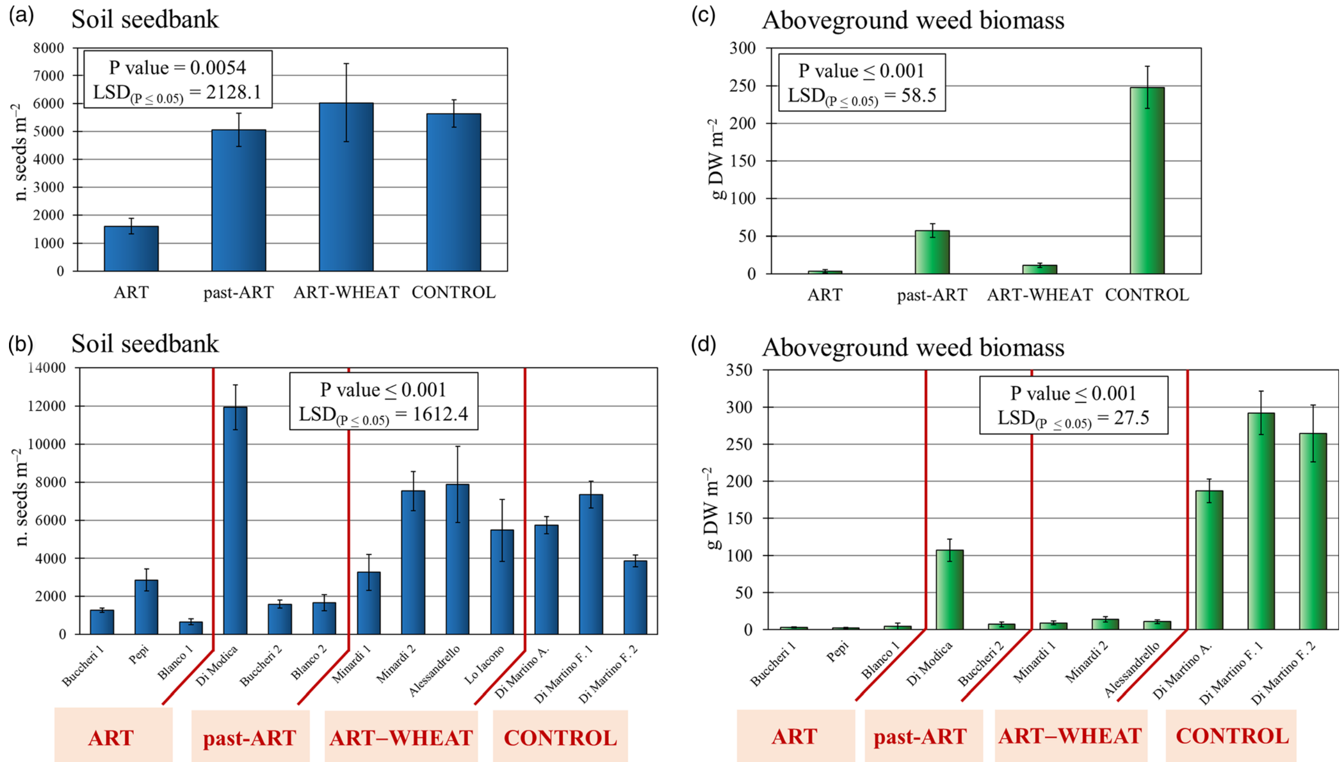

Figure 1. (A) Size of the weed soil seedbank (0–15 cm) averaged over treatments and (B) across all farms under study; (C) aboveground weed biomass (g dry weight [DW] m^{-2}) averaged over treatments and (D) across all farms under study. Bars indicate ±SD ($n = 3$). Least significant difference (LSD) value was calculated by applying one-way analysis of variance (ANOVA) with the Fisher's LSD test at $P \leq 0.05$. ART, repeated cultivation of globe artichoke; past-ART, past cultivation of globe artichoke; ART-WHEAT, globe artichoke–durum wheat rotation; CONTROL, globe artichoke never cultivated.

can contribute to obtaining robust data and to motivating its adoption by stakeholders, as also indicated by Murphy et al. (2006).

Responses of the Soil Seedbank to Globe Artichoke Inclusion Rate into Cropping Systems

On the average of cropping system treatments (Figure 1A), the lowest seedbank size in the top soil layer (0 to 15 cm) was found in ART (1,600 seeds m^{-2}), with a reduction of 71.7% compared with the control and 73.5% compared with ART-WHEAT. No significant differences were observed between past-ART, ART-WHEAT, and the control. Therefore, the repeated cultivation of globe artichoke significantly decreases the number of weed seeds in the soil below 16 million weed seeds ha^{-1}, which is assumed to be the threshold for low aboveground weed pressure (Scavo and Mauromicale 2020), whereas the past cultivation of globe artichoke did not affect the soil seedbank abundance. Moreover, the globe artichoke–durum wheat rotation, the most common rotation in the survey area, was not effective in reducing the seedbank size, thus requiring external inputs for actual weed control. These results corroborated, in the longer term, our previous findings about the 3-yr cultivation of globe artichoke on the soil seedbank (Scavo et al. 2019b). The reduction of the seedbank size caused by globe artichoke monoculture might be due to the buildup of its allelochemicals (sesquiterpene lactones and polyphenols) in the soil, released by root exudation, decomposition of the plant residues plowed every year, and leaching from plant foliage (Scavo et al. 2019a). This process may also be involved in the invasive ability of globe artichoke in Australian fields, as suggested by Uddin et al. (2020). The reduction of seedbank richness and seed density induced by allelochemicals was demonstrated in semiarid ecosystems by Arroyo et al. (2017), who found a lower seedbank abundance under the canopy of the allelopathic shrub white wormwood (*Artemisia herba-alba* Asso) than in bare soil. Another similar finding about the effects of allelochemicals on the soil seedbank was reported by Fabbro et al. (2013).

The ANOVA indicated significant differences across single farms (Figure 1B). The largest seedbank size was detected in the Di Modica farm (11,933.3 seeds m^{-2}), which had not carried out any tillage or weed control practice over the last 9 yr. Except for the Di Modica farm, the other two farms belonging to past-ART (Buccheri 2 and Blanco 2) showed seedbank size values similar to ART farms (1,600.0 and 1,666.7 seeds m^{-2}, respectively), corroborating the seeming residual allelopathic effect of globe artichoke in the soil. The very high number of seeds per square meter found on the Di Modica farm is attributable not only to the absence of any tillage, but also to its species composition. Indeed, the seedbank of this farm was mainly composed of the therophytes common purslane (*Portulaca oleracea* L.) (36.2% RD), *Chenopodium* sp. (30.2% RD), and redroot pigweed (*Amaranthus retroflexus* L.) (17.9% RD). Therophytes are known to dominate soil seedbanks of arid and semiarid climates, as they remain as seeds in the soil during unfavorable seasons and rely on regeneration from the soil seedbank on favorable conditions. On the contrary, *P. oleracea* and *A. retroflexus* were not found in Buccheri 2 and Blanco 2. The Di Modica farm is followed by control and ART-WHEAT farms, in decreasing order: Alessandrello (7,866.7 seeds m^{-2}), Minardi 2 and Di Martino F. 1 (both with 7,533.3 seeds m^{-2}). The smallest seedbank size was found on the Blanco 1 farm with just 666.7 seeds m^{-2}. Farm-specific results are common in on-farm studies where cultural

https://doi.org/10.1017/wsc.2024.5 Published online by Cambridge University Press

Table 2. Mean relative abundance indices (RAI) and mean relative densities (RD) of the weed species in the total seedbank (0–15 cm) across all farms under study.[a]

Weed binomial names	Botanical family	Life cycle	BG	ART	Past-ART	ART-WHEAT	CONTROL	RD %[b]
Amaranthus retroflexus L.	Amaranthaceae	Annual	T	0.09	0.05	0.04	0.10	6.9
Anagallis arvensis L.	Primulaceae	Annual	T	0.12	0.03	0.35	—	16.7
Avena sp.	Poaceae	Annual	T	0.03	0.08	0.01	—	2.8
Calendula arvensis (Vaill.) L.	Asteraceae	Biennial	H	—	—	—	0.06	0.8
Chenopodium sp.	Chenopodiaceae	Annual	T	0.09	0.15	—	0.09	7.6
Euphorbia falcata L.	Euphorbiaceae	Annual	T	—	0.02	0.01	—	0.4
Euphorbia helioscopia L.	Euphorbiaceae	Annual	T	0.04	0.02	0.03	0.01	1.5
Foeniculum vulgare Mill.	Apiaceae	Perennial	H	0.03	—	—	—	0.8
Fumaria sp.	Fumariaceae	Annual	T	0.16	0.06	0.05	0.08	8.6
Lavatera (*Malva*) *trimestris* L.	Malvaceae	Annual	T	—	—	—	0.04	0.6
Malva sylvestris L.	Malvaceae	Perennial	H	0.03	0.01	—	—	0.8
Medicago polymorpha L.	Fabaceae	Annual	T	0.07	0.02	0.03	0.06	3.3
Oxalis pes-caprae L.	Oxalidaceae	Perennial	G	—	—	—	0.13	3.1
Phalaris paradoxa L.	Poaceae	Annual	T	—	0.06	—	—	1.5
Picris echioides (L.) Holub	Asteraceae	Annual	T	0.03	0.04	—	—	2.1
Poa annua L.	Poaceae	Annual	T	—	0.01	—	—	0.0
Polygonum convolvulus (L.) Á. Löve	Polygonaceae	Annual	T	0.07	0.16	—	0.01	6.3
Portulaca oleracea L.	Portulacaceae	Annual	T	0.09	0.08	0.14	0.27	16.7
Raphanus raphanistrum L.	Brassicaceae	Annual	T	—	0.01	—	0.01	0.4
Silene sp.	Caryophillaceae	Perennial	H	0.09	0.13	0.28	0.10	16.3
Sinapis arvensis L.	Brassicaceae	Annual	T	—	—	—	—	0.2
Sonchus sp.	Asteraceae	Perennial	H	0.01	0.03	0.02	0.01	0.8
Torilis nodosa (L.) Gaertn.	Apiaceae	Annual	T	0.03	—	0.03	—	1.1
Trifolium repens L.	Fabaceae	Perennial	H	—	0.02	—	—	0.3
Trifolium subterraneum L.	Fabaceae	Annual	T	—	—	—	0.01	0.1
Veronica sp.	Scrophulariaceae	Annual	T	0.01	0.01	—	—	0.4

[a]Weeds are grouped by botanical family, life cycle, and biological group (BG). ART, repeated cultivation of globe artichoke; past-ART, past cultivation of globe artichoke; ART-WHEAT, globe artichoke–durum wheat rotation; CONTROL, globe artichoke never cultivated. T, therophytes; H, hemicryptophytes; G, geophytes.
[b]Averaged over all farms under study.

practices are not fixed and comparisons are therefore more difficult (Murphy et al. 2006). This suggests the high importance of agronomic management on weed abundance. At the same time, this approach provides robust data from real field conditions.

The total 0- to 15-cm soil seedbank throughout the 13 farms analyzed included 26 species or genera, 73% of which were annuals, 23% perennials, with the only biennial being field marigold (*Calendula arvensis* L.) (Table 2). Most of these weeds are recognized by farmers in the studied area as yield-reducing species. Sixteen botanical families were identified, the most representative (19%) of which were Asteraceae, Fabaceae, and Poaceae, namely the most common botanical families in Mediterranean agroecosystems (Restuccia et al. 2019), followed by Brassicaceae and Apiaceae (both at 13%). Concerning the biological groups, 73% of the identified taxa were therophytes and 23% hemicryptophytes, while the only geophyte was Bermuda buttercup (*Oxalis pes-caprae* L.). Therefore, the total seedbank was primarily composed of annual therophytes, similar to results from Scavo et al. (2022). Seven major species or genera (with an RD $\geq$ 6%) dominated the seedbank (Table 2): in decreasing order, scarlet pimpernel (*Anagallis arvensis* L.), *P. oleracea*, *Silene* sp., *Fumaria* sp., *Chenopodium* sp., *A. retroflexus*, and black bindweed [*Polygonum convolvulus* L. var. *convolvulus*; syn. *Fallopia convolvulus* (L.) Á. Löve], the sum of which accounted for 79% of the total seedbank density. This finding was in accordance with Wilson (1988), who stated that dominant weeds in low numbers compared with the total number of weeds generally comprise from 70% to 90% of the seedbank in cultivated soils. Species richness had no significant differences between farms and cropping system treatments (data not shown). However, the analysis of RAI data (Table 2) shows that, concerning major weeds, *A. arvensis* and *Silene* sp. were more abundant in ART-WHEAT farms, *A. retroflexus* and *P. oleracea* in control farms, and *Chenopodium* sp. and *P. convolvulus* in past-ART farms, while only *Fumaria* sp. was more abundant in ART farms. Furthermore, hood canarygrass (*Phalaris paradoxa* L.), annual bluegrass (*Poa annua* L.), and white clover (*Trifolium repens* L.) were exclusive to ART farms, while *C. arvensis* and subterranean clover (*Trifolium subterraneum* L.) were detected only on control farms.

Table 3 shows the results for the diversity indices of the soil seedbank. Interestingly, keeping in mind that D_{MG} measures gross species diversity by only considering species richness, J quantifies evenness, and H includes both diversity and evenness (Adeux et al. 2019), ART had the highest α-diversity for all three indices. This indicated that ART, in addition to a significant reduction of the seedbank size, contributes to maintain high levels of seedbank diversity and evenness, in contrast to ART-WHEAT, thus avoiding the development of a specialized weed flora. Our finding contrasts with Sosnoskie et al.'s (2006) report of higher H and J values for corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] and corn–oat (*Avena sativa* L.)–hay sequences than continuous corn in a 35-yr experiment performed in Ohio, USA. The highest α-diversity was measured on Blanco 1 farm, which also showed a $J = 1$, indicating the absence of dominant weeds. No significant differences were observed in terms of β-diversity among cropping system treatments.

ART-WHEAT showed the lowest seedbank diversity and evenness (Table 3), denoting a lower number of species present at high frequency. Its seedbank was dominated by *A. arvensis* (0.35 RAI), *P. oleracea* (0.14 RAI), and *Silene* sp. (0.28 RAI), which are recognized as some of the most harmful weeds for cereals in semiarid environments (Hassan et al. 2020). Therefore, the annual rotation with durum wheat may have favored the spread of such weeds—known to be hardly controlled by cereals, while the

Table 3. The α- and β-diversity indices of weeds in the total soil seedbank (0–15 cm) across all farms under study.[a]

	α-diversity			β-diversity
	Margalef	Shannon-Weiner	Pielou	Whittaker
ART	4.88 ± 2.25 A	2.02 ± 0.26 A	0.91 ± 0.08 A	2.8 ± 0.38 A
Buccheri 1	3.79 b	1.78 b	0.86 b	3.3 a
Pepi	3.38 c	1.98 b	0.86 b	2.6 b
Blanco 1	7.48 a	2.30 a	1.00 a	2.6 b
Past-ART	2.80 ± 0.56 B	1.69 ± 0.11 A	0.81 ± 0.12 AB	3.2 ± 0.56 A
Di Modica	2.20 c	1.61 a	0.70 b	2.6 c
Buccheri 2	2.89 b	1.82 a	0.93 a	3.7 a
Blanco 2	3.30 a	1.65 a	0.80 b	3.3 b
ART-WHEAT	1.93 ± 0.78 B	1.38 ± 0.36 B	0.70 ± 0.11 B	3.7 ± 0.73 A
Minardi 1	2.86 a	1.85 a	0.84 a	2.9 b
Minardi 2	1.38 c	1.29 b	0.72 a	4.3 a
Alessandrello	1.36 c	1.11 b	0.62 a	4.3 a
Lo Iacono	2.12 b	1.26 b	0.60 a	3.3 b
CONTROL	2.38 ± 0.89 B	1.71 ± 0.35 A	0.79 ± 0.07 AB	3.1 ± 0.69 A
Di Martino A.	2.09 b	1.59 b	0.76 a	3.3 b
Di Martino F. 1	1.67 c	1.43 b	0.74 a	3.7 a
Di Martino F. 2	3.38 a	2.10 a	0.88 a	2.4 c

[a]Different capital letters indicate significant differences between treatments at P ≤ 0.05 (Fisher's least significant difference [LSD] test). Different lowercase letters indicate significant differences within treatments at $p \leq 0.05$ (Fisher's LSD test). Data are mean ± SD. For values within groups, SD is always ≤ 0.1

cultivation of durum wheat might have broken the buildup of globe artichoke allelochemicals in the soil by promoting their leaching.

Responses of Aboveground Weeds to Globe Artichoke Inclusion Rate into Cropping Systems

Consistent with the seedbank abundance, when data were pooled over farms (Figure 1C), ART showed the lowest aboveground weed biomass (only 3.4 g dry weight [DW] m^{-2}) with a 99% reduction with respect to control. However, in contrast to the seedbank results, past-ART had a significant residual effect on aboveground weeds (77% less than control), and ART-WHEAT also exerted a marked weed-suppressive ability (96% reduction). In detail (Figure 1D), all control farms that never grew globe artichoke showed the highest values of aboveground weed biomass, with the Di Martino F. 1 farm having the greatest value (292.0 g DW m^{-2}) detected. It should also be highlighted that all ART farms registered very low weed aboveground biomass (3.2 g DW m^{-2} at Buccheri 1, 2.4 g DW m^{-2} at Pepi, and 4.7 g DW m^{-2} at Blanco 1). Chemical weed control performed at Buccheri 1, Blanco 1, Minardi 1, and Minardi 2 has probably contributed to lowering the aboveground weed biomass. Nevertheless, the very low biomass levels of aboveground weeds for ART might be attributed on the progressive decrease of the soil seedbank size on the one hand, and on its combined allelopathic plus competitive ability on the other hand. Similar findings were also reported by Alsaadawi et al. (2012) concerning the repeated cultivation of sunflower on weed number and biomass, with a higher weed-suppressive ability shown by allelopathic sunflower cultivars, and by Scavo et al. (2022) concerning durum wheat landraces. Concerning the differences between soil seedbank and aboveground weeds, especially about past-ART and ART-WHEAT, it is known that emerged weeds reflect a recent influence of farming practices, whereas seedbank communities are more representative of long-term effects associated with farming practices (Buhler et al. 1997; Dekker 1999). Furthermore, the weed emergence rate is dependent on seed age, dormancy level, seed predation, mortality, climatic conditions, and cultural practices (Miele et al. 1998). It should also be highlighted that on ART-WHEAT farms, the last year was cultivated with globe artichoke, thus causing a more prominent suppressive effect on aboveground weeds compared with that observed on the soil seedbank.

Throughout the 11 farms, aboveground weed communities were composed of 27 species or genera in total that showed a floristic composition similar to seedbank communities (Table 4). In the life-cycle analysis, 52% were annual, 30% perennial, and 18% biennial, while biological groups were as follows: 52% therophytes, 41% hemicryptophytes, and 7% geophytes. Most of the detected taxa belonged to Poaceae (54%), followed by Brassicaceae (38%) and Asteraceae (31%). We recognized six major weeds: common chickweed [*Stellaria media* (L.) Vill.], field bindweed (*Convolvulus arvensis* L.), white rocket [*Diplotaxis erucoides* (L.) DC.], common lambsquarters (*Chenopodium album* L.), bermudagrass [*Cynodon dactylon* (L.) Pers.], and crowfootgrass [*Dactyloctenium aegyptium* (L.) Willd.]. In contrast to the soil seedbank, total species richness was significantly lower in ART than in control (7 vs. 19 weeds), mainly due to Buccheri 1 and Pepi farms, which showed only 1 and 2 species, respectively, as can also be observed in their D_{MG} values (Table 5). Indeed, H was significantly lower in ART, as well as in the other cropping systems under study, than in the control, whereas J did not differ statistically. In addition, the Buccheri 1 and Pepi farms had the highest W values, and this is not surprising, because Whittaker's index is negatively related to the number of species (Nkoa et al. 2015; Travlos et al. 2018). Overall, ART showed the highest W value (15.3), which was statistically different from the other cropping system treatments, denoting a lower between-communities diversity (Table 5). It is likely that the low α-diversity and the high β-diversity found in ART aboveground weed communities was due to the farms' cultural practices, especially the chemical weed control. This is corroborated by Doucet et al. (1999), who indicated a higher contribution to total variation by weed management than crop rotation in a 10-yr crop rotation study. The RAI analysis indicated that only white mustard (*Sinapis arvensis* L.) was exclusive to ART, squirting cucumber [*Ecballium elaterium* (L.) A. Rich.] and vetch (*Vicia sativa* L.) were exclusive to past-ART, whereas English daisy (*Bellis perennis* L.) and spiny sowthistle [*Sonchus asper* (L.) Hill] were detected only in ART-WHEAT (Table 4). *Stellaria media* was prevalent in ART-WHEAT

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Table 4. Mean relative abundance indices (RAI) and mean relative densities (RD) of the weed species in the real flora across all farms under study.[a]

Weed binomial names	Botanical family	Life cycle	BG	ART	Past-ART	ART-WHEAT	CONTROL	RD %[b]
Amaranthus retroflexus L.	Amaranthaceae	Annual	T	—	—	0.03	0.01	0.6
Bellis perennis L.	Asteraceae	Perennial	H	—	—	0.04	—	0.6
Calendula arvensis (Vaill.) L.	Asteraceae	Biennial	H	—	—	—	0.06	1.6
Capsella bursa-pastoris (L.) Medik.	Brassicaceae	Biennial	H	—	—	—	0.03	0.3
Chenopodium album L.	Chenopodiaceae	Annual	T	—	0.28	—	0.01	8.1
Convolvulus arvensis L.	Convolvulaceae	Perennial	G	0.55	0.22	0.11	—	21.7
Cynodon dactylon (L.) Pers.	Poaceae	Annual	T	0.05	0.04	—	0.14	7.3
Cyperus rotundus L.	Cyperaceae	Perennial	H	—	—	—	0.01	0.2
Dactylis glomerata L.	Poaceae	Perennial	H	—	—	—	0.01	0.1
Dactyloctenium aegyptium (L.) Willd.	Poaceae	Annual	T	—	0.06	—	0.18	6.4
Diplotaxis erucoides (L.) DC.	Brassicaceae	Annual	T	0.07	—	0.03	0.26	12.1
Ecballium elaterium (L.) A. Rich.	Cucurbitaceae	Annual	T	—	0.06	—	—	0.5
Echium plantagineum L.	Boraginaceae	Biennial	H	—	—	—	0.01	0.1
Glebionis coronaria (L.) Cass. ex Spach	Asteraceae	Annual	T	—	0.04	0.06	0.02	1.1
Holcus lanatus L.	Poaceae	Perennial	H	0.07	—	—	0.04	2.1
Hordeum murinum L.	Poaceae	Annual	T	0.07	0.03	—	0.02	2.5
Lobularia maritima (L.) Desv.	Brassicaceae	Perennial	H	—	0.02	—	0.05	1.0
Medicago polymorpha L.	Fabaceae	Annual	T	—	0.02	0.04	—	0.7
Oxalis pes-caprae L.	Oxalidaceae	Perennial	G	—	—	—	0.06	2.2
Phalaris paradoxa L.	Poaceae	Annual	T	—	—	—	0.02	0.2
Portulaca oleracea L.	Portulacaceae	Annual	T	—	0.04	—	0.03	0.4
Raphanus raphanistrum L.	Brassicaceae	Annual	T	—	—	0.03	0.02	0.5
Rumex sp.	Polygonaceae	Perennial	H	—	0.04	—	0.02	0.5
Sinapis arvensis L.	Brassicaceae	Annual	T	0.06	—	—	—	1.3
Sonchus asper (L.) Hill	Asteraceae	Biennial	H	—	—	0.07	—	0.6
Stellaria media (L.) Vill.	Caryophyllaceae	Biennial	H	0.12	0.06	0.59	—	25.8
Vicia sativa L.	Fabaceae	Annual	T	—	0.09	—	—	1.6

[a]Weeds are grouped by botanical family, life cycle, and biological group (BG). ART, repeated cultivation of globe artichoke; past-ART, past cultivation of globe artichoke; ART-WHEAT, globe artichoke–durum wheat rotation; CONTROL, globe artichoke never cultivated. T, therophytes; H, hemicryptophytes; G, geophytes.
[b]Averaged over all farms under study.

Table 5. The α- and β-diversity indices of weeds in the real flora across all farms under study.[a]

	α-diversity			β-diversity
	Margalef	Shannon-Weiner	Pielou	Whittaker
ART	1.12 ± 1.33 A	0.75 ± 0.80 B	0.65 ± 0.03 A	15.30 ± 10.91 A
Buccheri 1	—	—	—	27.0 a
Pepi	0.77 b	0.66 a	0.95 a	13.50 b
Blanco 1	2.60 a	1.60 b	0.99 a	5.40 c
Past-ART	1.41 ± 0.34 A	0.89 ± 0.34 B	0.48 ± 0.20 A	4.18 ± 0.32 B
Di Modica	1.07 b	0.55 b	0.28 b	3.86 b
Buccheri 2	1.75 a	1.22 a	0.68 a	4.50 a
ART-WHEAT	1.02 ± 0.31 A	0.70 ± 0.26 B	0.50 ± 0.11 A	7.05 ± 1.82 B
Minardi 1	0.94 b	0.76 a	0.55 a	6.75 b
Minardi 2	0.73 b	0.42 b	0.38 a	9.00 a
Alessandrello	1.35 a	0.93 a	0.58 a	5.40 c
CONTROL	1.62 ± 0.27 A	1.61 ± 0.15 A	0.69 ± 0.07 A	2.65 ± 0.38 B
Di Martino A.	1.44 b	1.77	0.77 a	2.70 b
Di Martino F. 1	1.93 a	1.58	0.64 a	2.25 c
Di Martino F. 2	1.49 ab	1.47	0.67 a	3.00 a

[a]Different capital letters indicate significant differences between treatments at $P \leq 0.05$ (Fisher's least significant difference [LSD]). Different lowercase letters indicate significant differences within treatments at $P \leq 0.05$ (Fisher's LSD test). Data are mean ± SD. For values within groups, standard deviation is always ≤ 0.1

(0.59), *C. arvensis* was more abundant in ART (0.55), *D. erucoides*, *C. dactylon*, and *D. aegyptium* in the control (0.26, 0.14, and 0.18, respectively), and C. *album* in past-ART (0.28).

Relationships between Cropping System Treatments and Weed Communities

PCA on major weeds was carried out to graphically display the presence (if any) of associations between weed communities and cropping system treatments. Although the first three PCs showed eigenvalues > 1 (Supplementary Table S2), biplots with the first two PCs were used, as they accounted for a sufficient variation level (65.7% for the seedbank and 65.0% for the real weed flora), in agreement with Ratnasekera et al. (2014) and Scavo et al. (2022). In the soil seedbank, *A. retroflexus*, *P. convolvulus*, and *P. oleracea* accounted for 64.2% of the variance for PC1; *A. arvensis* and *C. album* captured another 56.9% of variance for PC2; while *Fumaria* sp. and *Silene* sp. added another 45.5% for PC3 (Supplementary Table S2). The weeds *A. arvensis*, *Silene* sp., *P. oleracea*, and *A. retroflexus* and the treatments ART-WHEAT

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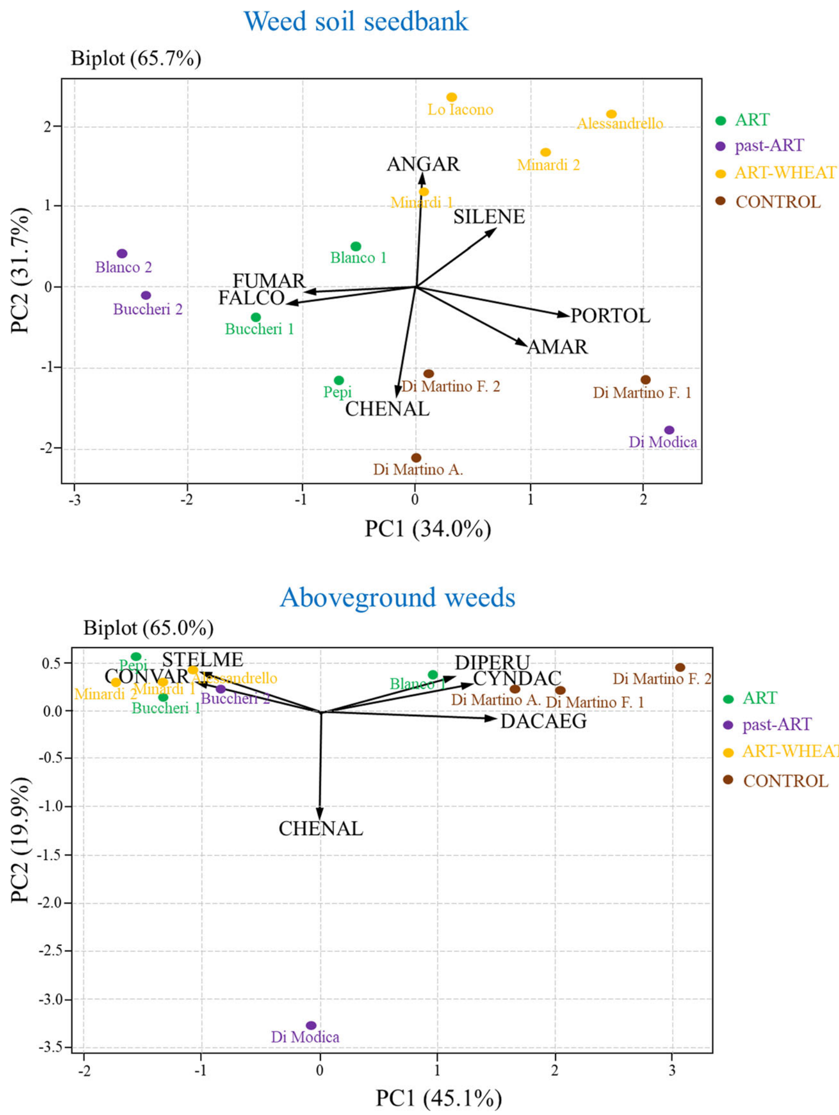

Figure 2. Principal component analysis (PCA) ordination biplots from the correlation matrix with the seven major weeds for the soil seedbank and with the six major weeds for the aboveground weeds across all farms under study. ART, repeated cultivation of globe artichoke; past-ART, past cultivation of globe artichoke; ART-WHEAT, globe artichoke–durum wheat rotation; CONTROL, globe artichoke never cultivated. AMAR, *Amaranthus retroflexus*; ANGAR, *Anagallis arvensis*; CHENAL, *Chenopodium album*; CONVAR, *Convolvulus arvensis*; CYNDAC, *Cynodon dactylon*; DACAEG, *Dactyloctenium aegyptium*; DIPERU, *Diplotaxis erucoides*; FALCO, *Fallopia convolvulus*; FUMAR, *Fumaria* sp.; PORTOL, *Portulaca oleracea*; SILENE, *Silene* sp.; STELME, *Stellaria media*.

and CONTROL were positively correlated to PC1 (right side of the biplot), whereas *Fumaria* sp., *F. convolvulus*, and *C. album*, together with ART and past-ART, were discriminated on the left side (Figure 2). Moreover, ART-WHEAT and the weeds *A. arvensis* and *Silene* sp. were positively correlated to PC2 (top of the biplot), while all the other cropping system treatments and weeds had a negative correlation. In agreement with the RAI analysis, ART-WHEAT was associated to *A. arvensis* and *Silene* sp.; ART with *Fumaria* sp. and *F. convolvulus*; and control with *A. retroflexus*, *P. oleracea*, and *C. album*. In the actual weed flora, all cropping system treatments and weeds, except for *D. aegyptium* and *C. album*, were positively correlated to PC2, and in fact, they are located on the top of the biplot (Figure 2). Control farms were highly infested by *D. euroides*, *C. dactylon*, and *D. aegyptium*; ART and ART-WHEAT farms by *C. arvensis* and *S. media*; and the Di Modica farm by *C. album*. In a similar experiment, studying the associations between old durum wheat landraces, modern cultivars, and major weeds under a semiarid climate, Scavo et al. (2022) also reported that PC1 showed the highest discrimination for the soil seedbank and PC2 for aboveground weeds. Here, a low correspondence was found between below- and aboveground weed communities, which is a poorly investigated topic in weed science when dealing with multiple species due to the effect of many confounding factors. An attempt was made by Davis et al. (2005), who also stated a low predictive value between below- and aboveground weed communities in a long-term corn–soybean–wheat crop sequence with four different cropping systems.

From this research it emerged that the globe artichoke monoculture can be effective in reducing below- and aboveground weed abundance, while at the same time increasing weed diversity (except for aboveground weeds) and avoiding the creation of a specialized weed flora. As a practical application, we believe that globe artichoke, due to its increasing cultivation as annual crop, can be profitably introduced into crop rotation schemes in

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Mediterranean agroecosystems, mainly under integrated approaches, to indirectly and sustainably manage weeds and to reduce the need for chemical weed control.

In our opinion, the approach proposed here may be adopted in similar research to obtain a realistic overview of the efficacy of sustainable weed control practices, especially in terms of soil seedbank communities. Possible future research lines comprise the investigation of more diversified crop rotations involving globe artichoke or the evaluation of the effects in other cropping systems, as well as the chemical characterization of globe artichoke allelochemicals from its rhizospheric soil and the study of their degradation in the soil system under natural conditions.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2024.5

Acknowledgments. This research received no specific grant from any funding agency or the commercial or not-for-profit sectors. No competing interests have been declared.

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