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Short-term responses in weed spatial patterns during early adoption of conservation agriculture practices

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Abstract

BACKGROUND: The aggregated spatial pattern of weeds in agricultural systems is a widespread phenomenon. Depending on species characteristics, for example life form, weed patches may maintain their location across growing seasons. These spatial and temporal patterns underpin site-specific weed control, where herbicide applications are tailored to within-field infestation levels using variable rates and targeted spot spraying, thereby reducing overall herbicide use. The various practices that comprise conservation agriculture, like tillage reduction or cover crops, may affect the spatial patterns and temporal stability of weeds. This study examines short-term responses of weed spatial and temporal patterns following the implementation of conservation agriculture practices. Ten large experimental plots, five for each of conservation and conventional agriculture, located in northern Israel, were surveyed over two consecutive years (2021–2022) to evaluate the spatio-temporal patterns of weeds.

RESULTS: Weed spatial patterns were influenced by both cropping system and species life form. Higher levels of weed aggregation were observed in conservation compared to conventional agriculture. Perennial species formed denser weed patches compared to annuals. Weed patch stability was mainly governed by species life form, with perennials demonstrating persistent patches.

CONCLUSION: The transition to conservation agriculture may enhance the phenomena of weed aggregation and weed patch stability even within a short time. Consequently, under these conditions, the benefits of site-specific weed control become even more significant compared to conventional systems. This suggests that two key objectives, mitigating soil degradation and decreasing the use of herbicides, can be accomplished through conservation agriculture and site-specific herbicide applications.

Supporting information may be found in the online version of this article.

Keywords: agroecology; no-till; patch stability; precision agriculture; spatio-temporal dynamics; weed aggregation

1 INTRODUCTION

Weed control is essential for crop management to ensure optimal growth conditions and support agricultural productivity.[1] Tillage and herbicide applications are the two most widely used practices for weed management in conventional farming systems. Recent estimates indicate that two-thirds of Europe's arable land is managed with conventional tillage.[2] Conventional tillage is linked to various environmental problems, including soil degradation, increased erosion, and nutrient depletion, all of which undermine long-term soil health.[3,4] To mitigate these impacts, it is essential to adopt practices that minimize or eliminate the use of conventional tillage, thereby preserving soil structure and promoting sustainable agriculture. Accordingly, alternative farming systems have been proposed.[5] Conservation agriculture is increasingly recognized as a sustainable cropping system, emphasizing principles such as minimal soil disturbance through no-tillage, permanent soil cover via cover crops and mulch, and diversified crop rotations.[6]

Since their introduction, herbicides have significantly improved crop yields by providing effective, systematic, and economical weed control.[7,8] Nowadays, herbicides account for more than

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50% of all pesticide applications worldwide, and their use continues to increase globally.[7,9] The reduction of tillage, as promoted in conservation agriculture, poses challenges for farmers, often leading to stronger reliance on herbicides.[10–12] Repeated and widespread herbicide use has led to the emergence of herbicide-resistant weed populations.[13–15] As a result, herbicides become less effective, making weed control more challenging. The decline in the efficacy of herbicides often results in increased frequency and volume of herbicide applications,[16] which in turn accelerates resistance development and escalates production costs.[17,18] Apart from the challenge posed to crop production, excessive herbicide use results in soil and water contamination, impacts non-target species, and contributes to global biodiversity loss.[4,19,20] Integrated weed management, through the application of mechanical and cultural practices, is suggested as a proactive and alternative tool to control herbicide-resistant weeds and help prevent their recurrence.[21] In conservation agriculture, cover crops and crop diversification may serve as weed management practices[22–25] as well as provide a range of valuable ecosystem services.[26–28] While these practices are reported to control weeds effectively, weed management in conservation agriculture still relies predominantly on herbicide treatments.[29,30]

A suggested approach to reduce herbicide usage is precision agriculture and, more explicitly, site-specific weed control (SSWC)[31] and time-specific weed control.[32,33] At the core of SSWC lies the common phenomenon of weed aggregation into patches. The SSWC approach involves the precise application of herbicides exclusively to weed-infested zones within a field, thereby reducing chemical use, costs and pollution. Time-specific weed control adds an important dimension by targeting weeds at their most susceptible stage, considering the time they are predicted to emerge.[32] Weed patch stability, defined as the tendency of weed patches to persist in the same locations across growing seasons,[34] can facilitate informed mapping based on the field history of high-risk zones. This enables early, targeted weed management in areas where weeds are most likely to recur.[35]

Weed aggregation is a prevalent phenomenon, whereas the temporal stability of weed patches varies.[36] Both generally depend on species traits, farming practices, and the interaction of the two.[36] Life forms, reproduction modes and dispersal mechanisms are most likely to impact weed spatio-temporal patterns. Annual weeds reproduce through seeds, which are spread by various mechanisms such as wind, water, and animals, typically resulting in scattered and temporary infestations. Perennial weeds, which spread through tubers, runners or rhizomes, typically form persistent, dense patches that gradually expand outward. Weak spatio-temporal stability of weed patches in a field may result from a high proportion of annual species in the community, with variable emergence patterns across years. Species that dominate in one year but fail to emerge in the following year (or vice versa) can lead to reduced patch stability over time, causing spatial weed patches to shift unpredictably from year to year. Nonetheless, the resulting pattern highly depends on field activities during crop production. For example, weed patches have been reported to be elongated along crop rows.[37–39] Perennial species and weeds that shed seeds close to the mother plant, without dispersal strategies, exhibit high patch stability.[34,37,40] A recent review by Blank *et al.*[36] found that spatio-temporal weed patterns have been widely studied under conventional agriculture practices, whereas in emerging farming systems such as conservation agriculture, remain unexplored.

The practices encompassed by conservation agriculture may differentially alter the spatio-temporal dynamics of individual weed species compared to conventional systems. Reducing soil disturbance limits vertical seed dispersal through the soil profile. In addition, reduced runoff resulting from conservation tillage[41] may further decrease seed movement.[42] Consequently, both horizontal and vertical seed movement are restricted,[43] potentially causing seeds to accumulate near the soil surface in localized areas, which can lead to the formation of compacted patches.[44] The lack of seed movement may stabilize the location of weed patches over time. No-till practices preserve root systems, enabling perennials to regenerate even after removing aboveground biomass,[45,46] thereby facilitating the establishment perennial weeds,[47] whose patches are generally more stable than annual patches.[34,37] In contrast, conservation cropping systems may select for wind-dispersed species,[48,49] that are associated with a random spatial pattern.[50] Some mechanical dispersal of weed seeds, such as by harvesters,[51] continues to occur across cropping fields irrespective of production system. Cover crops suppress weeds[23] through a combination of aboveground biomass, allelopathic compounds, and interactions with seed predators.[24,52,53] Variations in cover crop growth across space or time can lead to the emergence of weed patches in new locations. Crop diversification may serve as a weed control technique,[22,25] but the specific crops and their associated management practices can greatly influence the weed community.[54] Consequently, the occurrence of different weed species each year is likely to change the locations of weed patches. Therefore, considering all practices, weed aggregation and stability may both be elevated or decreased, as summarized in Table 1.

Increased clustering and patch stability in conservation compared with conventional agrosystems, likely driven by differences in soil disturbance and dominant species, were reported by Nikolić *et al.*[59] Integrating conservation agriculture with SSWC could potentially decrease the use of both tillage and herbicides, thereby mitigating their negative impacts. Moreover, the known benefits of SSWC could be amplified through conservation

Table 1. Potential effects of conservation agriculture practices on weed spatio-temporal dynamics, including their influence on aggregation and patch stability

Practice	Agronomic effect	Potential effect	
		Aggregation	Stability
No tillage	Reduced seed movement[44,55]	+	+
	Low-interference farming systems to support wind-dispersed species[48,49]	−	−
	Shift to perennial-dominated community[56,57]	+	+
Cover crops implementation	Heterogeneity in cover crop growth[58] and thereby variability in weed suppression[52]	+	−
Crop diversification	Varying weed communities[54]	+/−	−

agriculture if weed patches are dense and stable. The objective of this study is to examine the short-term spatial and temporal responses of two weed life forms (annuals and perennials) following the implementation of two key conservation agriculture practices: no-till and winter cover crops. The weed dynamics were compared with those in a conventional agriculture system (tillage and cultivated fallow). We hypothesize that differences in the spatial and temporal patterns of weeds between cropping systems will emerge after only two growing seasons. Specifically: (i) weed spatial patterns will be aggregated in both systems, but aggregation will be higher in conservation agriculture; (ii) the effect of cropping system on weed patterns will depend on life form, with perennial species exhibiting greater patchiness than annuals; and (iii) similarly, higher temporal stability of weed patches is expected in conservation agriculture and among perennial species.

2 METHODOLOGY

2.1 Study site

The experiment was conducted at the Helmsley Model Farm for Sustainable Agriculture, part of the Newe Ya'ar Research Centre (32°42′23.3″ N, 35°10′46.4″ E) situated on the edge of the Jezreel Valley in northern Israel. The area is characterized by an eastern Mediterranean climate, consisting of a cold, rainy winter and a hot, dry summer. During the two growing seasons, the average temperature and cumulative precipitation measured were 20.8 °C and 460 mm in 2021 and 20.1 °C and 470 mm in 2022, respectively.

2.2 Research area history and experimental design

Before the experiment, crop production in the research area followed conventional management practices. In 2019, wheat was planted across the entire research area. Afterwards, a randomized complete block design with five blocks was introduced, dividing the area into plots assigned to either conservation agriculture or conventional agriculture. The conservation agriculture system examined in this study was therefore in its early phase of implementation, with limited crop diversification. Nonetheless, in addition to its two core practices, no-till and winter cover crops, other management aspects differed between the systems, including herbicide treatments, planting equipment and technique, fertilizer application, and mulch cover (Table 2). Given these differences, we treat this as a comparison of two distinct cropping systems rather than a simple contrast between a single factor, such as cover crops versus cultivated fallow. The blocks were defined based on topography, which included a minor slope toward a stream, as well as soil survey results.[60] Within this experimental scheme, which consists of two distinct cropping systems, winter cover crops were sown in the conservation agriculture plots, while the conventional plots were ploughed and remained as fallow fields. This was followed by the planting of sunflower as the main crop in both cropping systems within this experimental scheme in 2020. Data was not collected for the first year of the transition and is not reported here.

Maize was sown in both years of the study in 2021 and 2022. While conservation agriculture typically involves diverse crop rotations, to ensure consistency and minimize confounding effects from crop-specific traits, such as herbicide use and sowing dates,[61] the same crop was used. This approach strengthens the comparison between cropping systems by isolating their effects on weed dynamics across years. The research set-up remained unchanged from the earlier description. The experimental plots were approximately 1 ha each, thereby demonstrating within-field heterogeneity and allowing for proper representation of species distribution and spatial pattern for each plot. The two cropping systems differed in the employed agronomic practices and herbicide applications (Table 2). A comprehensive list of active ingredients, mode of action, and rates for each herbicide application is provided in the Supporting Information Table S1.

2.2.1 *Conservation agriculture*

Conservation agriculture comprised no-till methods and winter cover crops (sown each year). In both years of the study, cover crops were sown in November/December and grew throughout winter. The cover crop species mixture remained consistent throughout both years, with only slight variations in seeding rates to improve species mixture balance, as informed by establishment success in the previous year. In 2021, *Avena strigosa* var. Saya was sown at 80 kg ha^{-1}, *Trifolium alexandrinum* var. Tabor at 15 kg ha^{-1}, and *Brassica napus* at 2 kg ha^{-1}. In 2022, the same species were sown at adjusted rates of 70, 8, and 3 kg ha^{-1}, respectively. To terminate cover crops before sowing the main crop, herbicides were applied, followed by a roller-crimper (Zach Agricultural Equipment Afula Ltd, Afula, Israel) 3 days later. This left the cover crops as mulch bedding throughout the summer growing season.

2.2.2 *Conventional agriculture*

Conventional agriculture reflected the more common practices of tillage and keeping the plots in a fallow state, not cultivated during winter. When left as fallow fields and in preparation for the growing season, plots were tilled with a disk plow (operating at 15–20 cm depth) and a paraplow subsoiler (operating at 60 cm depth). In addition, herbicides were applied to control high weed infestation. In 2021, herbicide applications on multiple occasions were required to handle repeated weed flushes that emerged throughout the winter. In 2022, weed infestation during this fallow period was not as severe, thus requiring only a single herbicide application upon maize sowing (Tables 2 and S1). During both growing seasons, field cultivation reached a depth of approximately 10–15 cm.

Maize was sown with an NG+ planter (Monosem Inc., Edwardsville, KS, USA) in a double-row layout with 80 cm spacing, at a rate of nine seeds per metre per row, totalling 18 seeds per square metre. In conservation agriculture plots, the planter had an apparatus to cut mulch layers. The conventional agriculture plots had maize sown about a week earlier due to favourable conditions at that time. Fertilization was applied via fertigation throughout the growing season, based on soil surveys.

2.3 Data collection

Weed surveys were conducted in two consecutive years (2021 and 2022). Each year, the plots were sampled once in late April, approximately 2 weeks after the main crop was sown and before the implementation of within-season weed control measures. A rectangular sampling area of 120 × 40 m^2 was positioned in the centre of each plot, allowing a distance from the plot margin to avoid the potential edge effect in which high weed density is observed.[62,63] Each plot was sampled using a grid with 10-m intervals using the 'Create Fishnet' tool in ArcGIS Pro 2.8 (ESRI, Redlands, CA, USA). This setup allowed for systematic sampling of 65 quadrats within each of the ten plots (Fig. 1). Each quadrat location was navigated using a Trimble Juno T41/5 global

Table 2. Timeline of field activities and critical weed management operations under the two cropping systems (conservation and conventional agriculture) during 2021 and 2022

	2020	2021											
	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Conservation agriculture	cc	cc	cc	cc	He, SM, Ws	He			Ha			He, cc	cc
Conventional agriculture	He	He		He, SM	Ws, He				Ha, Ti				

	2022							
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Conservation agriculture	cc	cc	cc	He, SM, Ws		He		Ha
Conventional agriculture	Ti	He		SM, Ws, Ti	He			Ha

Note: Each row represents one cropping system, and activities within each month are shown in chronological order. Activities include tillage (Ti), herbicide application (He), sowing of cover crops (cc), maize sowing (SM), weed surveys (Ws), and harvest (Ha).

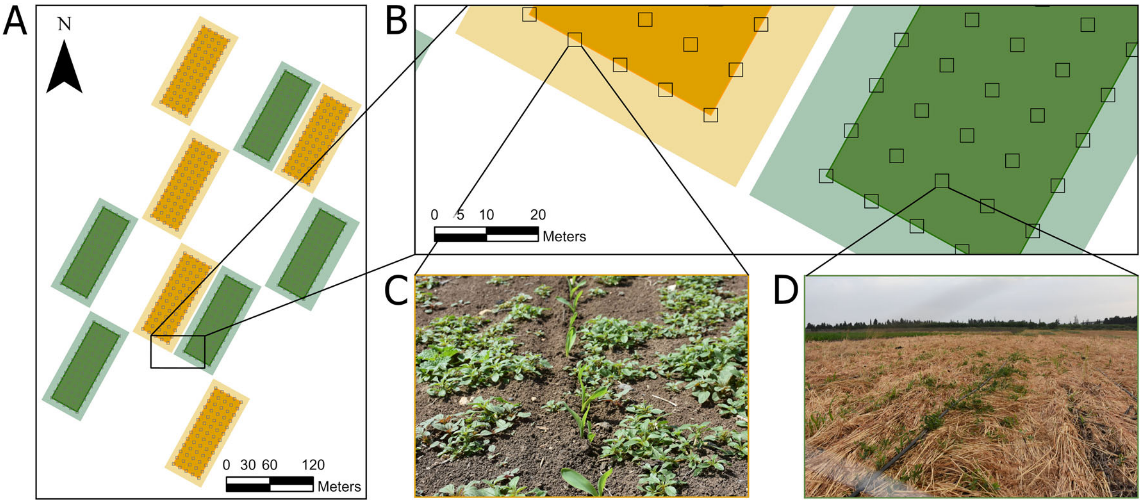

Figure 1. Experimental layout (A) and zoom-in of quadrats location placements within plots (B) where plots of conservation agriculture and conventional agriculture are represented by green and orange colours, respectively. Surveyed areas in the experimental plots are marked with darker colours of their respective cropping systems. Field conditions at the time of survey in conventional (C) and conservation agriculture (D).

positioning system (GPS, accuracy 1–4 m). To enhance location accuracy and minimize errors, sampling was conducted when high GPS precision was confirmed. The coordinates allowed for precise and consistent relocation of the same quadrat over the 2-year period. At each 0.5 m × 0.5 m quadrat, weeds were identified and counted at the species level, except for *Amaranthus* seedlings, which were identified to the genus level. Unidentified individuals were grouped under 'others' and counted.

2.4 Data analysis

In accordance with previous reports on the spatio-temporal differences between life forms, species counts were grouped into 'Annuals' and 'Perennials'. A third group, referred to as 'Total', was defined to include all recorded weed counts, including both annual and perennial species. The spatial distribution of the two life forms and the total weed community was mapped using the inverse distance weighting (IDW) interpolation method. Although poor scores in preliminary evaluation indices led to their exclusion from further statistical analyses, these interpolated maps provided an important representation of weed distribution.

The six most abundant species were examined for aggregation level and spatio-temporal stability: four annual species (*Chrozophora tinctoria* (L.) Raf., *Echinochloa colonum* (L.) Link, *Moluccella laevis* L. and *Amaranthus* spp.) and two perennials (*Cyperus rotundus* L. and *Convolvulus arvensis* L.). Characterized by distinct biological and dispersal mechanisms (Table 3), the populations of all species are naturally occurring and widely distributed in agricultural fields across the region.

Spatial pattern was evaluated by two indices. First, Lloyd's index of patchiness, which quantifies the level of aggregation, was calculated for each plot within each year separately using the *agg_index()* function from the *epiphy* package in R.[69] Values lower or equal to 1 indicate a uniform and random distribution, respectively, while values higher than 1 represent an aggregated pattern, and larger values correspond to higher levels of aggregation.[70,71] Second, Moran's I, which measures spatial autocorrelation by quantifying the degree of clustering among similar values, was calculated.[72] With values ranging from −1 to 1, Moran's I indicates clustering when positive, dispersion when negative, and randomness at 0. Both indices are widely used for

Table 3. Biological and dispersal traits of the six most abundant weed species established in the experimental site

Scientific name	Family	Life form	Morphological group	Dispersal mechanism(s)
Chrozophora tinctoria (L.) Raf.	Euphorbiaceae	Annual	Dicot	Explosive dehiscence, ant-mediated seed dispersal[64]
Echinochloa colonum (L.) Link	Poaceae	Annual	Monocot	Machinery, water, contaminated seed, animals[65]
Moluccella laevis L.	Lamiaceae	Annual	Dicot	Gravity
Amaranthus spp.	Amaranthaceae	Annual	Dicot	Gravity, water, wind, animals, machinery, and contaminated seed[66]
Cyperus rotundus L.	Cyperaceae	Perennial	Monocot	Rhizomes, tubers, water, machinery[67]
Convolvulus arvensis L.	Convolvulaceae	Perennial	Dicot	Seeds, rhizomes, machinery[68]

evaluating the spatial pattern of species[73] and are particularly employed to characterize weed spatial patterns in agricultural fields.[50,74–76] The two indices complement each other by providing a comprehensive view of the spatial pattern. Lloyd's index of patchiness is based on the statistical characteristics of the dataset and indicates the pattern of weed count heterogeneity. Moran's I, however, accounts for the spatial relationship between similar values, such as the formation of larger patches. The spatio-temporal pattern was evaluated by calculating the Spearman rank correlations of weed densities between the same quadrats across years for each plot. The spatial pattern indices and patch stability correlations were calculated for the six most abundant species, as well as at the life form scale and their combined total counts.

To calculate the estimated marginal means of Lloyd's index, Moran's I, and Spearman correlations and compare the two cropping systems, generalized linear mixed models were fitted using the glmmTMB package[77] in R. These models evaluated the effect of the cropping system within each year and the two life forms ('Annuals' and 'Perennials'); 'Total', which was modelled separately as it includes both life forms; and the six most abundant species. The interactions of weed life form or species with the cropping system, and the sampling year with the cropping system were considered fixed effects. For modelling the six most abundant species, we also included the interaction between species and year. 'Block', 'Block:Year' and 'Plot' were considered random effects to account for potential variability due to the experimental blocks and the repeated measures within the same plots across years. For Lloyd's patchiness index, an additional dispersion parameter was included for the different life forms to accommodate potential heteroscedasticity. To quantify temporal stability, we examined the correlation across quadrats placed in the same location between years. The correlation values were then fitted with the interaction of the cropping system and life forms while considering 'Block' as a random effect and a dispersion parameter for the cropping system, as this was found significant. A similar model was fitted to the species level, but without a separately calculated dispersion parameter. A Gamma distribution and a log-link function were used in all cases. Because the Gamma distribution is limited to positive values, a constant was added to Moran's I and the correlation prior to model fitting to ensure all values were positive. The reported values were then back-transformed to their original scale. Model assumptions were validated using the *simulateResiduals()* function from the DHARMa package.[78] Estimated marginal means (EMM) were computed via *emmeans* package.[79]

Type III analysis of variance (ANOVA) from the car[80] package in R was used to test the significance of each predictor. Patchiness indices and spatio-temporal stability were compared between conservation and conventional agriculture for Annuals, Perennials and Total weed communities. For the six most abundant species, values for Lloyd's index, Moran's I, and Spearman correlations are presented but not statistically compared across cropping systems due to low counts and their absence in some plots.

3 RESULTS

Substantial variations in weed densities were found at a plot level, with some areas highly infested while others are weed-free (Fig. 2). Heterogenous spatial distributions occurred for 'Annuals', 'Perennials' and 'Total', that is, their combined total densities, and in both cropping systems. Overall, weed densities were numerically higher in conventional plots in 2021 across both life forms and in total. By 2022, 'Annuals' weed densities were similar between the two cropping systems, while 'Perennials' and 'Total' weed densities remained slightly higher on average in conventional plots (Table S2). The overall weed counts of annual and perennial weeds were 54% and 46%, respectively. Four annual species (*Chrozophora tinctoria*, *E. colonum*, *Moluccella laevis*, and *Amaranthus* spp.), accounted for 92% of all annual individuals. *Cyperus rotundus* and *Convolvulus arvensis* accounted for 99% of all perennial individuals. Species weed densities (plants quadrat^{-1}) ranged from 0 (indicating absence from the cropping system) for *Chrozophora tinctoria* and *Moluccella laevis* under conservation agriculture in 2021, to 13.05 ± 19.02 (mean ± standard deviation) for *Amaranthus* spp. under conventional agriculture the same year (Table S2). The standard deviation exceeded the mean in most cases, reflecting pronounced spatial heterogeneity.

3.1 Spatial pattern

3.1.1 Patchiness by cropping system and life form

The spatial pattern of weeds was shaped by their life form and the cropping system applied. Lloyd's patchiness index was significantly affected by the life form and cropping system, but not by year or their interactions (Table 4). This indicates differences in patchiness levels between 'Annuals' and 'Perennials', as well as between conservation and conventional agriculture systems. Similarly, the cropping system significantly affected Moran's I, underscoring its overall impact.

In both years, 'Annuals', 'Perennials', and 'Total' exhibited an aggregated spatial pattern, indicated by a high Lloyd's patchiness

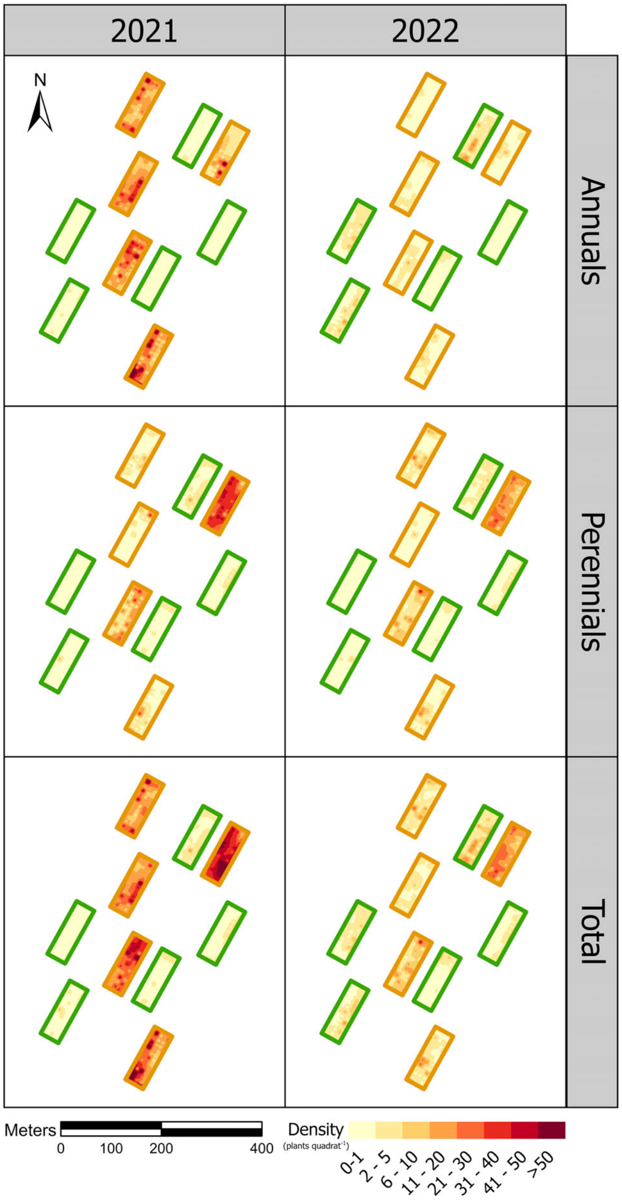

Figure 2. Density maps showing the spatial distribution of two weed life forms ('Annuals', 'Perennials') and the Total weed community in 2021 and 2022. Density is expressed as the number of individuals per 0.25 m^2 quadrat and interpolated using the inverse distance weighting (IDW) method. Darker areas indicate higher weed density. Plot border colours denote cropping systems: conservation agriculture (green) and conventional agriculture (orange).

index (>1) (Fig. 3). Cropping system was a significant predictor of Lloyd's patchiness (Table 4), with conservation agriculture typically displaying higher values, although significance was attained in only a few pairwise comparisons (Fig. 3). This suggests that although both systems had weed patches interspersed with zones where no (or only a few) weeds were present, the patches under conservation agriculture were generally denser. Conservation agriculture significantly increased the observed patchiness only for 'Annuals' in both years. In contrast, 'Perennials' exhibited high patchiness values in both cropping systems, with no significant difference. This may indicate that while perennials remain highly aggregated regardless of management practices, annuals tend to be less aggregated overall but were more strongly influenced by the cropping system. The 'Total' weed community was significantly higher in conservation agriculture in 2021 but similar between the cropping systems in 2022.

Moran's I scores were positive across cropping systems and life forms (Fig. 3). Values ranged approximately between 0 and 0.2, indicating that the patches represented small-scale aggregations rather than large weed patches. In 2021, 'Annuals' in conservation agriculture exhibited a marginally significant ($P = 0.06$) lower Moran's I value (0.03) compared to conventional agriculture (0.13), with smaller, more dispersed weed patches under conservation management and larger, well-defined clusters under conventional management. However, this difference diminished the following year. 'Perennials' exhibited similar values in both years with no significant difference between cropping systems. In 2021, 'Total' weed community Moran's I was similar among cropping system; yet found significantly higher in conservation agriculture in 2022. Overall, Moran's I values for conservation agriculture increased in the second year of the experiment, hence the significance of Year (Table 4).

3.1.2 *Patchiness at a species level*

At the species level, differences in spatial patterns between cropping systems were less pronounced (Fig. 4). It should be noted that although statistical analyses were precluded due to insufficient data for certain species, clear descriptive patterns were still observed. In 2021, conservation agriculture exhibited higher Lloyd's patchiness index compared to conventional agriculture for *Cyperus rotundus* and *Echinochloa colonum*. For the other two species present in both systems, differences were negligible. *Amaranthus* spp. and *Chrozophora tinctoria* displayed lower Lloyd's patchiness index relative to the other species in 2021. By 2022, overall patchiness levels declined, further reducing contrasts between systems. However, the two perennial species, *Cyperus rotundus* and *Convolvulus arvensis*, consistently exhibited higher spatial patchiness. Moran's I values were relatively consistent across species and cropping systems in 2021. In 2022, three of the six species showed higher Moran's I values under conservation agriculture. *Chrozophora tinctoria*, which was absent from conservation plots in 2021, exhibited lower spatial autocorrelation (Moran's I) in conservation plots in 2022.

3.2 Temporal stability

Temporal stability was significantly affected by life form ($P = 0.05$), but not by cropping system ($P = 0.66$) or their interaction ($P = 0.53$). 'Total' weed density showed intermediate correlations of 0.25 for conservation and 0.20 for conventional agriculture (Table 5). 'Annuals' showed weak correlation ($r = 0.11$ and 0.07 for conservation and conventional agriculture, respectively). Species-level correlations for annuals were generally weak, except for *Echinochloa colonum*, which reached a correlation of 0.32 (Table 5). 'Perennials' had moderate correlations, stronger in conventional ($r = 0.56$) than in conservation agriculture ($r = 0.41$). *Convolvulus arvensis* had a stronger correlation in conservation ($r = 0.76$) compared to conventional agriculture ($r = 0.45$), while *Cyperus rotundus* showed a weaker correlation in conservation agriculture ($r = 0.27$) (Table 5).

4 DISCUSSION

Weed aggregation is a common phenomenon that generally depends on numerous factors including species traits, cropping

Table 4. Type III analysis of variance (ANOVA) results for Lloyd's index of patchiness and Moran's I, showing the effects of life form, cropping system, year, and their interactions

	Lloyd's index patchiness			Moran's I		
Predictor	Chi-square	df	*P*-Value	Chi-square	df	*P*-Value
Life form	5.32	1	**0.02**	0.62	1	0.43
Cropping system	4.91	1	**0.03**	4.10	1	**0.04**
Year	0.10	1	0.75	4.27	1	**0.04**
Life form × Cropping system	0.03	1	0.86	2.37	1	0.12
Cropping system × Year	0.11	1	0.74	2.97	1	0.09

Note: Significant *P*-values ($\alpha < 0.05$) are shown in bold.

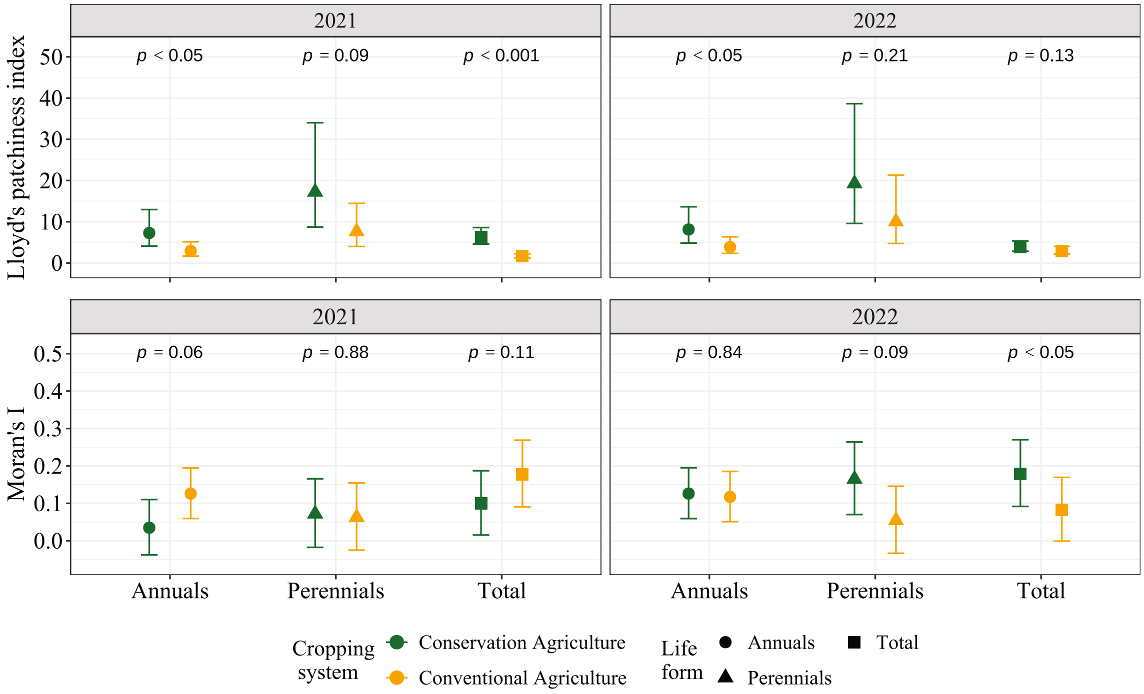

Figure 3. Comparison of cropping systems based on Lloyd's patchiness index and Moran's I, indicating spatial heterogeneity across weed life forms ('Annuals', 'Perennials') and the 'Total' weed community. Values represent estimated marginal means (± standard error) for each cropping system, with pairwise comparisons made within each year × life form combination (*P*-values shown above).

practices, and the combinations of these factors.[36,81] The effect of cropping systems on weed infestation or community assembly is covered in numerous studies,[82–85] whereas their potential impact on weed spatial patterns is inadequately represented in the literature.[36] This study evaluated the impact of conservation agriculture practices, specifically no-till combined with winter cover crops, compared to conventional agriculture, on the spatio-temporal dynamics of annuals, perennials and the overall weed community across two consecutive years. Conducted during the early phase of transitioning from a conventional cropping system to conservation agriculture, the results should therefore be interpreted as early-stage, short-term responses rather than long-term outcomes. We hypothesized that spatial and temporal patterns would differ between conventional and conservation agriculture cropping systems, as well as between perennial and annual life forms. Additionally, it was hypothesized that differences in the spatio-temporal dynamics between perennials and annuals would depend on the type of cropping system, indicating an interaction between these factors. Weeds were more aggregated in conservation agriculture (Table 4 and Fig. 3). Temporal stability was similar in both cropping systems and was mainly influenced by the life form (Table 5). Differences in aggregation and temporal stability were observed across life forms, with perennials demonstrating denser patches and greater patch stability. Given the costs and herbicide savings attributed to SSWC,[86,87] and the growing global adoption of conservation agriculture,[6] our results provide valuable insights into the phenomenon of the spatio-temporal dynamics of weeds. These findings extend their relevance to conservation agriculture and suggest complementary benefits of integrating these practices.

4.1 Weeds spatial pattern

Spatial aggregation was observed for both cropping systems and life forms, which is consistent with reports of field heterogeneity and weed clustering in various crops and orchards.[34,37,74,76,88–90] Conservation agriculture exhibited higher patchiness across the

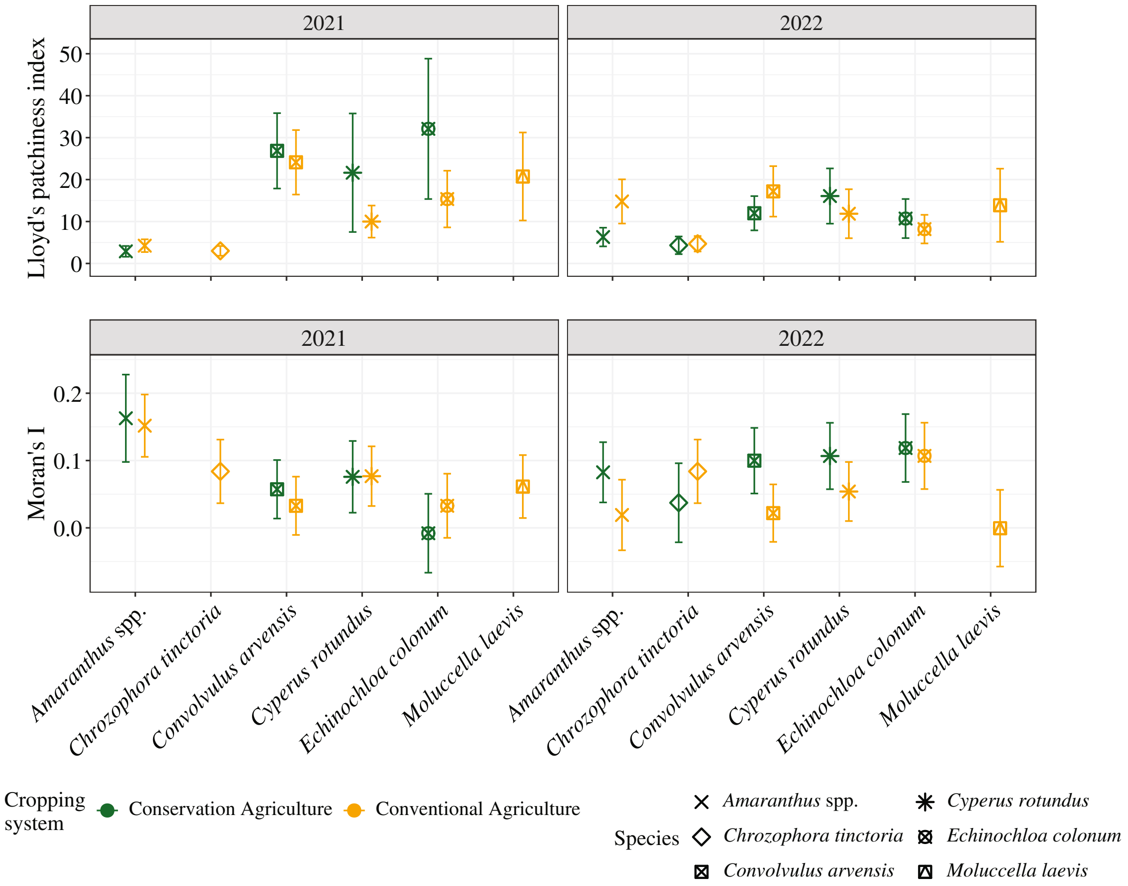

Figure 4. Comparison of cropping systems based on Lloyd's patchiness index and Moran's I, indicating spatial heterogeneity across the six most abundant species. Values represent estimated marginal means (± standard error) for each cropping system, with comparisons made within each year × life form combination.

Table 5. Estimated marginal means (EMM) with 95% confidence intervals (CIs) [lower, upper] for cross-year correlations computed at both the species and life form levels

	Spearman's correlation (EMM, 95% CI)			
Species	Conservation agriculture		Conventional agriculture	
Annuals				
Amaranthus spp.	0.12 [−0.08, 0.37]	0.07 [−0.09, 0.25]	0.11 [−0.06, 0.30]	0.11 [0.03, 0.19]
Chrozophora tinctoria	NA [NA, NA]		0.17 [0.02, 0.32]	
Moluccella laevis	NA [NA, NA]		0.21 [0.03, 0.43]	
Echinochloa colonum	0.02 [−0.16, 0.25]		0.32 [0.15, 0.52]	
Perennials				
Cyperus rotundus	0.27 [0.08, 0.50]	0.41 [0.22, 0.64]	0.63 [0.44, 0.85]	0.56 [0.44, 0.68]
Convolvulus arvensis	0.76 [0.53, 1.03]		0.45 [0.28, 0.65]	
Total				
	0.25 [0.06, 0.46]		0.20 [0.14, 0.26]	

Note: Correlations are reported for each species within cropping systems and for aggregated life form categories (e.g., 'Annuals', 'Perennials'). Higher values indicate stronger temporal stability in species or life form occurrence across years. NA indicates cases where correlation could not be calculated due to the absence or insufficient data for a species in a cropping system's plot.

two life forms and their combined 'Total', thus supporting our first hypothesis regarding the influence of cropping system. Stronger aggregation was observed in 'Perennials' compared to 'Annuals', highlighting a complex difference in spatial dynamics. The interaction between life form and cropping system was not significant. However, differences between cropping systems were consistently significant only for 'Annuals' across both years, suggesting that the cropping systems influence likely differs between life forms. These complementary findings support our second hypothesis, reflecting pronounced patchiness observed in perennials and a differential impact of cropping systems on weed spatial patterns across life forms. Lloyd's index values varied considerably among different life forms and species, aligning with previous studies.[91,92] In comparison, Moran's I values indicated some degree of spatial autocorrelation, peaking around 0.3, but remained relatively low. For instance, Rozenberg *et al.*[76] documented Moran's I values ranging from 0.1 to 0.6 when analysing weeds spatial patterns in multiple onion fields. The high Lloyd's index values observed for both life forms and their combined 'Total' group suggest substantial spatial variability in species counts, indicating a patchy distribution. In contrast, the low positive Moran's I scores reflect weak spatial autocorrelation, implying that these patches are irregularly scattered and vary in densities, rather than forming a continuous spatial pattern.

Consistent with the broader pattern observed between life forms, all six species exhibited a patchy spatial distribution. This finding was expected, as none of these species, each with distinct dispersal mechanisms, is exclusively wind-dispersed (Table 3). In contrast, while significant differences in spatial patterns were evident between conservation and conventional agriculture at the life form level, species-level differences were less pronounced. These results align with previous findings showing that aggregation patterns can vary widely among species, regardless of life form or management regime.[39] Although life form classification offers valuable insights, species-specific patterns can emerge. For example, here, *Echinochloa colonum* displayed notable spatial aggregation and patch stability, comparable to those of perennial species. Nonetheless, the six most abundant species are recognized as problematic weeds, particularly *Amaranthus* spp., *Echinochloa colonum*, *Cyperus rotundus*, and *Convolvulus arvensis*,[65,93–95] with *Amaranthus* spp. and *Echinochloa colonum* having multiple documented cases of herbicide resistance.[96–100] These findings underscore the value of SSWC in improving control efficacy and reducing the risk of resistance development.

4.2 Patch temporal stability

Both cropping systems exhibited similar patterns of weed patch recurrence in which 'Annuals', 'Perennials', and the 'Total' exhibited very weak, moderate, and intermediate correlations in weed densities across years, respectively. This partially supports our third hypothesis, as 'Perennials' exhibited greater consistency in patch locations, while stability remained similar between cropping systems. At the species level, the results concurred with those obtained for life forms. Correlation scores were typically higher for perennial species compared to annuals, whose scores varied across cropping systems. Given that the temporal aspect covers only two growing seasons and conservation agriculture was only recently implemented, the scope is inherently limited. However, our results align with previous findings on patch stability, showing that perennial species tend to maintain stable patch locations,[34,37] while annual species exhibit more variability, with some reporting stability and others showing spatial shifts across years.[101] Notably, contrasting results were observed for the two perennial species *Convolvulus arvensis* and *Cyperus rotundus* under conservation agriculture. *Convolvulus arvensis* showed high patch stability, consistent with reports of its persistence in no-till systems.[102] This may be attributed to its deep, resilient network of roots and rhizomes, which supports long-term spatial consistency across years.[95,102] In contrast, *Cyperus rotundus*, which reproduces via underground tubers, may sprout in response to local micro-conditions,[94] which may lead to lower patch stability over time. Nonetheless, both species exhibited spatially consistent weed patches (as indicated by moderate to high correlations). Vegetative reproductive strategies beyond seeds, for example rhizomes and tubers, may be favoured in no-till agrosystems, potentially contributing to the increasing dominance of perennial species in these systems[48,57,85]; though, other studies reported no such dominance.[82,103] Temporal patch stability will allow to accurately predict the location of weed patches without the need to survey each year, thereby decreasing the overall costs of SSWC.[35,104] The increase use of unmanned aerial vehicles (UAVs) and satellites[105,106] for weed detection,[76,86,107,108] which has also been tested in conservation agriculture,[59] would ease field mapping and precise spraying, decrease costs, and thereby elevate SSWC applicability.[35]

Weed presence in agricultural fields results from local (within field) and regional settings.[109,110] The spatial pattern of weeds depends on field history, within-field heterogeneity, management techniques, and regional differences, including climate and topography.[36,62,111,112] The experimental setup included two cropping systems with large-scale plots, enabling robust sampling to capture heterogeneity and allow system level comparisons. While the core principles of conservation agriculture are broadly defined,[6] considerable *in situ* variations in their implementation have been reported.[113] In principle, conservation agriculture should incorporate diversified crop rotation. However, crop rotation is already common among local farmers, and the rotation implemented in this study area (wheat–sunflower–maize–maize) largely reflects their typical sequences, regardless of whether they adopt the other conservation practices discussed. Consequently, the potential effect of crop diversification, as suggested in the introduction, is limited in this context. Our results indicate that weed spatial pattern is influenced by both the cropping system, even over short periods following its adoption, and by species' life form, whereas temporal dynamics are primarily governed by life form. The relatively limited effect of cropping systems, observed both spatially and temporally, may be due to the contrasting effects of individual conservation agriculture practices on weed spatio-temporal dynamics (Table 1). Additionally, other field activities that affect spatio-temporal patterns, such as harvesting,[51] remain similar among cropping systems, potentially decreasing differences between them. The observed limited effect may also be partly due to the recent transition to conservation agriculture, as weed communities composition often requires several crop cycles to stabilize under new conditions.[114] Nonetheless, conservation agriculture practices were reported to exert immediate effects on species establishment[115–117] allowing meaningful insights during the transition phase, while emphasizing the need for long-term research. It is anticipated that conservation agriculture cropping system will continue to shape weed communities,[43] likely influencing weed spatial distribution.[44] These communities are often dominated by perennial species,[57] which, although typically more difficult to control,[94,95,118,119] tend to form dense patches with stable distribution that may facilitate location prediction and enable precision management.

5 CONCLUSIONS

Conservation agriculture practices offer multiple ecosystem services but face challenges in weed management, potentially hindering its adoption by farmers. Eliminating tillage, a common weed control practice, raises concerns about increased herbicide reliance. The transition to conservation agriculture is further complicated by the projected shift to a perennial-dominated weed community that is challenging to control. As shown in this study, conservation agriculture generally increased patchiness levels across life forms, with particularly strong effects observed in annual species. Moreover, perennial weeds tended to form more aggregated and persistent patches over time compared to annuals. Therefore, conservation agriculture holds promise to enhance the benefits of SSWC, reducing the areas needing to be sprayed, lowering costs, and improving precision. Integrating SSWC with conservation agriculture could synergistically reduce the use of both tillage and herbicides and promote more sustainable cropping while effectively managing weeds. Two key objectives of mitigating soil degradation and reducing the use of herbicides can be achieved through conservation agriculture and site-specific herbicide applications, addressing two challenges in the development of sustainable cropping systems.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

REFERENCES

1 Wyse DL, New technologies and approaches for Weed Management in sustainable agriculture systems. *Weed Technol* **8**:403–407 (1994).
2 Agri-environmental indicator – tillage practices https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_tillage_practices (accessed 4 May 2025).
3 Lal R, Tillage effects on soil degradation, soil resilience, soil quality, and sustainability. *Soil Tillage Res* **27**:1–8 (1993).
4 Sánchez-Moreno S, Castro J, Alonso-Prados E, Alonso-Prados JL, García-Baudín JM, Talavera M *et al.*, Tillage and herbicide decrease soil biodiversity in olive orchards. *Agron Sustain Dev* **35**:691–700 (2015).
5 Aune JB, Conventional, organic and conservation agriculture: production and environmental impact, in *Agroecology and Strategies for Climate Change*, ed. by Lichtfouse E. Springer Netherlands, Dordrecht, pp. 149–165 (2012).
6 Kassam A, Friedrich T and Derpsch R, Global spread of conservation agriculture. *Int J Environ Stud* **76**:29–51 (2019).
7 Gianessi LP, The increasing importance of herbicides in worldwide crop production. *Pest Manag Sci* **69**:1099–1105 (2013).
8 Duke SO and Powles SB, Glyphosate: a once-in-a-century herbicide. *Pest Manag Sci* **64**:319–325 (2008).
9 FAO, Pesticides use and trade – 1990–2022. FAOSTAT Analytical Briefs No. 89, FAO, Rome (2024). https://doi.org/10.4060/cd1486en.
10 Moyer JR, Roman ES, Lindwall CW and Blackshaw RE, Weed management in conservation tillage systems for wheat production in north and South America. *Crop Prot* **13**:243–259 (1994).
11 Melander B, Munier-Jolain N, Charles R, Wirth J, Schwarz J, van der Weide R *et al.*, European perspectives on the adoption of nonchemical Weed Management in reduced-tillage systems for arable crops. *Weed Technol* **27**:231–240 (2013).
12 Mal P, Schmitz M and Hesse JW, Economic and environmental effects of conservation tillage with glyphosate use: a case study of Germany. *Outlooks on Pest Management* **26**:24–27 (2015).
13 Heap I, The International Herbicide-Resistant Weed Database https://www.weedscience.org (accessed 4 May 2025).
14 Heap I, Global perspective of herbicide-resistant weeds. *Pest Manag Sci* **70**:1306–1315 (2014).
15 Green JM, Current state of herbicides in herbicide-resistant crops. *Pest Manag Sci* **70**:1351–1357 (2014).
16 Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM *et al.*, Reducing the risks of herbicide resistance: best management practices and recommendations. *Weed Sci* **60**:31–62 (2012).
17 Wechsler SJ, McFadden JR and Smith DJ, What do farmers' weed control decisions imply about glyphosate resistance? Evidence from surveys of US corn fields. *Pest Manag Sci* **74**:1143–1154 (2018).
18 Peterson MA, Collavo A, Ovejero R, Shivrain V and Walsh MJ, The challenge of herbicide resistance around the world: a current summary. *Pest Manag Sci* **74**:2246–2259 (2018).
19 Gaba S, Gabriel E, Chadœuf J, Bonneu F and Bretagnolle V, Herbicides do not ensure for higher wheat yield, but eliminate rare plant species. *Sci Rep* **6**:30112 (2016).
20 Wan N-F Fu L Dainese M Kiær LP Hu Y-Q Xin F Goulson Dave Woodcock Ben A. Vanbergen Adam J. Spurgeon David J. Shen Siyuan Scherber Christoph Pesticides have negative effects on non-target organisms *Nat Commun* **16** 1360 Nature Publishing Group 2025
21 Owen MDK, Diverse approaches to herbicide-resistant Weed Management. *Weed Sci* **64**:570–584 (2016).
22 Anderson RL, Integrating a complex rotation with no-till improves weed management in organic farming. A review. *Agron Sustain Dev* **35**:967–974 (2015).
23 Osipitan OA, Dille JA, Assefa Y and Knezevic SZ, Cover crop for early season weed suppression in crops: systematic review and meta-analysis. *Agron J* **110**:2211–2221 (2018).
24 Osipitan OA, Dille JA, Assefa Y, Radicetti E, Ayeni A and Knezevic SZ, Impact of cover crop management on level of weed suppression: a meta-analysis. *Crop Sci* **59**:833–842 (2019).
25 Weisberger D, Nichols V and Liebman M, Does diversifying crop rotations suppress weeds? A meta-analysis. *PLoS One* **14**:e0219847 (2019).
26 Schipanski ME, Barbercheck M, Douglas MR, Finney DM, Haider K, Kaye JP *et al.*, A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agric Syst* **125**:12–22 (2014).
27 Tamburini G, Bommarco R, Wanger TC, Kremen C, van der Heijden MGA, Liebman M *et al.*, Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci Adv* **6**: eaba1715 (2020).
28 Eshel G, Egozi R, Goldwasser Y, Kashti Y, Fine P, Hayut E *et al.*, Benefits of growing potatoes under cover crops in a Mediterranean climate. *Agric Ecosyst Environ* **211**:1–9 (2015).
29 Chauhan BS, Singh RG and Mahajan G, Ecology and management of weeds under conservation agriculture: a review. *Crop Prot* **38**:57–65 (2012).
30 Neve P, Matzrafi M, Ulber L, Baraibar B, Beffa R, Belvaux X *et al.*, Current and future glyphosate use in European agriculture. *Weed Res* **64**:181–196 (2024).
31 Maxwell BD and Luschei EC, Justification for site-specific Weed Management based on ecology and economics. *Weed Sci* **53**:221–227 (2005).

32 Marschner C, Colucci I, Stup R, Westbrook A, Brunharo C, DiTommaso A *et al*., Modeling weed seedling emergence for time-specific weed management: a systematic review. *Weed Sci* **72**:1–44 (2024).
33 Nikolić N, Rizzo D, Marraccini E, Ayerdi Gotor A, Mattivi P, Saulet P *et al*., Site- and time-specific early weed control is able to reduce herbicide use in maize—a case study. *Ital J Agron* **16**:1780 (2021).
34 Blank L, Birger N and Eizenberg H, Spatial and temporal distribution of Ecballium elaterium in almond orchards. *Agronomy* **9**:751–751 (2019).
35 Lati R, Gerhards R, Eizenberg H, Matzrafi M, Blank L and Christensen S, Advances in precision application technologies for weed management, in *Advances in Integrated Weed Management*, ed. by Kudsk P. Burleigh Dodds Science Publishing, Cambridge, UK, pp. 229–254 (2022).
36 Blank L, Rozenberg G and Gafni R, Spatial and temporal aspects of weeds distribution within agricultural fields – a review. *Crop Prot* **172**:106300 (2023).
37 Colbach N, Forcella F and Johnson GA, Spatial and temporal stability of weed populations over five years. *Weed Sci* **48**:366–377 (2000).
38 Hamouz P and Hamouzová K, Analysis of sampling precision in low-density weed populations. *Precis Agric* **23**:603–621 (2022).
39 Izquierdo J, Milne AE, Recasens J, Royo-Esnal A, Torra J, Webster R *et al*., Spatial and temporal stability of weed patches in cereal fields under direct drilling and harrow tillage. *Agronomy* **10**:452 (2020).
40 Wilson BJ and Brain P, Long-term stability of distribution of *Alopecurus myosuroides Huds*. Within cereal fields. *Weed Res* **31**:367–373 (1991).
41 Du X, Jian J, Du C and Stewart RD, Conservation management decreases surface runoff and soil erosion. *Int Soil Water Conserv Res* **10**:188–196 (2022).
42 de Rouw A, Ribolzi O, Douillet M, Tjantahosong H and Soulileuth B, Weed seed dispersal via runoff water and eroded soil. *Agric Ecosyst Environ* **265**:488–502 (2018).
43 Nichols V, Verhulst N, Cox R and Govaerts B, Weed dynamics and conservation agriculture principles: a review. *Field Crop Res* **183**:56–68 (2015).
44 Kumar V, Mahajan G, Dahiya S and Chauhan BS, Challenges and opportunities for weed management in no-till farming systems, in *No-Till Farming Systems for Sustainable Agriculture: Challenges and Opportunities*, ed. by Dang YP, Dalal RC and Menzies NW. Springer International Publishing, Cham, pp. 107–125 (2020).
45 Eslami SV, Weed management in conservation agriculture systems, in *Recent Advances in Weed Management*, ed. by Chauhan BS and Mahajan G. Springer, New York, NY, pp. 87–124 (2014).
46 Klimešová J and Martínková J, Clonal growth, resprouting and vegetative propagation of weeds, in *Persistence Strategies of Weeds*, ed. by Upadhyaya MK. John Wiley & Sons, Ltd, Clements DR and Shrestha A, pp. 200–218 (2022).
47 Légère A and Samson N, Tillage and Weed Management effects on weeds in barley-red clover cropping systems. *Weed Sci* **52**:881–885 (2004).
48 Derrouch D, Chauvel B, Cordeau S and Dessaint F, Functional shifts in weed community composition following adoption of conservation agriculture. *Weed Res* **62**:103–112 (2022).
49 Zanin G, Otto S, Riello L and Borin M, Ecological interpretation of weed flora dynamics under different tillage systems. *Agric Ecosyst Environ* **66**:177–188 (1997).
50 Heijting S, Werf WVD, Kruijer W and Stein A, Testing the spatial significance of weed patterns in arable land using Mead's test. *Weed Res* **47**:396–405 (2007).
51 Walsh MJ, Broster JC, Schwartz-Lazaro LM, Norsworthy JK, Davis AS, Tidemann BD *et al*., Opportunities and challenges for harvest weed seed control in global cropping systems. *Pest Manag Sci* **74**:2235–2245 (2018).
52 Buchanan AL, Kolb LN and Hooks CRR, Can winter cover crops influence weed density and diversity in a reduced tillage vegetable system? *Crop Prot* **90**:9–16 (2016).
53 MacLaren C, Swanepoel P, Bennett J, Wright J and Dehnen-Schmutz K, Cover crop biomass production is more important than diversity for weed suppression. *Crop Sci* **59**:733–748 (2019).
54 Smith RG and Gross KL, Assembly of weed communities along a crop diversity gradient. *J Appl Ecol* **44**:1046–1056 (2007).
55 Marshall EJP and Brain P, The horizontal movement of seeds in arable soil by different soil cultivation methods. *J Appl Ecol* **36**:443–454 (1999).
56 Streit B, Rieger SB, Stamp P and Richner W, The effect of tillage intensity and time of herbicide application on weed communities and populations in maize in central Europe. *Agric Ecosyst Environ* **92**: 211–224 (2002).
57 Trichard A, Alignier A, Chauvel B and Petit S, Identification of weed community traits response to conservation agriculture. *Agric Ecosyst Environ* **179**:179–186 (2013).
58 Futerman SI, Laor Y, Eshel G and Cohen Y, The potential of remote sensing of cover crops to benefit sustainable and precision fertilization. *Sci Total Environ* **891**:164630 (2023).
59 Nikolić N, Mattivi P, Pappalardo SE, Miele C, De Marchi M and Masin R, Opportunities from unmanned aerial vehicles to identify differences in weed spatial distribution between conventional and conservation agriculture. *Sustainability* **14**:6324 (2022).
60 Israeli A, Emmerich M, Litaor M and Shir O, *Statistical Learning in Soil Sampling Design Aided by Pareto Optimization. Proceedings of the Genetic and Evolutionary Computation Conference; 2019 Jul 13-17; Prague, Czech Republic*, Association for Computing Machinery (ACM), New York (2019).
61 Fried G, Norton LR and Reboud X, Environmental and management factors determining weed species composition and diversity in France. *Agric Ecosyst Environ* **128**:68–76 (2008).
62 Gafni R, Ziv GA, Eizenberg H and Blank L, A regional-scale study of the contribution of local, management and climate factors to the infestation of processing tomato fields with Amaranthus species. *Eur J Agron* **143**:126722 (2023).
63 Marshall EJP, Distribution patterns of plants associated with arable field edges. *J Appl Ecol* **26**:247–257 (1989).
64 Cervantes E, Martín-Gómez JJ, del Pozo DG and Tocino Á, Curvature analysis of seed silhouettes in the Euphorbiaceae. *Seeds* **3**:608–638 (2024).
65 Peerzada AM, Bajwa AA, Ali HH and Chauhan BS, Biology, impact, and management of *Echinochloa colona* (L.) link. *Crop Prot* **83**:56–66 (2016).
66 Assad R, Reshi ZA, Jan S and Rashid I, Biology of amaranths. *Bot Rev* **83**:382–436 (2017).
67 Horowitz M, Growth, tuber formation and spread of Cyperus Rotundus L. from single tubers. *Weed Res* **12**:348–363 (1972).
68 Cortat G, Convolvulus arvensis (bindweed). *CABI Compendium*, Record No. 15101, CABI https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.15101 [accessed 4 May 2025] (2016).
69 Gigot C, Sparks AH and Leinweber K, epiphy: Analysis of Plant Disease Epidemics (2023).
70 Lloyd M, Mean crowding. *J Anim Ecol* **36**:1–30 (1967).
71 Wade MJ, Fitzpatrick CL and Lively CM, 50-year anniversary of Lloyd's “mean crowding”: ideas on patchy distributions. *J Anim Ecol* **87**: 1221–1226 (2018).
72 Moran PA, Notes on continuous stochastic phenomena. *Biometrika* **37**:17–23 (1950).
73 Shefy D, Guerrini G, Marom N, Shashar N and Rinkevich B, Settling in aggregation: spatial planning consideration for brooding coral transplants. *Mar Environ Res* **176**:105612 (2022).
74 Cardina J, Sparrow DH and McCoy EL, Analysis of spatial distribution of common Lambsquarters (*Chenopodium album*) in No-till soybean (Glycine max). *Weed Sci* **43**:258–268 (1995).
75 Mulugeta D and Boerboom CM, Seasonal abundance and spatial pattern of Setaria faberi, Chenopodium album, and Abutilon theophrasti in reduced-tillage soybeans. *Weed Sci* **47**:95–106 (1999).
76 Rozenberg G, Kent R and Blank L, Consumer-grade UAV utilized for detecting and analyzing late-season weed spatial distribution patterns in commercial onion fields. *Precis Agric* **22**:1317–1332 (2021).
77 Brooks M, Bolker B, Kristensen K, Maechler M, Magnusson A, McGillycuddy M *et al*., glmmTMB: Generalized Linear Mixed Models using Template Model Builder (2024).
78 Hartig F and Lohse L, DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models (2022).
79 Lenth RV, emmeans: Estimated Marginal Means, aka Least-Squares Means (2023).
80 Fox J and Weisberg S, *Car: Companion to Applied Regression*. Sage, Thousand Oaks, CA (2019).
81 Pollnac FW, Rew LJ, Maxwell BD and Menalled FD, Spatial patterns, species richness and cover in weed communities of organic and conventional no-tillage spring wheat systems. *Weed Res* **48**:398–407 (2008).
82 Fonteyne S, Singh RG, Govaerts B and Verhulst N, Rotation, mulch and zero tillage reduce weeds in a long-term conservation agriculture trial. *Agronomy* **10**:962 (2020).

83 Légère A, Stevenson FC and Ziadi N, Contrasting responses of weed communities and crops to 12 years of tillage and fertilization treatments. *Weed Technol* **22**:309–317 (2008).

84 Alarcón R, Hernández-Plaza E, Navarrete L, Sánchez MJ, Escudero A, Hernanz JL *et al*., Effects of no-tillage and non-inversion tillage on weed community diversity and crop yield over nine years in a Mediterranean cereal-legume cropland. *Soil Tillage Res* **179**:54–62 (2018).

85 Pratibha G, Srinivas I, Madhavi M, Indoria A, Murthy K, Reddy S *et al*., Weed shift and community diversity in conservation and conventional agriculture systems in pigeonpea-castor systems under rainfed semi-arid tropics. *Soil Tillage Res* **212**:105075 (2021).

86 Castaldi F, Pelosi F, Pascucci S and Casa R, Assessing the potential of images from unmanned aerial vehicles (UAV) to support herbicide patch spraying in maize. *Precis Agric* **18**:76–94 (2017).

87 Timmermann C, Gerhards R and Kühbauch W, The economic impact of site-specific weed control. *Precis Agric* **4**:249–260 (2003).

88 Gerhards R, Sökefeld M, Schulze-Lohne K, Mortensen DA and Kühbauch W, Site specific weed control in winter wheat. *J Agron Crop Sci* **178**:219–225 (1997).

89 Martín CS, Andújar D, Fernández-Quintanilla C and Dorado J, Spatial distribution patterns of weed communities in corn fields of central Spain. *Weed Sci* **63**:936–945 (2015).

90 Nordmeyer H, Patchy weed distribution and site-specific weed control in winter cereals. *Precis Agric* **7**:219–231 (2006).

91 Hamouz P, Hamouzová K, Holec J and Tyšer L, Impact of site-specific weed management on herbicide savings and winter wheat yield. *Plant Soil Environ* **59**:101–107 (2013).

92 Hamouz P, Soukup J, Holec J and Jursík M, Field-scale variability of weediness on arable land. *Plant Soil Environ* **50**:134–140 (2011).

93 Gafni R, Blank L and Eizenberg H, Variability in germination fractions of Amaranthus albus in response to weed management and abiotic maternal conditions. *Eur J Agron* **152**:127009 (2024).

94 Peerzada AM, Biology, agricultural impact, and management of Cyperus rotundus L.: the world's most tenacious weed. *Acta Physiol Plant* **39**:270 (2017).

95 Davis S Mangold J Menalled F Orloff N Miller Z Lehnhoff E A meta-analysis of field bindweed (*Convolvulus arvensis*) management in annual and perennial systems *Weed Sci* **66** 540 547 Cambridge University Press 2018

96 Gafni R, Nassar JA, Matzrafi M, Blank L and Eizenberg H, Unraveling the reasons for failure to control Amaranthus albus: insights into herbicide application at different growth stages, temperature effect, and herbicide resistance on a regional scale. *Pest Manag Sci* **80**: 4757–4769 (2024).

97 Widderick MJ, Bell KL, Boucher LR and Walker SR, Control by glyphosate and its alternatives of glyphosate-susceptible and glyphosate-resistant *Echinochloa colona* in the fallow phase of crop rotations in subtropical Australia. *Weed Biol Manag* **13**:89–97 (2013).

98 Kim D-S, Caseley JC, Brain P, Riches CR and Valverde BE, Rapid detection of propanil and fenoxaprop resistance in *Echinochloa colona*. *Weed Sci* **48**:695–700 (2000).

99 Tranel PJ, Herbicide resistance in *Amaranthus tuberculatus*†. *Pest Manag Sci* **77**:43–54 (2021).

100 Matzrafi M, Scarabel L, Milani A, Iamonico D, Torra J, Recasens J *et al*., *Amaranthus palmeri* S. Watson: a new threat to agriculture in Europe and the Mediterranean region. *Weed Res* **65**:e12596 (2025).

101 Clay SA, Kreutner B, Clay DE, Reese C, Kleinjan J and Forcella F, Spatial distribution, temporal stability, and yield loss estimates for annual grasses and common ragweed (*ambrosia artimisiifolia*) in a corn/soybean production field over nine years. *Weed Sci* **54**:380–390 (2006).

102 Jurado-Expósito M, López-Granados F, González-Andújar JL and García-Torres L, Spatial and temporal analysis of *Convolvulus arvensis* L. populations over four growing seasons. *Eur J Agron* **21**:287–296 (2004).

103 Rafenomanjato A, Ripoche A, Marnotte P, Letourmy P, Autfray P, Randriamampianina JA *et al*., No-till with cover crop affects weed community and improves weed management in upland rainfed rice in Madagascar. *Weed Res* **63**:175–185 (2023).

104 Koller M and Lanini WT, Site-specific herbicide applications based on weed maps provide effective control. *Calif Agric* **59**:182–187 (2005).

105 Mor-Mussery A, Zaady E, Lansky I, Shuker S, Abu-Glion H and Blank L, Quantifying the dynamic of cereals and broadleaf plants in semi-arid grasslands using a high-spatial-resolution satellite imaging. *Agric Ecosyst Environ* **377**:109233 (2025).

106 Mor-Mussery A, Zaady E, Muklada H and Blank L, Wild cereal species change as an indicator of desertification in arid lands. *Remote Sens Appl Soc Environ* **38**:101605 (2025).

107 Gašparović M, Zrinjski M, Barković Đ and Radočaj D, An automatic method for weed mapping in oat fields based on UAV imagery. *Comput Electron Agric* **173**:105385 (2020).

108 Rozenberg G, Dias JLCS, Anderson WM, Sellers BA, Boughton RK, Piccolo MB *et al*., Using a low-cost unmanned aerial vehicle for mapping giant smutgrass in bahiagrass pastures. *Precis Agric* **24**:971–985 (2023).

109 Booth BD and Swanton CJ, Assembly theory applied to weed communities. *Weed Sci* **50**:2–13 (2002).

110 Bourgeois B, Gaba S, Plumejeaud C and Bretagnolle V, Weed diversity is driven by complex interplay between multi-scale dispersal and local filtering. *Proc R Soc Lond B Biol Sci* **287**:20201118 (2020).

111 Freckleton RP, Hicks HL, Comont D, Crook L, Hull R, Neve P *et al*., Measuring the effectiveness of management interventions at regional scales by integrating ecological monitoring and modelling. *Pest Manag Sci* **74**:2287–2295 (2018).

112 Pätzold S, Hbirkou C, Dicke D, Gerhards R and Welp G, Linking weed patterns with soil properties: a long-term case study. *Precis Agric* **21**:569–588 (2020).

113 Derrouch D, Chauvel B, Felten E and Dessaint F, Weed Management in the transition to conservation agriculture: farmers' response. *Agronomy* **10**:843 (2020).

114 Derrouch D, Dessaint F, Fried G and Chauvel B, Weed community diversity in conservation agriculture: post-adoption changes. *Agric Ecosyst Environ* **312**:107351 (2021).

115 Cordeau S, Guillemin J-P, Reibel C and Chauvel B, Weed species differ in their ability to emerge in no-till systems that include cover crops. *Ann Appl Biol* **166**:444–455 (2015).

116 Zamljen SA, Rovanšek A and Leskovšek R, Weed seed bank response during the early conversion period to less intensive tillage systems. *Soil Tillage Res* **242**:106164 (2024).

117 Odhiambo JA, Norton U, Ashilenje D, Omondi EC and Norton JB, Weed dynamics during transition to conservation agriculture in western Kenya maize production. *PLoS One* **10**:e0133976 (2015).

118 Buhler DD, Stoltenberg DE, Becker RL and Gunsolus JL, Perennial weed populations after 14 years of variable tillage and cropping practices. *Weed Sci* **42**:205–209 (1994).

119 Ciaccia C, Armengot Martinez L, Testani E, Leteo F, Campanelli G and Trinchera A, Weed functional diversity as affected by agroecological service crops and no-till in a mediterranean organic vegetable system. *Plants* **9**:689 (2020).