



Unveiling the impact of winter cover crops and weedy fallow on the soil seedbank

Giorgia Raimondi^a, Donato Loddo^b, Vittoria Giannini^{a,c,*}, Maurizio Borin^a

^a Department of Agronomy, Food, Natural Resources, Animals and Environment – DAFNAE, University of Padua, Agripolis Campus, Viale dell'Università 16, Legnaro, PD, Italy

^b Institute for Sustainable Plant Protection, National Research Council of Italy, Agripolis Campus, Viale dell'Università 16, Legnaro, PD, Italy

^c Department of Land, Environment, Agriculture and Forestry – TESAF, University of Padua, Agripolis Campus, Viale dell'Università 16, Legnaro, PD, Italy

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ABSTRACT

Cover crops (CCs) are recognised as valuable for weed management, while fallow soil between cash crop seasons likely increases weed presence. Weeds may offer similar ecosystem services as CCs, although they pose a risk of seedbank buildup. This study evaluated the impact of two winter CC systems (3-year triticale cultivation, TRIT; and a 3-year succession of rye, clover, and mustard, RCM) compared to weedy fallow (WF) on weed seedbank size and composition in a 3-year 'maize (*Zea mays* L.)–maize–soybean (*Glycine max* (L.) Merr)' crop succession. After 3 years, seed density of spring/summer weeds reduced in all treatments, potentially stemming from herbicide use during cash crop seasons and tillage operations. Triticale had the lowest seedbank density (9,487 seeds m⁻²) and higher diversity (Shannon Index 6.9) compared to WF (28,543 seeds m⁻² and 4.1, respectively). Furthermore, stochastic analysis revealed a lower risk of enlarging weed seedbanks in TRIT compared to WF (for seed densities above 900 seeds m⁻²). Moreover, management practices (CCs, cash crop sowing, termination/harvest) synchronised with weed seed production and germination likely contributed to the decreasing seed density of species including *Portulaca oleracea* and *Chenopodium album*, which were reduced by 90 and 80 %, respectively, by the study's end. Over three years, autumn/winter and indifferent weed seed densities increased 4.2 times more in WF and RCM (22,638 seeds m⁻²) than in TRIT. This may be due to the varying growth rates among CC species in RCM, whereas TRIT consistently established rapidly, potentially outcompeting weeds until termination. Fallow periods between cash crops may increase weed species linked to that season and future crop–weed interference in varied crop rotations. Introducing CCs can mitigate this effect, although the choice of CC species may influence the extent of the impact.

1. Introduction

In the context of increasing global demand for sustainable agricultural practices, the directive of the European Common Agricultural Policy (CAP) 2023–2027 (https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-2023-27_en) advocates the integration of cover crops (CCs) in agricultural rotations, especially in organic production systems, emphasising their potential to enhance sustainability and reduce reliance on synthetic inputs (Smit et al., 2019). Moreover, the European Action Plan for the Development of Organic Production (https://agriculture.ec.europa.eu/farming/organic-farming/organic-action-plan_en) encourages the introduction of CC and fallow

periods as management practices in the cropping system.

Cover crops (CCs), defined as non-harvested crops cultivated in addition to the primary cash crop to enhance soil fertility and yield (Scavo et al., 2022), are recognised as a sustainable agricultural practice that provides various agroecosystem services. These services include soil health improvement, soil erosion mitigation, nutrient loss reduction, and weed control (Bergtold et al., 2019; Reicosky, 2020; Lamichhane et al., 2023). Furthermore, the literature highlights that CCs are effective components of integrated weed control management strategies (Sias et al., 2021). Historical observations indicate that certain species have a notable ability to compete with weeds, as detailed in a review by Scavo et al. (2022). They can indeed be utilised in conjunction with

* Corresponding author at: Department of Agronomy, Food, Natural Resources, Animals and Environment – DAFNAE, University of Padua, Agripolis Campus, Viale dell'Università 16, Legnaro, PD, Italy.

E-mail address: vittoria.giannini@unipd.it (V. Giannini).

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mechanical, physical, and cultural methodologies aimed at decreasing reliance on herbicide application (Gerhards and Schappert, 2020; Adeux et al., 2023), although a recent study reported the use of CCs in contexts of increased use of herbicides (Guinet et al., 2023). The introduction of CCs could be highly valorised in the context of increasing herbicide resistance phenomena, the absence of discovery of new herbicide modes of action, and more regulatory restrictions (Patzoldt et al., 2005; Price et al., 2011; Bunchek et al., 2020; MacLaren et al., 2020; Loddio et al., 2021). The role of CCs as a valuable tool within an integrated weed management strategy is highly acknowledged by farmers (Arbuckle and Lasley, 2013), who recognise the potential persistent threat posed by weeds to crop productivity, as they can compete for resources and harbour pests and diseases (Zimdahl, 2018).

Nevertheless, it has been reported in the literature that under fallow periods, weeds can provide ecosystem services similar to those offered by CCs (Wortman, 2016; Moreau et al., 2020). Thus, 'weedy fallows', which involve leaving naturally occurring weeds unmanaged in the off-season between cash crops, might appear a simpler and more affordable alternative to CCs. However, crucial concerns arise regarding their potential influence on the increment of seedbanks (Nichols et al., 2020). Progressively reducing the size of the weed soil seedbank is a central component of long-term sustainable weed management, and this can be achieved by limiting seed production below the seedbank replenishment value, that is, the amount of seeds necessary to replace all seeds lost from the seedbank due to germination, predation, or decay (Norris, 2007; Schwartz-Lazaro and Copes, 2019). The majority of troublesome weeds are annual species whose persistence is contingent upon yearly seedbank replenishment (Davis, 2006). Even seed persistence in the soil varies significantly between species (Baskin and Baskin, 2006). Many important weeds show a significant decrease in seed viability after a relatively short burial period in the soil, and several studies have reported a dramatic reduction in the seedbank size when seed return is avoided for 4–5 years (Roberts, 1968; Schweizer and Zimdahl, 1984; Burnside et al., 1986). Conversely, 1–2 years without effective weed control can completely replenish the weed seedbank (Burnside et al., 1986), frustrating years of correct weed management. Hence, there is particular significance in examining the diverse impact of utilising CCs or 'weedy fallows' on weed seedbanks. Specifically, both the analysis of the seedbank size and composition can provide valuable insights into the weed dynamics (Ryan et al., 2010).

Introducing CCs in the off-season of the primary cash crop can decrease the community mean of weeds germinating during that period (Adeux et al., 2023). Conversely, fallow periods in the off-season may augment the weed species associated with that season, potentially impairing cash crops introduced in subsequent crop rotation cycles. Concerns arise due to the mandatory crop rotation advocated by the CAP (Raffelsiefen, 2021).

Considering the maize (*Zea mays* L.)–soybean (*Glycine max* (L.) Merr.) succession, which is prevalent in various regions including the Midwest in the USA (O'Neal et al., 2005; Dold et al., 2017) and northern Italy, where 95.7 and 99.5 % of Italian maize and soybean, respectively, are cultivated (Cortignani and Dono, 2020), leaving the soil as fallow over the winter season risks increasing winter weed seedbanks, complicating weed management in subsequent autumn-sown cash crops, such as wheat and barley. Introducing CCs instead of fallow periods might have the potential to mitigate this phenomenon.

Nevertheless, it is imperative to acknowledge that weed seeds can persist in the soil for several years, creating a legacy effect that may overshadow short-term changes in management practices (Nichols et al., 2020).

These potential trade-offs and synergies associated with the use of CCs and fallow periods within agricultural rotations underscore the necessity for additional investigations. In addition, understanding the effects of winter CCs or fallow periods on weed dynamics, particularly in maize–soybean crop rotation systems, remains incomplete. Further research is warranted to address these knowledge gaps.

Within this framework, this study aimed to determine the impact of three management systems – two distinct winter CCs and one weedy fallow with no weed control – on the weed seedbank size and composition in a 3-year 'maize–maize–soybean' crop succession in northeast Italy. We examined the evolution of the species pool that typically grows during the spring–summer cash crop cycle and those that grow during the autumn–winter off-season, focusing on agronomic aspects and potential management implications.

2. Materials and methods

2.1. Site description

The field experiment spanned October 2019 to October 2022 and was conducted at an approximately 5.5-hectare site situated in the experimental farm "L. Toniolo" in Legnaro (PD), located in north-eastern Italy at coordinates 45°20'53" N, 11°57'11" E with an elevation of 6 m above sea level. The location is sited in a flat region of fluvial genesis, with soil categorised as Fulvi-calcaric Cambisol according to the classification outlined in the World Reference Base for Soil Resources (WRBRS, 2014). The site's average conditions in the upper soil layer (0–40 cm depth), based on pre-trial analyses, consisted of loamy-silty loam texture, with a soil organic matter (SOM) content of 1.4 %, total Kjeldahl nitrogen content of 0.9 g kg⁻¹, and inorganic nitrogen (NO₃-N) content of 57 mg kg⁻¹ in the soil profile at 0–40 cm. The pH ranged from 7.6 to 8.1, and the total available phosphorus potassium contents were 1.97 and 131.5 mg kg⁻¹, respectively. The prevailing climate is categorised as humid subtropical (Cfa class in Köppen classification), characterised by excessive water availability in fall and spring and water stress during the summer months (Rubel et al., 2017). Meteorological data for the experimental period were reported in detail by Raimondi et al. (2023b). The mean annual precipitation for the period spanning from 1992 to 2022 was 830 mm, whereas the mean annual temperature for the same period was 13.9°C. The minimum annual average temperature was 8.7°C, with January exhibiting the lowest temperatures (averaging −0.15°C). Conversely, the maximum annual average temperature was 18.6°C, with July recording the highest temperature (averaging 29.5°C).

2.2. Experimental layout and crop management

The experimental site of the current investigation had been managed conventionally since 1996, with a non-strict succession of maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), soybean (*Glycine max* (L.) Merr.), sorghum (*Sorghum bicolor* L.), and sugar beet (*Beta vulgaris* var. *saccharifera* L.). Details concerning crop cultivation and fertiliser application procedures were outlined by Tolomio and Borin (2019). Soil tillage operations consisted of ploughing and harrowing across all cultivated crops. Moldboard ploughing (depth: up to 35 cm) was conducted either immediately following the application of manure or liquid manure (aimed at integrating organic amendments into the soil) or closer to sowing when solely mineral fertilisers were employed. Harrowing was performed prior to seeding. Crop residues from sugar beet, soybean, and maize were integrated into the soil via ploughing, while wheat straw was harvested and utilised as a bedding material for livestock on the farm.

In the autumn of 2019, CCs were introduced. The experimental layout was a randomised split-plot comprising 2 blocks with 3 CC treatments × 2 replicates each (for a total of 4 replicates per CC treatment). The experiment unfolded over a 3-year winter CC–cash crop sequence (year 1–2019/2020; year 2–2020/2021; year 3–2021/2022). Winter CC management comprised (i) a fixed treatment (TRIT), entailing triticale (x *Triticosecale* var. *Claudius*) cultivation throughout the three years; a succession treatment (RCM), involving the sequential cultivation of three CC species (rye (*Secale cereale* L.) var. *Dukato* in year 1; crimson clover (*Trifolium incarnatum* L.) var. *Alberobello* in year 2;

mustard (*Sinapis alba* L.) var. Signal in year 3); and weedy fallow (WF), characterised by the absence of both CCs and weed control, thus reproducing 'weedy fallow' conditions wherein weed growth is permitted to optimise the ecosystem services they offer. The cash crops included silage maize (*Zea mays* L.; Pioneer P-2088, FAO-700) in years 1 and 2, and soybean (*Glycine max* (L.) Merr.; c.v. Hiroko) in year 3.

After the harvest of the previous spring crops, subsoil tillage (30 cm depth) and rolling harrowing were performed in September across all plots, including those of the WF treatment. The CCs were sown in the RCM and TRIT treatments on October 10, 2019, October 9, 2020, and September 24, 2021. The seeding rates were 160 kg ha⁻¹ for rye and triticale, 40 kg ha⁻¹ for crimson clover, and 35 kg ha⁻¹ for mustard. Termination was performed every year on March 31st in all treatments through shredding with a rotary mulcher, incorporating the residues at stem elongation for grasses, before flowering at the late bud stage for clover, and at flowering for mustard. In the first year, rye CC produced more biomass (2.5 Mg ha⁻¹) than triticale (1.9 Mg ha⁻¹) and WF (0.7 Mg ha⁻¹). In the second year, treatments averaged 1.9 Mg ha⁻¹ with no significant differences. In the third year, mustard CC had a higher biomass (3.9 Mg ha⁻¹) than WF and triticale (2.5 Mg ha⁻¹). More details about the CC's performances are reported in Raimondi et al. (2023) a, b).

The cash crops were sown on April 17, 2020 (maize: 7.5 plants m⁻²), April 26, 2021 (maize: 7.5 plants m⁻²), and May 10, 2022 (soybean: 45 plants m⁻²). Harvesting was conducted using a combine harvester on August 25, 2020 and 2021, and October 13, 2022.

Tillage operations for cash crop sowing across all treatments comprised subsoil tillage at a depth of 30 cm after CC termination and the use of a rolling harrow for cash crop seedbed preparation. Maize was fertilised with 200 kg N ha⁻¹ (16 % urea before sowing and the remainder as topdressing on May 25, 2020, and May 29, 2021), 80 kg of P₂O₅ ha⁻¹ (superphosphate), and 80 kg of K₂O ha⁻¹ (potassium sulphate) before sowing. Soybean was fertilised with only 46 kg of P₂O₅ ha⁻¹ before sowing. Annual irrigation was applied during the cash crop cycle, amounting to 40 mm in 2020, 30 mm in 2021, and 40 mm in 2022. Weeds were controlled in maize with the pre-emergence application of terbuthylazine (750 g ai ha⁻¹), S-metolachlor (1250 g ai ha⁻¹), and mesotrione (150 g ai ha⁻¹) and post-emergence mechanical control (hoeing). For soybean, glyphosate (1550 g ae ha⁻¹) was applied before crop sowing to clean the seedbed, and pre-emergence control was performed at sowing with a tank mixture of clomazone (108 g ai ha⁻¹), metribuzin (175 g ai ha⁻¹), and pendimethalin (455 g ai ha⁻¹). Lambda-cyhalothrin (25 g ai ha⁻¹) was applied in mid-July in 2020 and 2021 for pest control in maize.

2.3. Sample collection

Fifteen soil cores of the 0–10 cm soil layer were collected per replicate at the beginning of the experiment in October 2019 (Assay 1) and at the end of the experiment in October 2022 (Assay 2) after the harvest of the cash crop and before sowing of the following autumn CC. Soil cores were collected using a manual sampler (diameter 5 cm), and each core was handled separately throughout the successive steps for seedbank determination, which was conducted with the seedling emergence method as described by Otto et al. (2023). Seedbank determination was conducted separately for soil samples in Assays 1 and 2 to avoid detrimental effects of long-term storage on seed vitality and germinability. After collection, in both assays, seedbank determination was performed in the greenhouse for approximately 18 months. During this time span, quantification and identification of emerged seedlings was performed every 1–3 weeks and was interrupted when no further seedling emergence was observed for approximately 2 months. For both assays, at the end of seedbank determination, the total number of seedlings observed for the different weed species was averaged across 15 soil samples of each replicate, and the seedbank density was expressed as seeds m⁻².

Weed species were categorised into biological (plant life-forms) and ecophysiological (periodicity types) groups according to classifications

by Raunkiaer (1934) and Montegut (1982), and referring to a previous study on local flora by Zanin et al. (1997).

To better investigate how shifts in the botanical composition of seedbanks could impact crop management, weed species were also classified into two agronomical-functional groups: one including the species mainly present during the spring–summer cash crop season and potentially harmful to the main crops ('Cash Crop group', CG) and (ii) one for the species mainly present during the autumn–winter CC season in our study area ('Off-season group', OG). This classification was based on ecophysiological groups as adapted to local conditions by Zanin et al. (1997), with spring- (Sp) and summer- (Su) germinating species included in CG while autumn- (Au) and winter- (W) germinating or indifferent (In) species included in OG.

2.4. Species diversity and community similarity indices

The differences in the diversity of the weed community were analysed using diversity metrics, such as the Shannon–Wiener diversity index (H) (Eq. 1), the Simpson index (D) (Eq. 2) (Simpson, 1949; Jost, 2006), and Pielou's evenness index (J) (Eq. 3) (Sienkiewicz, 2010). Both H and D are diversity indices. However, H responds most strongly to changes in the importance of the rarest species, whereas D responds most strongly to changes in the proportional abundance of the most common species (Nagendra, 2002).

Specifically, the H index is calculated by taking the number of each species, the proportion each species is of the total number of individuals, and sums the proportion times the natural log of the proportion for each species. Since this is a negative number, we then take the negative of the negative of this sum. The higher the number, the higher the species diversity (Jost, 2006).

D characterises the species dominance of the community. It expresses the probability of two individuals of the same species being present in a random sample. For this index, 0 indicates infinite diversity and 1 indicates no diversity; hence, the higher the D value, the lower the diversity (Sienkiewicz, 2010).

Evenness (J index) describes how a given species richness is distributed and ranges from 0 to 1, with 1 signifying that all species are equally present. It is a measure of abundance heterogeneity among the species in a community (Jost, 2006).

All indices were computed for each experimental replicate using the following equations:

Shannon–Wiener index (H)

$$H = - \sum_{i=1}^s p_i \ln(p_i) \quad (1)$$

Simpson's index (D)

$$D = \sum_{i=1}^s p_i^2 \quad (2)$$

Pielou's evenness index (J)

$$J = \frac{H'}{\ln(S)} \quad (3)$$

where p is the proportion (n/N) of individuals of one particular species found (n) divided by the total number of individuals found (N), \ln is the natural log, Σ is the sum of the calculations, and s is the number of species.

2.5. Statistical analysis

Descriptive statistics were computed for all datasets to examine the main features of data distribution, and normality was assessed using Shapiro–Wilk's test.

All response variables were modelled as a function of the CCs (WF, TRIT, RCM), Assay (1, 2), and interaction between them as fixed factors, whereas block was included in the models as a random factor.

Generalised linear models (GLM) (R function 'glmer') (McCulloch and Neuhaus, 2013) with different distributions were fitted for each response variable. A GLM model with a 'log-linked Poisson' distribution was fitted for the seedbank density of the two agronomical functional groups (CG and OG). Six GLM models were fitted for (i) 3 CG species with the highest seed density in Assay 1 (*Chenopodium album* L.; *Echinochloa crus-galli* (L.) P.Beauv; *Portulaca oleracea* L.) and (ii) 3 OG with the greatest seed density in Assay 2 (*Capsella bursa-pastoris* (L.) Medik.; *Poa annua* L.; *Veronica persica*). All of the models had a 'log-linked Poisson' distribution except for *P. annua*, which was fitted with a log-linked 'negative-binomial' distribution. The post hoc analyses were conducted using the emmeans package (Lenth et al., 2018) to calculate the least-squares means, and all pair-wise comparisons were conducted using Tukey for single contrasts or Sidak for multiple contrasts at a significance level of 0.05.

Density data (seed m^{-2}) were normalised with a min-max scaling normalisation using a 'caret' library to reduce the dispersion of the datasets. The preProcess() function enabled us to scale the value to a range of 0–1 using method = c('range') as an argument (Patro and Sahu, 2015). For graphical representation, all densities (seed m^{-2}) were reported as normalised (min-max scaling) to facilitate the visualisation of values across a consistent scale in the graphs.

We employed a first- and second-order stochastic dominance analysis to compare weed seedbank density cumulative distribution curves between the three investigated treatments (TRIT, RCM, and WF) of Assay 2 (Levy, 1992; Nichols et al., 2020). Given a stochastic variable, stochastic dominance analysis is used to identify the likelihood of favourable outcomes for a given scenario (Nichols et al., 2020). In the present case study, the assumption was that farmers aim to minimise the magnitude of the weed seedbank using different land management systems. Therefore, the inverse of the cumulative probability distribution was used to evaluate outcomes associated with the use of the three CC treatments. According to first-order stochastic dominance, a treatment dominates when, at a given value of weed seedbank density, the value of the inverse of the cumulative distribution curve is greater than that of another treatment. For a given range of seedbank density, the area under the curve (second-order statistics) determines the risk associated with a given treatment; i.e. the increased magnitude of the area under the curve within a given density range correlates with an elevated risk of exhibiting density within said range (Hardaker et al., 2004).

All analyses were performed using R software (R Core Team, 2021).

3. Results

3.1. Overview of seedbank assays

The total weeds' average density was significantly affected by the interaction between the CC treatments and Assay (Fig. 1). The highest and lowest total weed densities were registered in Assay 2, specifically in the WF (28,543 seed m^{-2}) and TRIT (9487 seed m^{-2}) treatments, respectively. None of the other treatments showed significant differences (20,592 seed m^{-2} , on average).

As shown in Tables 1 and 1S, in Assay 1, *Portulaca oleracea* accounted for 62.5 % of the total seed density, with the other top 6 species (*Echinochloa crus-galli*; *Digitaria sanguinalis* (L.) Scop.; *Chenopodium album*; *Capsella bursa-pastoris*; *Veronica persica*; *Poa annua*) collectively constituting an average of 5.6 % of total seed density and 33.7 % overall. Among these top 7 species, representing over 95 % of total seed density observed (Assay 1), 3 germinated during the CC-growing season (*Capsella bursa-pastoris*; *Veronica persica*; *Poa annua*).

Specifically, *Portulaca oleracea* and *Echinochloa crus-galli* represented the first and second highest percentages of total average seed density, respectively, in all treatments. The former represented 82.5 % in WF, 42.3 % in TRIT, and 54.1 % in RCM. *Echinochloa crus-galli* showed an average of 4.9 % in WF, 14.7 % in TRIT, and 8.4 % in RCM. The top 5 species (*Digitaria sanguinalis*; *Chenopodium album*; *Capsella bursa-pastoris*;

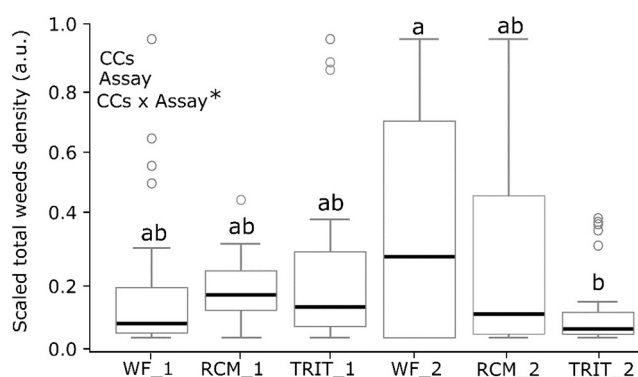


Fig. 1. The density of total weeds species (a.u. = arbitrary unit. Data normalized using min-max scaling normalization) measured in the Assays conducted at the beginning (1) and the end of the experimentation (2) in each CC treatment (WF- weedy fallow; RCM- 3-year CC succession with rye, clover, and mustard in the year 1, 2, 3 respectively; TRIT- 3-year cultivation of triticale as CC). Lowercase letters indicate significant differences among CC treatments and Assay - significance (p -value ≤ 0.01) obtained with the Sidak post hoc test. The box shows the quartiles of the dataset while the whiskers extend to show the rest of the distribution.

Veronica persica; *Poa annua*) accounted for a total of 10.7 % in WF, 36.8 % in TRIT, and 33.1 % in RCM.

In Assay 2 (Tables 1 and 2S), the cumulative average density of all species recorded in the WF treatment amounted to 28,543 seeds m^{-2} (24,257–33,386 seeds m^{-2}), whereas for TRIT, it accounted for 9488 seeds m^{-2} (6953–11,624 seeds m^{-2}). For RCM, it was equal to 21,669 seeds m^{-2} (14,225–86,677 seeds m^{-2}).

In Assay 2 (Tables 1 and 2S), *Veronica persica* represented 35.6 % of the total seed density, whereas *Capsella bursa-pastoris* and *Poa annua* showed an average of 15 %. The other top 5 species (*Stellaria media* (L.) Vill; *Cerastium holosteoides* Fr; *Portulaca oleracea*; *Chaenorhinum minus* (L.) Lange; *Lamium purpureum* L.) represented 5.6 % of the total seed density, on average, and 28.2 %, overall. Among the top 8 species measured, which overall accounted for almost 94 % of the total seed density in Assay 2, 6 germinated during the CC-growing season (*Veronica persica*; *Capsella bursa-pastoris*; and *Poa annua*; *Stellaria media*; *Cerastium holosteoides*; *Lamium purpureum*).

Veronica persica represented the highest percentage of the total average seed density in both the WF (43.9 %) and RCM (37.7 %) treatments. In both treatments, the top 7 species (*Poa annua*; *Capsella bursa-pastoris*; *Cerastium holosteoides*; *Stellaria media*; *Lamium purpureum*; *Portulaca oleracea*; *Chaenorhinum minus*) constituted 7.3 and 8.1 % of the total average seed density in WF and RCM, respectively. The remaining species represented an average of 0.2 % (WF) and 0.3 % (RCM).

In the TRIT treatment, 26.3 % of the total average seed density was represented by *Stellaria media*, followed by *Poa annua* (21.4 %). *Portulaca oleracea*, *Cerastium holosteoides*, *Chaenorhinum minus*, *Veronica persica*, *Chenopodium album*, *Capsella bursa-pastoris*, *Cardamine hirsuta* L., and *Digitaria sanguinalis*, constituting 6.2 % of the total average seed density, whereas all the remaining species constituted 0.2 %.

3.2. Weed agronomical functional group

The species belonging to CG exhibited a significantly higher average density (17,352 of seed m^{-2}) in Assay 1 compared to 2504 seed m^{-2} in Assay 2 (Fig. 2). In Assay 1, there were 18 CG species, representing 85.9 % of the total density of species (CG + OG). In contrast, in Assay 2, only 15 SG species were observed, representing 12.6 % of the total density of species (group S + group W). No significant differences were observed among treatments in Assay 2.

Among the 3 most abundant CG species in Assay 1, *P. oleracea* and *C. album* were significantly affected by the Assay (Fig. 3), with the last

Table 1
Average (Minimum - Maximum) seed density m^{-2} of the major weed species identified in the seed bank assays at experiment beginning (Assay 1) (2019) and end (Assay 2) (2022). The results are also presented by cover crop treatment (WF- weedy fallow; RCM- 3-year CC succession with rye, clover, and mustard in the year 1, 2, 3 respectively; TRIT- 3-year cultivation of triticale as CC). Each species was classified into biological and ecophysiological groups.

Species	Assay 1			Assay 2				
	BG ¹	EG ²	Seed m^{-2} (3)	Seed m^{-2} (3)	Seed m^{-2} (3)	Seed m^{-2} (3)	Seed m^{-2} (3)	Seed m^{-2} (3)
<i>Portulaca oleracea</i> L.	Th	Su	20816.3 (3348–57547)	7339.7 (2070–17957)	9803.6 (6843–13384)	1287 (212–2335)	1127.9 (849–1327)	1075 (531–1486)
<i>Echinochloa crus-galli</i> (L.) P. Beauv.	Th	Su	1247.3 (0–4868)	2547.7 (34–8458)	1531.3 (987–2072)	0	39.8 (0–531)	199 (53–531)
<i>Digitaria sanguinalis</i> (L.) Scop.	Th	Su	153.4 (0–424)	2063.7 (84–7371)	2425.2 (0–9647)	40 (0–106)	199.0 (0–425)	13 (0–53)
<i>Chenopodium album</i> L.	Th	Sp/ Su	79.6 (159–1513)	192.1 (637–2242)	739.9 (541–1064)	146 (53–318)	384.8 (159–902)	66 (53–106)
<i>Capsella bursa-pastoris</i> (L.) Medik. subsp. <i>bursa-pastoris</i>	Th	In	1066.9 (416–1743)	881.1 (647–1019)	1182.6 (333–1805)	7033 (5892–7962)	305.2 (159–531)	2057 (902–2707)
<i>Veronica persica</i> Poir.	Th	In	428.3 (33–779)	786.1 (425–1698)	1025.5 (34–1539)	12540 (10244–16083)	570.6 (318–796)	8160 (5839–10563)
<i>Poa annua</i> L.	Th	In	262.2 (222–318)	918.8 (140–2208)	633.2 (208–1008)	2799 (2335–3238)	2030.3 (1752–2229)	3715 (2548–5361)
<i>Cerastium holosteoides</i> Fr.	Th.	In	21.8 (0–212)	192.1 (53–318)	156.1 (53–238)	809 (318–1380)	1074.8 (796–1433)	1738 (265–3769)
<i>Stellaria media</i> (L.) Vill.	Th	In	26.5 (0–106)	256.4 (0–584)	67.9 (0–204)	849 (531–1327)	2494.7 (106–5169)	1367 (1274–1486)
<i>Lamium purpureum</i> L.	Th	In	78.6 (0–227)	74.8 (34–106)	143.8 (87–265)	1061 (584–1858)	66.3 (0–106)	1353 (212–2548)
<i>Chaenorhinum minus</i> (L.) Lange subsp. <i>minus</i>	Th	Sp	51.0 (0–135)	139.1 (53–238)	86.0 (0–170)	769 (425–1433)	743 (425–1221)	968 (425–1380)
Other species (30)			2360.9 (0–1247)	4745.8 (0–2547)	2748.9 (0–1513)	1207.5 (0–464)	451.2 (0–238)	955.4 (0–371)
Total			25229.3 (0–20816.3)	17332.3 (0–7339.7)	18138.5 (0–9803.6)	28543 (0–12539)	9487.8 (0–2494)	21669 (0–8160)

¹ Biological group (plant life-forms) classification according to Raunkiaer (1934) with Th = annual Therophyte; Hr = Hemicryptophyte; G = Geophyte
² Ecophysiological groups (periodicity types) according to Montegut (1982) and Zanin et al. (1997) with Sp, Su, Au, W = spring, summer, autumn, winter germinating species and In = indifferent species
³ Minimum and Maximum values are reported to illustrate the range variability among replicates

Table 2
Shannon Index (H'), Simpson Index (D'), Evenness (J') values (\pm SE) calculated in each cover crop (CCs) treatment, in both Assay 2019 (B) and 2022 (E) (WF- weedy fallow; RCM- 3-year CC succession with rye, clover, and mustard in the year 1, 2, 3 respectively; TRIT- 3-year cultivation of triticale as CC). Different lowercase letters indicate significant differences among CC treatments and Assay; uppercase letters represent significant differences between Assays - Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1) obtained with Sidak post hoc test.

Assay	CCs	Indices		
		H'	D'	J'
1	WF	2.6 \pm 0.7 b	0.6 \pm 0.2 a	0.3 \pm 0.09 b
	RCM	4.2 \pm 0.8 ab	0.4 \pm 0.1 ab	0.4 \pm 0.05
	TRIT	6.3 \pm 2.9 a	0.3 \pm 0.2 b	0.5 \pm 0.2 a
2	WF	5.5 \pm 0.5 b	0.3 \pm 0.1 a	0.5 \pm 0.02 b
	RCM	6.9 \pm 0.9 ab	0.2 \pm 0.1	0.6 \pm 0.03
	TRIT	7.4 \pm 1.2 a	0.2 \pm 0.1 b	0.6 \pm 0.0
Assay		**	**	**
CCs		**	**	**
Assay* CCs				4 a

one being also influenced by the CC treatment. *Echinochloa crus-galli* was affected neither by the factors under analysis nor by their interactions. *Portulaca oleracea* showed higher seed density in Assay 1 (12,653 seed m^{-2}) compared to Assay 2 (1163 seed m^{-2}), similar to *C. album* (1094 seed m^{-2} in Assay 1 and 199 seed m^{-2} in Assay 2) (Fig. 3). *Chenopodium album* showed a higher seed density in the TRIT treatment (1063 seed m^{-2}) compared to both WF and RCM (438 seed m^{-2} , on average). The density of species belonging to OG varied between the two

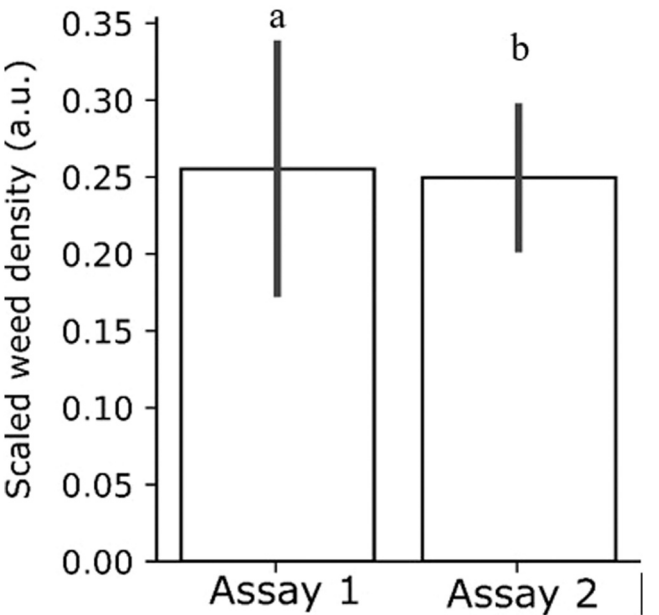


Fig. 2. Density of weeds species potentially present during the cash crop season (CG) (a.u. = arbitrary unit. Data normalized using min-max scaling normalization) measured in the Assays conducted at the beginning (1) and the end of the experimentation (2) averaged across all treatments. Error bars represent the standard error.

Assays and showed an opposite result compared to the CG species. A significantly higher total average density was measured in Assay 2 (17,396 seed m^{-2}) compared to Assay 1 (2881 seed m^{-2}). A total of 16

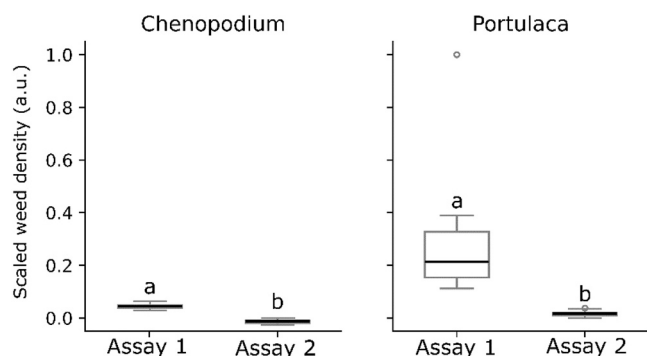


Fig. 3. The seed density of *Chenopodium album* L., and *Portulaca oleracea* L.; two CG species (potentially present during the cash crop season) measured in the Assays conducted at the beginning (1) and the end of the experimentation (2). a.u. = arbitrary unit, data normalized using min-max scaling normalization. Lowercase letters indicate significant differences between Assay - significance (p -value ≤ 0.01) obtained with the Tukey post hoc test. The box shows the quartiles of the dataset while the whiskers extend to show the rest of the distribution.

OG species were observed in Assay 1, comprising 14.1 % of the total average density of the species. In contrast to Assay 2, 14 OG species were registered, representing 87.4 % of the total species density. Additionally, the total average density of OG species was significantly affected by the Assay \times CC interaction effect. Under both WF and RCM, Assay 2 showed the highest OG species density (22,638 seed m^{-2}), which was 4.8 times higher than that of all other treatments (Fig. 4).

The three most abundant OG species in Assay 2 were all significantly affected by the CC \times Assay interaction (Fig. 5). *Capsella bursa-pastoris* showed the highest and lowest seed densities in Assay 2, with the highest density in WF (7033 seed m^{-2}) being 22 times higher than the lowest density measured in TRIT. Under RCM, in Assay 2, the *C. bursa-pastoris* seed density (2057 seed m^{-2}) was lower than the maximum recorded values but higher than the minimum observed in TRIT. All the other treatments showed intermediate values (1044 seed m^{-2}), which did not differ significantly between RCM and TRIT in Assay 2.

Poa annua exhibited the highest seed density under RCM in Assay 2 (3715 seed m^{-2}), whereas the lowest values were registered in WF in Assay 1 (262 seed m^{-2}). Intermediate values were registered in all other

treatments, with WF in Assay 2 (2800 seed m^{-2}) not significantly different from the highest values (RCM in Assay 2) and the lower value registered in TRIT in Assay 2 (2030 seed m^{-2}). The latter was similar to TRIT and RCM in Assay 1 (776 on average), which did not differ from the lowest density value measure in WF in Assay 1.

Veronica persica had the highest seed density in WF in Assay 2 (12,540 seed m^{-2}), followed by the value registered in RCM in Assay 2 (8161 seed m^{-2}). All other treatments showed the lowest seed density (703 seed m^{-2} , on average).

3.3. Seedbank community composition

All biodiversity indices were significantly affected by the Assay and CC treatment. No Assay \times CC interaction effect was detected (Table 2). All indices were significantly higher at the end of the experiment (Assay 2) compared to the beginning (Assay 1). The H diversity index was 47.3 % times lower (on average) in Assay 1 compared to Assay 2 ($H=6.5$). A value of 0.22, on average, was measured for the D index in Assay 2, whereas an average $D=0.4$ was observed in Assay 1. The Pielou's evenness value measured in Assay 2 was, on average, 25 % higher than the value measured on average in Assay 1 ($J=0.4$).

The H diversity index was higher under TRIT ($H=6.9$) than under WF ($H=4.1$). There were no differences in H between RCM and the other CC treatments. Opposite results were observed for the diversity dominance index D. Higher values were registered in WF ($D=0.4$) compared to TRIT ($D=0.2$). RCM was not significantly different from the other treatments.

Pielou's evenness followed the same pattern as the H diversity index, showing higher values in TRIT ($J=0.6$) compared to WF ($J=0.4$), with RCM exhibiting no significant difference.

3.4. Risk of increasing seedbanks

Stochastic dominance analysis (Fig. 6) showed that under TRIT and WF, with a seedbank density lower than 900 seeds m^{-2} , there was no risk of increasing the seedbank. In contrast, as seedbank densities increased above 900 seeds m^{-2} , the probability of having a greater seedbank was consistently higher under WF than under TRIT. The larger area under the curve of WF compared to TRIT (Fig. 6) was proportional to the higher risk of increasing the weed seedbank density. Under RCM, the curve showed a similar pattern to that under WF, regardless of the seedbank density. Both RCM and WF exhibited similar areas under their curves, proportional to their similar risk of increasing weed seedbank densities.

4. Discussion

The observed variability among the theses or replicates at the outset of the experiment (Assay 1) is not ascribable to the experimental factor; rather, it should be attributed to casual spatial variability. This variability serves as an initial point from which we evaluate evolutionary processes.

The introduction of CCs and 'weedy fallow' control during the off-season of a maize-maize-soybean succession in the present study had established intervals of undisturbed soil (without tillage operations between CC sowing and termination) lasting 5 months, thus fostering a "window of opportunity" for weed proliferation. During these periods, autumn-emerging species and other indifferent species might have potentially had the temporal space to complete their life cycles and disseminate. However, introducing specific CC species rather than leaving the soil as 'weedy fallow' prevented the total weed density from soaring (Fig. 1), confirming the results of previous studies reviewed by Osipitan et al. (2019) and Sias et al. (2021) and the findings of Alonso-Ayuso et al. (2018). In this study, sowing triticale as a CC for three consecutive autumns led to a reduction in total weed density, whereas the succession of rye-clover-mustard CCs kept it steady. Such findings validate prior research reporting the potential of grass species,

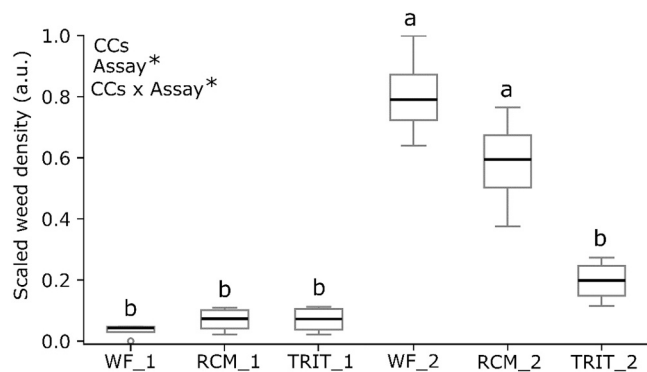


Fig. 4. The density of weed species potentially present during the autumn/winter off-season (OG) (a.u. = arbitrary unit. Data normalized using min-max scaling normalization) measured in the Assays conducted at the beginning (1) and the end of the experimentation (2) in each CC treatment (WF- weedy fallow; RCM- 3-year CC succession with rye, clover, and mustard in the year 1, 2, 3 respectively; TRIT- 3-year cultivation of triticale as CC). Lowercase letters indicate significant differences among CC treatments and Assay - significance (p -value ≤ 0.01) obtained with the Sidak post hoc test. The box shows the quartiles of the dataset while the whiskers extend to show the rest of the distribution.

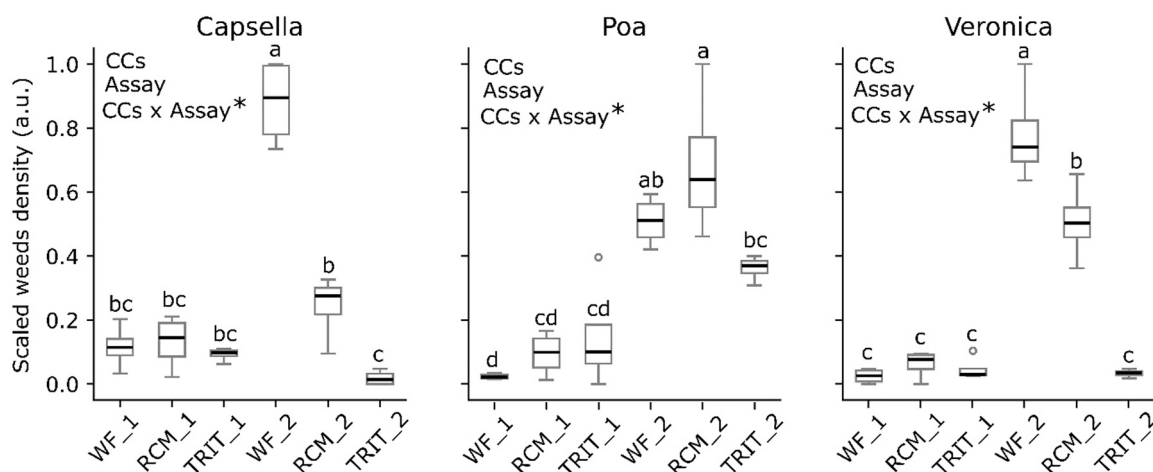


Fig. 5. The seed density of *Capsella bursa-pastoris* (L.) Medik.; *Veronica persica* Poir.; *Poa annua* L., (potentially present during the autumn/winter off-season - OG) measured in the Assays conducted at the beginning (1) and the end of the experimentation (2) in each CC treatment (WF- weedy fallow; RCM- 3-year CC succession with rye, clover, and mustard in the year 1, 2, 3 respectively; TRIT- 3-year cultivation of triticale as CC). a.u. = arbitrary unit, data normalized using min-max scaling normalization. Lowercase letters indicate significant differences among CC treatments and Assay - significance (p-value ≤ 0.01) obtained with Sidak post hoc test. The box shows the quartiles of the dataset while the whiskers extend to show the rest of the distribution.

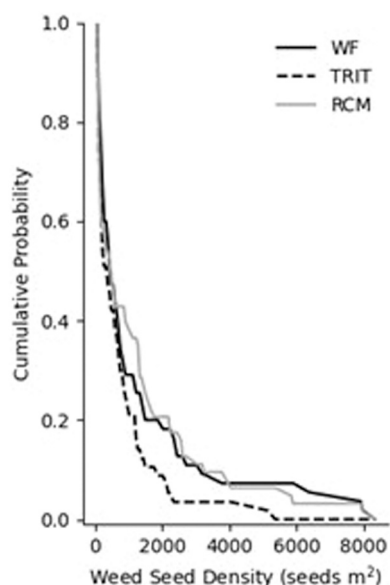


Fig. 6. Cumulative distribution curves of seedbank size for each cover crop (CC) treatment (TRIT- 3-year cultivation of triticale as CC; RCM- 3-year CC succession with rye, clover, and mustard in the year 1, 2, 3 respectively; WF- weedy fallow) compared with a first- and second-order stochastic dominance analysis (Levy, 1992). The area under the curve has to be considered proportional to the risk of increasing weed seedbank density.

particularly triticale (Smith et al., 2019), to suppress weeds (Osipitan et al., 2019). In addition to reducing the total weed density, the introduction of triticale as a CC augmented the α -diversity and abundance heterogeneity among the weed species compared to the 'weedy fallow' soil, confirming previous observations (Edesi et al., 2012; Jastrzebska et al., 2013; Gerasimova and Mitova, 2020). Similar results were not observed in the RCM treatment (with the succession of three CC species). The effects (positive or negative) of CCs on the weed community remain unclear and contradictory in many studies (Moonen et al., 2004; Campiglia et al., 2012; Andrade et al., 2017; Restuccia et al., 2020), frequently depending on the site-specific conditions of field experiments (Barberi, 2002) and the selected CC species.

Maintaining weed diversity is crucial for sustainable crop

production, as the reduction in diversity within weed communities fosters the prevalence of a few highly adapted, troublesome weed species. This outcome amplifies competition with crops and escalates expenditures associated with weed management (Storkey and Neve, 2018). However, reducing the potential competition of weeds with the cash crop has a crucial role in agroecosystems, where the maintenance of cash crop yield is of primary importance (Milberg and Hallgren, 2004; Den Hollander et al., 2007). Consequently, the identification of agricultural practices capable of preserving weed diversity while minimising yield losses has been recognised as a critical research priority in weed science (Neve et al., 2018). In this context, the results of the present study revealed that triticale CCs showed a notable performance after 3 years, as it diminished the total quantity of weeds and increased their diversity without diminishing the maize or soybean yield compared to the other treatments (Raimondi et al., 2023a). In addition, based on the stochastic analysis we performed, triticale CC exhibited a lower risk of enlarging weed seedbanks compared to no-cover systems (in the case of weed seed densities above 900 seeds m⁻²). A similar result was observed by Nichols et al. (2020) in a maize-soybean rotation with rye as a winter CC, where the seed density threshold was lower (300 seed m⁻²). Nevertheless, Nichols et al. (2020) confirmed the observations of the present study, as they registered a higher risk of having increased weed seed density in the control treatment compared to grass CCs.

In addition to the effects on the total weed seedbank, it is widely reported that the temporal placement of CCs (either summer or winter CCs) can significantly determine changes in the weed communities (Mirsky et al., 2010), regardless of the CC species selected. Indeed, autumn-sown CCs coexist and therefore might have a direct competitive effect on autumn and winter-emerging weeds, while they can exert only indirect effects, such as the promotion or inhibition of seed germination, on spring- and summer-emerging weeds.

The findings from the current study revealed a decrease in seed density of spring- and summer-emerging weeds (CG) following both CCs and 'weedy fallow' soil. These results align with prior research by Fried et al. (2012) and Adeaux et al. (2023). However, in both studies, such outcomes have been attributed to herbicide applications and tillage operations during cash crop cultivation rather than to CC introduction. Despite indications from the literature suggesting that CC residues may impede weed germination through both direct and indirect mechanisms, such as the mulching effect or allelopathy (Mohler, 2001; Reberg-Horton et al., 2005), it is conceivable that agronomic practices such as tillage and herbicide application might exert a strong impact, potentially

masking the impact of CCs (Adeux et al., 2023), regardless of the species used.

Nonetheless, in the current study, the decline in spring- and summer-emerging species could be plausibly linked to alterations in the windows of opportunity for their growth related to CC introduction. This phenomenon was particularly significant for the predominant species within CG, *P. oleracea*, which ranks among the most prevalent weed species in maize cultivation in Italy (Vidotto et al., 2016). A substantial reduction (approximately 90 %) in seedbank density was recorded for *P. oleracea* over the three years. The species under consideration, which requires high temperatures for seed germination, commonly displays seedling emergence during the summer months (Baskin and Baskin, 1988). However, it can germinate during late summer or early autumn and complete its life cycle under cooler conditions by extending its life cycle (Feng et al., 2015). Thanks to this flexible and opportunistic behaviour, *P. oleracea* can capitalise on the late summer to early autumn period, following cash crop harvest (e.g., maize), when temperatures remain relatively high in the study area, to grow and produce seeds before subsequent tillage operations (typically occurring in late October). This mechanism potentially explains its initially high seed density at the beginning of the experiment. The introduction of fall-sown CCs led to tillage operations for seedbed preparation in late summer or early autumn, immediately after maize or soybean harvest, curtailing the time available for *P. oleracea* to produce seed during this period compared to previous conditions. Notably, in our study, the weedy fallow, unlike the typical soil management adopted prior to the experiment, involved soil tillage in late summer–early autumn. This intervention similarly reduced the period of time available to grow and produce seeds (“window of opportunity”) for these species, as observed in the other treatments. Disruption of this advantageous mechanism may have substantially reduced its density. This underscores the importance of synchronising management practices with weed germination periodicity for effective weed control, as highlighted by Mirsky et al. (2010).

Another troublesome spring- and summer-emerging weed, *C. album*, which is the most common weed species in maize fields in Italy (Vidotto et al., 2016), experienced a distinct process. Progressive accumulation over the years of its seeds in the seedbank, thanks to their remarkable longevity (Brown, 1946), might justify the high abundance of this species at the beginning of the experiment, due to the historical cultivation of these two cash crops (Tolomio and Borin, 2019). However, a decline of almost 80 % in its seedbank density was recorded within the 3 years of the experiment. The species has been reported to have two germination peaks in Europe, one between March and May and the other between August and October (Fryer and Makepeace, 1977). These two moments, in our experiment, corresponded to CC termination–cash crop sowing and cash crop harvest–CC sowing times. The soil tillage operations performed in these periods (at an average depth of 30 cm) might have affected germination and seedling establishment of *C. album* (Weber et al., 2017), considering that the maximum depth from which buried seeds can emerge is 5 cm (Korsmo et al., 1981). This led to a decrease in seedbank size due to fatal germination and the early killing of emerged seedlings. Moreover, optimal control of this species was achieved during the three growing seasons of the cash crops, further impeding the replenishment of the seedbank, which was also diluted along the soil profile by ploughing.

Examining autumn, winter-emerging, and indifferent species that coexist and potentially compete with CCs and autumn-sown crops, their most significant increase occurred in the ‘weedy fallow’ (WF). This suggests that the absence of vegetative cover and competition, regardless of the CC species, during the winter season allowed weeds to proliferate, a phenomenon extensively documented in the literature (Moonen and Barberi, 2004; Campiglia et al., 2012; Adeux et al., 2022). This finding holds particular importance in light of regulations advocating for fallow periods as an alternative to CCs in organic production systems (<https://agriculture.ec.europa.eu/farming/organic-farming>

[/organic-action-plan_en](#)). Incorporating ‘weedy fallow’ periods during the off-season of the cash crop may increase the seedbank of weed species characteristic of that season, thereby potentially disrupting the cultivation of subsequent cash crops. This observation is confirmed by the results of a meta-analysis conducted by Wortman (2016). The author argues that although the concept of a ‘weedy fallow’ may offer various ecosystem services, it can result in potential crop–weed interference (both direct and indirect) in diversified rotations in the future. In contrast, integrating CCs has been reported as a promising system-based weed control method (Liebman and Davis, 2009), offering long-term management potential (Riemens et al., 2007) in both organic and conventional farming (Kloen and Daniels, 2000). The presence of vegetative cover is widely reported to compete with weeds sharing the same growing season (Adeux et al., 2022), although the extent of these effects may vary depending on the CC species (Rueda-Ayala et al., 2015; Baraibar et al., 2018). The succession of rye, clover, and mustard in the RCM treatment had a similar effect to WF treatment on the total seedbank density of OG. This could be attributed to the variation in growth rates among CC species, which are widely recognised to affect their competitive interactions with weeds (Brennan and Smith, 2005; Baraibar et al., 2018). Triticale demonstrated rapid establishment and early growth during autumn, with biomass production (1.9 Mg ha^{-1}) 72.7 % higher than rye by the end of February 2020, and 71.4 % higher than clover (0.7 Mg ha^{-1}) by the end of January 2021 (Raimondi et al., 2023a). This growth pattern may have reduced weed proliferation during late autumn and early winter in TRIT compared to RCM in the first two years. However, the lack of annual seedbank data prevented us from confirming this hypothesis.

Different processes occurred with the mustard CC, known for its early growth in northern Italy (Gabbrielli et al., 2022), but it is often vulnerable to winterkill due to factors such as frost (Björkman et al., 2015; Gabbrielli et al., 2022). As detailed in Raimondi et al. (2023a), in the present study, mustard exhibited rapid growth and development in autumn with biomass production (2.0 Mg ha^{-1}) 81.8 % higher than triticale by the end of February, confirming its potential efficacy for winter weed control (Osipitan et al., 2019). However, it was subsequently killed by frost in February. This early death likely created ample space for the growth of opportunistic weed species capable of emerging towards the end of winter and completing their life cycle before spring crop seedbed preparation. This effect might have been particularly pronounced in our study, as mustard CC was followed by soybean, resulting in tillage operations being conducted several weeks later than for maize sowing, thereby allowing additional time for weed development. Similar findings were reported by Grimmer and Masiunas (2004), who observed that mustard had a weed density comparable to bare soil at spring crop sowing.

For species such as *V. persica* and *C. bursa-pastoris* (two of the three species with the highest seed density at the end of the experiment), they both thrived significantly in the ‘weedy fallow’ condition, whereas both CC treatments, regardless of the CC species, effectively restrained their proliferation, confirming the previous findings of Adeux et al. (2022).

In contrast, *P. annua* exhibited a higher and similar seed density in WF and RCM compared to TRIT. The increased prevalence of this species in the RCM treatment may be attributed to the presence of a winter-killed mustard in the final experimental year. However, the lack of annual seedbank data prevented us from tracking the development pattern of this species over the years in the RCM treatment. In the third year, during the late winter to early spring period, which coincides with the *P. annua* flowering stage in the experimental region (Adeux et al., 2022), elevated soil nitrate levels were observed in mustard plots compared to triticale, indicating an earlier onset of decomposition and N release from CC residues (Raimondi et al., 2023b). These conditions likely facilitated the growth of nitrophilic *P. annua* (Warwick, 1979). A comparable scenario, wherein mustard performance and N nutrient status promoted the development of *P. annua*, was documented by Adeux et al. (2022).

Attributing the RCM treatment outcome to a single CC species may be inappropriate due to the challenges in distinguishing the short- and long-term effects of agricultural practices (Cordeau et al., 2022) and the inability to isolate the effects of the three CC species. Thus, future studies are warranted to investigate the interactions between CCs and weed species, both competitive and non-competitive, and the cascading effects among weed species under varying resource availability (Rouge et al., 2022).

The methodology adopted in this study for characterising the weed community, i.e. seedbank analysis, did not enable an accurate estimation of the density of perennial species. Given that many common and troublesome weed species, such as *Cirsium arvense* (L.) Scop., *Cyperus esculentus* L., and *Sorghum halepense* (L.) Pers., can also propagate through vegetative organs such as rhizomes or tubers, future efforts should also be directed to investigate the potential effect of autumn CCs or 'weedy fallow' on the population dynamics of perennial species.

5. Conclusions

The introduction of CCs and 'weedy fallow' during spring crop off-seasons alters weed proliferation windows, shifting weed communities. However, trends varied across treatments. 'Weedy fallow' in 'maize–maize–soybean' succession increased the winter weed presence after three years, heightening crop–weed interference risks. Winter CCs reduce the weed seedbank density within the same season, even though the choice of CC species affects the extent of this impact.

The consistent cultivation of triticale as CC reduced weed seedbank density compared to WF and RCM. The exact mechanisms for this increase are unclear, but may be due to the rapid initial and sustained soil coverage as compared to the other CCs.

The succession of different CC species (in the succession treatment) exhibited overall lower weed control efficacy compared to triticale, potentially due to their slower initial growth rate or shorter life cycle. Synchrony of management practices (e.g. seedbed preparation, CC termination, cash crop harvest, herbicide application) with weed germination or seed production periodicity likely reduces spring- and summer-emerging species, such as *P. oleracea* and *C. album*, potentially competing with cash crops.

CRedit authorship contribution statement

Georgia Raimondi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Donato Loddo:** Writing – review & editing, Resources, Investigation, Data curation, Conceptualization. **Maurizio Borin:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Vittoria Giannini:** Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127309.

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