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Weed control efficacy and economic profitability of three contrasting cropping systems in semiarid rainfed zones

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Abstract

Promoting sustainable agriculture in the semiarid, rainfed areas of central Spain requires understanding how weed populations respond to different cropping systems and evaluating the economic profitability of these systems. A 6-yr field experiment compared three systems: a no-till barley (*Hordeum vulgare* L.) monoculture with fertilizers and herbicides (NT); a 2-yr rotation of grain legume or false flax [*Camelina sativa* (L.) Crantz] followed by barley, with reduced tillage and agrochemicals (MW); and a 3-yr fallow–grain legume–barley rotation under organic practices (ORG). Results showed that NT consistently provided the most effective weed control, reducing total weed density by 79% to 84% compared with ORG over the last 3 yr of the study. MW also significantly reduced total weed density by 11% to 75% relative to ORG, although some species increased. ORG was the least effective system, with weed densities reaching 395 plants m^{-2} and the lowest control efficacy. Weed population dynamics varied by management. Rigid ryegrass (*Lolium rigidum* Gaudin) was effectively controlled in NT through a consistent annual herbicide program and in MW by combining periodic tillage with targeted herbicide applications; however, it was extremely difficult to manage in ORG. Corn poppy (*Papaver rhoeas* L.) increased over time in all systems, while other species showed no clear trends. Weed species diversity was lowest in NT, with mean species richness reduced by 34% to 39% compared with ORG and by 13% to 17% compared with MW. Economic analysis revealed the highest adjusted net returns in MW and the lowest in ORG, driven by differences in crop sequences, yields, and subsidies from the European Common Agricultural Policy. These findings offer valuable insights for optimizing weed management in rainfed cereal systems, highlighting the importance of integrated approaches that balance effective weed control, crop productivity, and economic viability.

Introduction

Modern agriculture faces several challenges, including feeding a growing global population, adapting to a changing and more unstable climate, managing finite resources, and providing diverse ecosystem services (Arowolo et al. 2018; Yang et al. 2024). To address these demands, the concept of sustainable intensification—hereafter referred to as sustainable productivity enhancement—has emerged as a guiding framework, aiming to increase agricultural output while upholding rigorous environmental, economic and social standards (Pretty et al. 2018; Pretty and Bharucha 2014).

Among strategies for sustainable productivity enhancement, conservation agriculture and organic farming have received significant attention (Gamage et al. 2023; Jat et al. 2020; Peigné et al. 2016; Rigby and Cáceres 2001; Tahat et al. 2020). Conservation agriculture emphasizes minimal soil disturbance to reduce erosion, lower carbon emissions, decrease energy use, and make production more cost-efficient (Jat et al. 2020, 2021; Neeraj et al. 2025). No-tillage farming, a cornerstone of this approach, is now practiced on about 125 million ha worldwide (Kassam et al. 2019). However, the sustainability of no-till practices remains debated due to concerns about yield variability across farming contexts (Giller et al. 2015; Pittelkow et al. 2015), reliance on herbicides for weed control (Friedrich and Kassam 2012), and their limited effectiveness in mitigating climate change (Powlson et al. 2014).

Organic farming, in contrast, prioritizes ecosystem health and avoids synthetic inputs, relying instead on mechanical and cultural management. Despite these benefits, organic systems are often criticized for lower productivity, which may require greater land use, potentially leading to deforestation and biodiversity loss (Balmford et al. 2018; Seufert and Ramankutty 2017; Seufert et al. 2012; Trewavas 2001).

Weed management remains a persistent challenge in all cropping systems due to its direct impact on crop productivity and profitability (Oerke 2006). In no-till systems, weed control is heavily dependent on herbicides like glyphosate applied before sowing (Neve et al. 2024). While effective initially, this reliance has led to widespread herbicide resistance (Powles and Yu 2010; Price et al. 2011) and environmental concerns about herbicide contamination of water resources (Mortensen et al. 2012). Organic systems, by contrast, rely on labor-intensive weed management practices, which are often less effective and more costly (Benaragama et al. 2016). Frequent tillage in organic systems can also exacerbate soil erosion and deplete organic matter (Jordan and Davis 2015; Williams and Hedlund 2013).

To address these limitations, integrated weed management strategies have been proposed, combining elements from conventional, conservation, and organic systems (Jordan and Davis 2015). This "middle-way" approach is based on three core principles: (1) diversifying crop rotations with species of varying phenology and management needs; (2) employing real-time weed control measures based on weed community dynamics during the season; and (3) focusing on reducing weed seedbanks as a long-term strategy (Davis et al. 2012). Judicious herbicide use is reserved for fine-tuning rather than routine reliance, offering a promising path toward sustainable weed management.

Weed communities are highly adaptive to local cropping systems. Research has shown that crop sequencing and tillage practices influence weed density, diversity, and community structure (Benaragama et al. 2016, 2019; Cardina et al. 2002; Davis et al. 2005; Sosnoskie et al. 2006). Monoculture no-till systems can aggravate weed problems compared with diversified rotations (Nichols et al. 2015). For example, a comprehensive 35-yr study in the United States demonstrated that crop rotation and tillage practices—including no-till, conventional, and minimum tillage systems—significantly influence the composition of the weed seedbank (Sosnoskie et al. 2006). Similarly, an 18-yr study in the Canadian Prairies found that reducing tillage and agrochemical use is feasible but that improved crop rotations are essential to eliminate herbicide reliance (Benaragama et al. 2016). Subsequent research in the same region identified cropping system and annual environmental variation as the main drivers of weed community changes (Benaragama et al. 2019). In Spain, studies have highlighted the strong influence of tillage practices on weed community composition in dryland cereal systems (Alarcón et al. 2018; Dorado et al. 1999; Dorado and López-Fando 2006; Hernández-Plaza et al. 2015; Sans et al. 2011). For instance, reduced tillage in a 3-yr organic rotation led to significantly higher total and perennial weed cover than conventional treatments (Sans et al. 2011). Cereal monocropping combined with no-tillage often increases the prevalence of weeds like *L. rigidum* and ripgut brome (*Bromus diandrus* Roth) (Recasens et al. 1996), although targeted management (e.g., delayed sowing, selective herbicides) can be effective (García et al. 2014).

In the semiarid, rainfed agricultural systems of central Spain, winter cereals account for about 73% of dryland areas, while grain legumes represent only 7% (MAPAMA 2025), mainly due to perceived lower profitability (Preissel et al. 2015). However, research indicates that rotations including grain legumes can yield equal or higher gross margins than standard rotations in Spain and elsewhere in Europe (Nemecek et al. 2008; Preissel et al. 2015). Grain legumes also help mitigate environmental impacts and offer benefits such as reduced nitrogen fertilizer needs and improved yields in subsequent crops (Nemecek et al. 2008; Preissel et al. 2015).

This study evaluates three contrasting cropping systems adapted to the semiarid conditions of central Spain: continuous no-tillage barley (*Hordeum vulgare* L.) monoculture, an integrated middle-way approach featuring a 2-yr crop rotation, and an organic farming system with a 3-yr crop rotation scheme. The objectives were to assess weed control efficacy, analyze weed population dynamics, and provide an economic evaluation of each approach under local conditions.

Materials and Methods

Experimental Site and Design

A long-term field experiment was conducted at La Poveda Research Station, Arganda del Rey, Madrid, Spain (40.314602°N, 3.486397°W), from the 2014 to 2015 to the 2020 to 2021 cropping seasons. Hereafter, seasons are referred to by their harvest years. The experimental site, located in the Jarama River basin at an altitude of 535 m, features a loam Entisol (Xerofluvent) soil with 34% sand, 43% silt, and 23% clay; organic matter content of 2.13%; and a pH (measured in water) of 8.1. The study area has a semiarid dryland climate characterized by an average annual precipitation of 400 mm, significant thermal variation (mean annual temperature of 13.5 C), high evapotranspiration rates, and irregular precipitation patterns. During the six cropping seasons, accumulated precipitation from November to June ranged from 190 mm in 2019 to 383 mm in 2018, as shown in Figure 1. This figure also illustrates monthly values of the Standardized Precipitation Evapotranspiration Index (SPEI), obtained from the map visualization tool at http://monitordesequia.csic.es (Vicente-Serrano et al. 2017) for the period September 2015 to August 2021 at the research station. The uneven rainfall distribution, with marked droughts during winter (e.g., 2016, 2018, and 2019) and spring (e.g., 2017 and 2019), likely impacted both weed emergence and crop yields.

The experiment was set up as a split-plot design with four replicates. Main plots were assigned to three cropping systems differing in objectives, constraints, and decision-making protocols (Table 1): (1) intensive no-till (NT), featuring a barley monoculture under no-till with standard fertilization and herbicide inputs; (2) middle way (MW), involving a 2-yr pea (*Pisum sativum* L.) or false flax [*Camelina sativa* (L.) Crantz]–barley rotation with reduced tillage and minimal inputs; and (3) organic farming (ORG), comprising a 3-yr fallow–grain legume–barley rotation managed according to organic standards. To account for rotational phases, main plots were subdivided into subplots (Figure 2): NT (monoculture) consisted of a single subplot, while MW and ORG main plots were divided into two (MW1, MW2) and three (ORG1, ORG2, ORG3) subplots, respectively, each representing a different crop sequence. This design ensured annual representation of all rotational crops (Lechenet et al. 2017). Each subplot measured 50 m by 21 m, covering a total experimental area of approximately 3 ha (6 subplots by 1,050 m^2 by 4 blocks).

In 2015, before the cropping systems were initiated, a uniform barley crop was established under conventional tillage without targeted weed control to homogenize field conditions.

Field Operations

The NT cropping system involved monoculture barley ('Hispanic') sown in 18-cm rows using a Solà SD-1303 no-till seed drill (Maquinària Agrícola Solà, 08280 Calaf, Barcelona, Spain) at a rate of 180 kg ha^{-1}. Sowing dates ranged from mid-November to mid-

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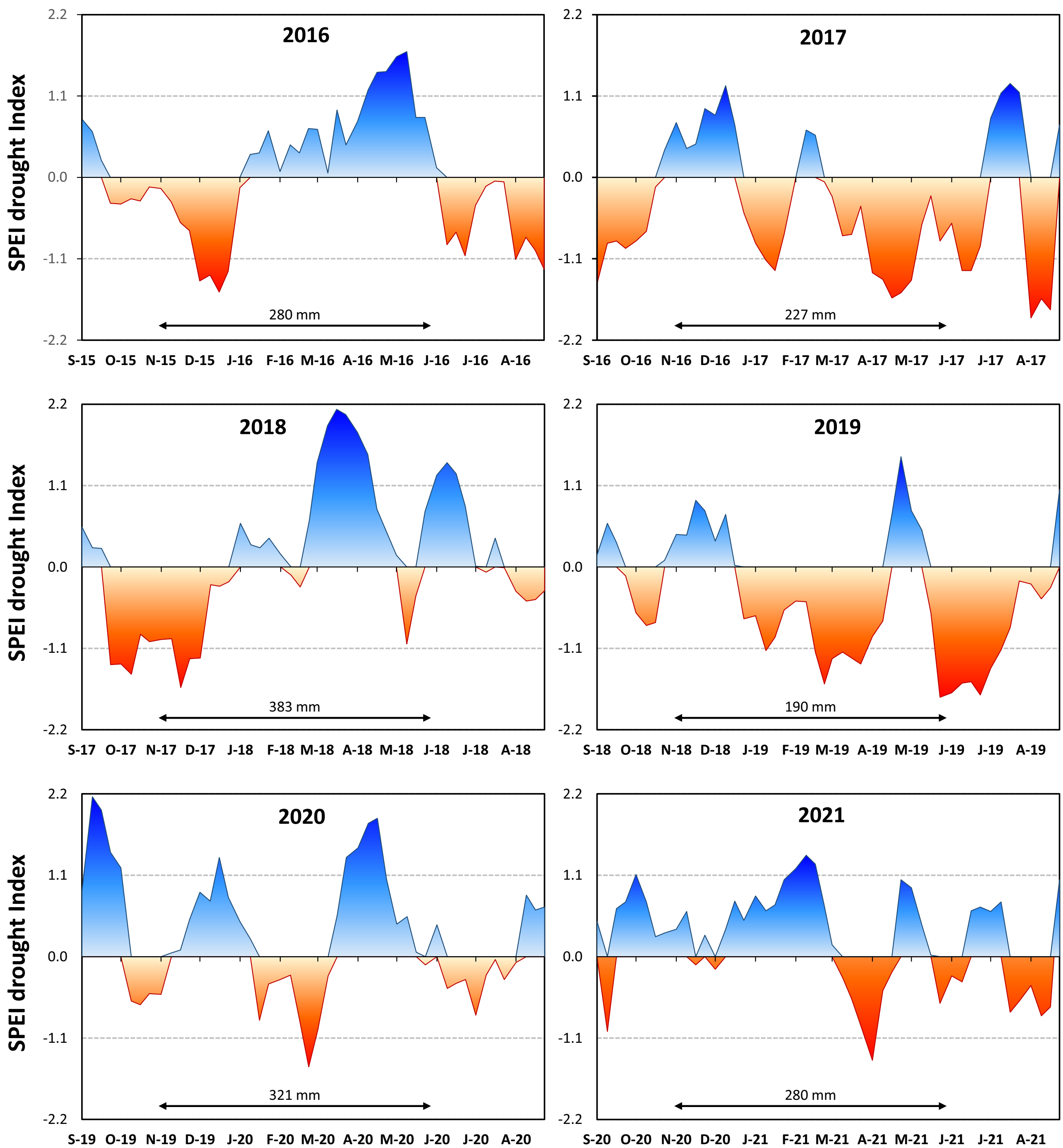

Figure 1. Standardized Precipitation Evapotranspiration Index (SPEI) drought index (Vicente-Serrano et al. 2017) calculated from the environmental data recorded at the Arganda del Rey weather station (located 750 m from the experimental site), for the years 2016 to 2021. The values expressed in millimeters (mm) represent the accumulated precipitation during the cropping season, defined here as the period from November to June.

December, depending on the year. In 2017, shallow rototillage (~10 cm) was required to incorporate excessive straw from the previous crop into the soil, thereby enabling no-till seeding. Weed control included a pre-sowing glyphosate (Touchdown Premium, 1,080 g ai ha^{-1}, Syngenta España SAU, 28042 Madrid, Spain) application and two postemergence treatments: one for broadleaved weeds with thifensulfuron + tribenuron (Amadeus Top, 16+6 g ai ha^{-1}, Syngenta), and one for grasses with diclofop (Iloxan, 426 g L ai ha^{-1}, Bayer Hispania SL, 08970 Sant Joan Despí, Barcelona, Spain) or pinoxaden (Axial Pro, 42 g ai ha^{-1}, Syngenta). Additionally, a postharvest glyphosate (Touchdown Premium, 1,080 g ai ha^{-1}, Syngenta) application was applied in 2018 to manage weeds in the stubble. Fertilization included 400 kg ha^{-1} of 8-15-15 N-P-K before sowing and 190 kg ha^{-1} of ammonium sulfate nitrate (26%) in spring.

The MW cropping system consisted of a two-phase annual rotation, alternating barley with winter peas or false flax. Barley (Hispanic) was sown from mid-November to mid-December, in

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Table 1. Objectives, constraints, and decision rules of the three cropping systems: no-till (NT), middle way (MW), and organic farming (ORG).

	NT	MW	ORG
Objectives	Reducing production costs, labor input, and soil erosion	Reducing reliance on herbicides and soil tillage Optimizing economic profitability	Avoiding the use of agrochemicals Minimizing environmental impacts
Constraints	High reliance on herbicide use	High complexity	High reliance on soil tillage Low yields
Decision rules:			
Crop rotation	Monoculture	2 yr	3 yr
Soil tillage	No	Every 2 yr	Intensive
Herbicides	Prophylactic	Only if needed	No
Mechanical weeding	No	Every 2 yr	Every year
Fertilizers	Synthetic NPK	Synthetic NPK	Organic PK

Block	Cropping system	Crop sequence (2016 to 2021)	Crop growing in year						
			2015	2016	2017	2018	2019	2020	2021
1	NT	B-B-B-B-B-B	Barley	Barley	Barley	Barley	Barley	Barley	Barley
	MW2	B-A-B-A-B-A	Barley	Barley	Winter peas	Barley	False flax	Barley	False flax
	MW1	A-B-A-B-A-B	Barley	Winter peas	Barley	False flax	Barley	False flax	Barley
	ORG3	B-F-A-B-F-A	Barley	Barley	Fallow	Spring peas	Barley	Fallow	Spring peas
	ORG1	F-A-B-F-A-B	Barley	Fallow	Vetch	Barley	Fallow	Spring peas	Barley
	ORG2	A-B-F-A-B-F	Barley	Winter peas	Barley	Fallow	Spring peas	Barley	Fallow
2	MW1	A-B-A-B-A-B	Barley	Winter peas	Barley	False flax	Barley	False flax	Barley
	MW2	B-A-B-A-B-A	Barley	Barley	Winter peas	Barley	False flax	Barley	False flax
	ORG2	A-B-F-A-B-F	Barley	Winter peas	Barley	Fallow	Spring peas	Barley	Fallow
	ORG1	F-A-B-F-A-B	Barley	Fallow	Vetch	Barley	Fallow	Spring peas	Barley
	ORG3	B-F-A-B-F-A	Barley	Barley	Fallow	Spring peas	Barley	Fallow	Spring peas
	NT	B-B-B-B-B-B	Barley	Barley	Barley	Barley	Barley	Barley	Barley
3	ORG2	A-B-F-A-B-F	Barley	Winter peas	Barley	Fallow	Spring peas	Barley	Fallow
	ORG1	F-A-B-F-A-B	Barley	Fallow	Vetch	Barley	Fallow	Spring peas	Barley
	ORG3	B-F-A-B-F-A	Barley	Barley	Fallow	Spring peas	Barley	Fallow	Spring peas
	MW1	A-B-A-B-A-B	Barley	Winter peas	Barley	False flax	Barley	False flax	Barley
	MW2	B-A-B-A-B-A	Barley	Barley	Winter peas	Barley	False flax	Barley	False flax
	NT	B-B-B-B-B-B	Barley	Barley	Barley	Barley	Barley	Barley	Barley
4	MW1	A-B-A-B-A-B	Barley	Winter peas	Barley	False flax	Barley	False flax	Barley
	MW2	B-A-B-A-B-A	Barley	Barley	Winter peas	Barley	False flax	Barley	False flax
	NT	B-B-B-B-B-B	Barley	Barley	Barley	Barley	Barley	Barley	Barley
	ORG3	B-F-A-B-F-A	Barley	Barley	Fallow	Spring peas	Barley	Fallow	Spring peas
	ORG1	F-A-B-F-A-B	Barley	Fallow	Vetch	Barley	Fallow	Spring peas	Barley
	ORG2	A-B-F-A-B-F	Barley	Winter peas	Barley	Fallow	Spring peas	Barley	Fallow

Figure 2. Plot distribution by block and crop rotation sequences (2015–2021) for each cropping system: MW1 and MW2, two different crop sequences within the middle-way system; NT, no-tillage (single sequence); ORG1, ORG2, and ORG3, three different crop sequences within the organic system. The crop sequence column shows the yearly succession of crops grown on the same plot. Crop codes: A, alternative crop (winter peas or false flax in the middle-way system; winter peas, vetch, or spring peas in the organic system); B, barley; F, fallow.

18-cm rows using the same drill and rate as NT. Weed management in barley crop employed a comprehensive strategy. Pre-sowing glyphosate (Touchdown Premium, 1,080 g ai ha^{-1}, Syngenta) was applied annually. Postemergence herbicide use varied by year, based on weed sampling and IPMWise recommendations (Montull et al. 2020), including: diclofop (Iloxan, 540 g ai ha^{-1}, Bayer) in 2016; thifensulfuron + tribenuron (Amadeus Top, 20+10 g ai ha^{-1}, Syngenta) and pinoxaden (Axial Pro, 42 g ai ha^{-1}, Syngenta) in 2017; thifensulfuron + tribenuron (Amadeus Top, 19+9 g ai ha^{-1}, Syngenta) and pinoxaden (Axial Pro, 45 g ai ha^{-1}, Syngenta) in 2018; bromoxynil (Buctril, 281 g ai ha^{-1}, Bayer) and iodosulfuron (Hussar® Plus, 8 g ai ha^{-1}, Bayer) in 2019; thifensulfuron + tribenuron (Amadeus Top, 16+6 g ai ha^{-1}, Syngenta) and pinoxaden (Axial Pro, 41 g ai ha^{-1}, Syngenta) in 2020; and florasulam + tritosulfuron (Biathlon® 4D, 3+37 g ai ha^{-1}, BASF Española SLU, 08017 Barcelona, Spain) and pinoxaden (Axial Pro, 60 g ai ha^{-1}, Syngenta) in 2021. In the alternative crop phase, peas ('Comanche') were sown either in late November (2016) or early January (2017) at a sowing rate of 120 kg ha^{-1}. Soil preparation involved a moldboard plow and a rototill, followed by roller operations. Postemergence herbicides were bentazone (Troy®, 461 g ai ha^{-1}, UPL Iberia SA, 08109 Barcelona, Spain) and diclofop (Iloxan, 540 g ai ha^{-1}, Bayer). From 2018 to 2021, false flax was broadcast seeded (8 kg ha^{-1}) between late November and early December, using a Kverneland DA Pneumatic seed drill (Kverneland Group UK, Walkers Lane, Lea Green, St Helens, Merseyside, WA9 4AF, UK), and incorporated via harrowing. No herbicides were applied. Soil preparation involved one to three tillage operations using a disk harrow, rototill, and/or field cultivator. Fertilization included ammonium sulfate nitrate (190 kg ha^{-1}) for barley and 8-11-11 N-P-K (365 kg ha^{-1}) for peas. False flax received no fertilizers.

The ORG cropping system implemented a three-phase annual rotation, including barley, legumes, and fallow. Barley (Hispanic) was sown from mid-November to mid-December, in 12-cm rows using a Kverneland DA Pneumatic drill at a rate of 160 kg ha^{-1}. Pre-sowing tillage involved one to three passes (rototill, field cultivator, or moldboard plow when necessary). A tine harrow was used in early spring 2016 and 2017 to manage broadleaved weeds, but this practice was discontinued due to crop damage. In our study, fallow management—according to the European Union's Common Agricultural Policy (CAP) framework—consisted of leaving the land uncultivated for 1 yr while maintaining it weed-free through three to five tillage operations, using a disk harrow and a rototill. During the legume phase of the crop rotation, different legume species were grown sequentially over the years: winter peas (Comanche) in 2016; a mixture of common vetch (*Vicia sativa* L.) and oat (*Avena sativa* L.) in 2017; and spring peas from 2018 to 2021 ('Arthur' in 2018 and 2019; 'Viriato' in 2020; 'Ganster' in 2021). These adjustments were made in response to the high weed pressure observed during the initial years of the study (2016 to 2017), particularly during the legume phase, which prompted the evaluation of more competitive legume species and the implementation of improved weed control strategies under organic management. Notably, the adoption of spring peas allowed for wider row spacing, thereby facilitating mechanical interrow cultivation. This modification reflects the adaptive cropping systems approach described by Lechenet et al. (2017), which supports dynamic adjustments to crop selection and management practices in response to emerging agronomic challenges throughout the cropping cycle. Seeding rates and row spacing varied by species and season: winter peas and the vetch–oat mixture were sown in 18-cm rows with a Solà SD-1303 seed drill at rates of 120 kg ha^{-1} and $80 + 17$ kg ha^{-1}, respectively, while spring peas were sown with the same drill, adjusted to 54-cm rows, at a rate of 90 kg ha^{-1}. Weed management relied on mechanical operations only, involving two to seven operations per season. These included pre-sowing tillage with a rototill and field cultivator, along with one or two interrow cultivations. An organic 0-15-10 N-P-K fertilizer was applied at a rate of 300 kg ha^{-1} in barley and 250 kg ha^{-1} in peas or vetch.

Data Collection

Weed density for each species was monitored annually in February, just before tillage or herbicide application, using 15 quadrats of 0.1 m^2 per subplot placed systematically on 5 m by 10 m grid, ensuring comprehensive coverage of the experimental area. From 2017 onward, surviving weed biomass was assessed in May using nine 1-m^2 quadrats per subplot distributed in a 5 m by 15 m grid. The annual growth rate (λ), defined as the ratio of weed density in a given year to that of the previous year ($\lambda = D_{t2}/D_{t1}$, where D is weed density), was calculated as a quantitative indicator of year-to-year changes in population dynamics This metric was used to evaluate the effectiveness of management practices in controlling weed populations over time: values of $\lambda > 1$ indicate population growth, $\lambda \approx 1$ indicate stability, and $\lambda < 1$ indicate a decline from one year to the next. Community structure was assessed via species richness, Shannon's evenness index (Shannon and Weaver 1949), and Simpson's diversity index (Simpson 1949).

Crop yields were assessed at crop maturity, typically in late June. In 2016, barley or peas were harvested in each subplot with a small-plot combine on a 1.5 m by 50 m central strip. From 2017 to 2021, barley, peas, or false flax crops were hand harvested from six 1.0- m^2 quadrats within each individual subplot, arranged in a 7 m by 12 m grid. Samples were processed using a laboratory thresher to separate the grains, which were then air cleaned and weighed. Yields were recorded at a moisture level of 10%.

Economic Analysis

Gross profit was calculated for each system, excluding fixed costs (such as land tenure, investment, administration, sales, distribution, and human labor, among others). Net returns were estimated by subtracting variable costs (e.g., diesel fuel, seeds, fertilizers, herbicides, mechanized agricultural operations) from total outputs. For calculating total outputs (€ ha^{-1}), the yields for each crop were multiplied by their corresponding market price (barley: €180 ton^{-1}; organic barley: €216 ton^{-1}; peas: €230 ton^{-1}; organic peas: €240 ton^{-1}; organic vetch: €230 ton^{-1}; false flax: €350 ton^{-1}) and adding the income support (i.e., direct payments) from CAP contribution, calculated using the application developed by the Spanish Unión de Pequeños Agricultores y Ganaderos (UPA 2024).

Statistical Analysis

The RStudio v. 2021.09.1 (RStudio Team 2020) LME4 and EMMEANS packages were used to assess weed density, biodiversity indices, and weed biomass, while the RStudio v. 2022.07.0 VEGAN and INDICSPECIES packages were used to analyze weed community composition. To avoid confounding due to high interannual variability, analyses were conducted separately by season.

Linear mixed-effects models were used to assess differences in weed density and biodiversity indices (measured in February), as well as weed biomass (measured in May), both among cropping systems (NT, MW, ORG) and among the different crop sequences implemented within these systems in the same year (NT, MW1, MW2, ORG1, ORG2, ORG3). In these models, cropping system or crop sequence was included as a fixed effect, while block nested within year was treated as a random effect to account for spatial and temporal variability. The complete model specification was as follows (Bates et al. 2014):

$$Y_{ijkl} = \mu + \alpha_i + b_{j(k)} + \varepsilon_{ijkl} \quad [1]$$

where Y_{ijkl} is the response variable (weed density, biodiversity index, or weed biomass) for the lth observation in the jth block within the kth year and the ith cropping system or crop sequence; μ is the overall mean; α_i is the fixed effect of the ith cropping system or crop sequence; $b_{j(k)}$ is the random effect of the jth block nested within the kth year; and ε_{ijkl} is the residual error term. Assumptions of normality and homogeneity were verified using Shapiro-Wilk and Levene's tests, respectively ($\alpha = 0.05$). Post hoc comparisons used Bonferroni-corrected t-tests. Results are presented as estimated means with standard errors or confidence intervals where appropriate.

Weed community composition was analyzed using nonmetric multidimensional scaling (NMDS) based on Bray-Curtis dissimilarities to represent in two dimensions the pattern and relationship in the data with stress values <2 indicating reliable representation (Oksanen et al., 2022). This analysis covered the years 2018 to 2021, following the completion of a full crop rotation in the MW system—that is, a compromise between the single-year (NT) and 3-yr (ORG) crop sequences. Species with less than 2% relative abundance were removed from the analysis. Differences among cropping systems were tested via permutational multivariate analysis of variance

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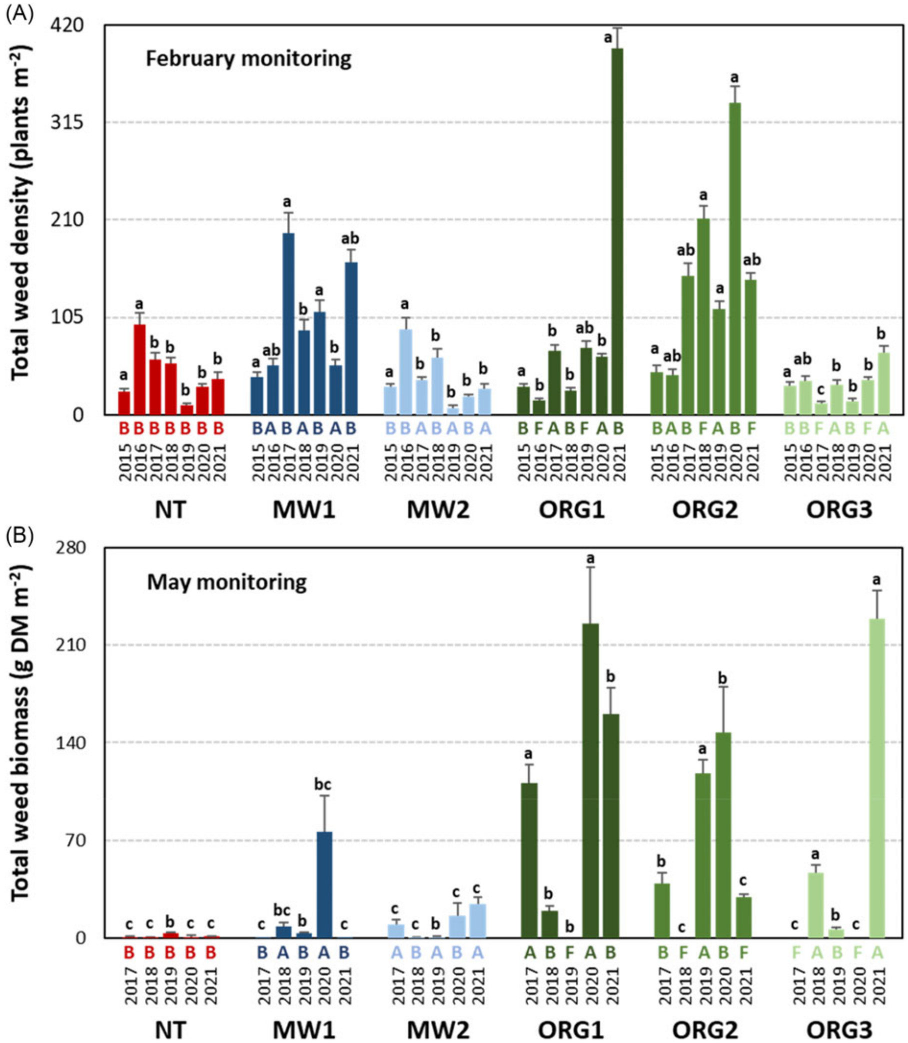

Figure 3. (A) Total weed densities (plants m^{-2}) recorded in winter samplings from 2015 to 2021, and (B) total weed biomass (g dry matter m^{-2}) recorded in spring samplings from 2017 to 2021. Crop sequences within cropping systems: MW1 and MW2, middle way system with different crop sequences; NT, no-tillage; ORG1, ORG2 and ORG3, organic system with different crop sequences. Crop codes: A, alternative crop (winter peas or false flax in the middle-way system; winter peas, vetch, or spring peas in the organic system); B, barley; F, fallow. Values followed by the same letter in the same year are not significantly different according to Bonferroni test at $P \leq 0.05$.

(PERMANOVA) with the *adonis2* function (limit = 999 permutations). Significant results were followed by pairwise tests with the *pairwise.adonis* function. An analysis to identify the species representative of each cropping system was conducted using the *multipatt* function.

Results and Discussion

Effects on Total Weed Density

In 2015, before the implementation of the treatments, winter weed populations ranged from 25 to 46 plants m^{-2} across the experimental area, with no significant differences among subplots (Supplementary Material). These values were considered the baseline weed infestations for each treatment. The evolution of total weed abundance in February (i.e., potential weed infestation) during the 2019 to 2021 period—corresponding to the seasons following the completion of a full crop rotation in ORG—revealed statistically significant differences among cropping systems. NT consistently maintained the lowest weed densities throughout this period, indicating stable suppression performance across years and across weed species. In contrast, ORG exhibited the highest weed infestations, with peak values reaching up to 395 plants m^{-2} in 2021. MW showed intermediate levels of weed abundance, accompanied by marked interannual variability. These results indicate that NT achieved the most consistent weed suppression, with reductions in winter weed density ranging from 79% to 84% relative to ORG. MW also resulted in significant reductions, although the magnitude of suppression varied by year (11% to 74%), and some weed species increased in density (Supplementary Material).

Total weed population growth rate (λ) varied among crop sequences within each cropping system (Figure 3A). In the NT system, total weed populations generally remained low between 2018 and 2021, with an average λ of 1.32, except for a marked increase in 2020 (λ = 2.90; Table 2). In contrast, the MW system showed variable λ depending on the crop: rates increased in barley plots but decreased in false flax plots, and weed densities increased in barley plots but decreased in false flax plots. Although no herbicides were applied during the false flax phase, the late sowing

Table 2. Annual rates of population growth (λ) of *Lolium rigidum*, *Papaver rhoeas*, and total weeds across different crop sequences within each cropping system[a].

Weed species	Cropping system[b]	2015 Crop	2016 Crop	2016 λ	2017 Crop	2017 λ	2018 Crop	2018 λ	2019 Crop	2019 λ	2020 Crop	2020 λ	2021 Crop	2021 λ	2018–2021 Avg. λ
L. rigidum	NT	B	B	8.51	B	0.18	B	1.29	B	0.10	B	2.31	B	2.68	1.60
	MW1	B	A	2.12	B	0.97	A	1.18	B	0.50	A	0.96	B	2.47	1.27
	MW2	B	B	6.99	A	0.03	B	2.91	A	0.34	B	1.55	A	2.69	1.87
	ORG1	B	F	0.78	A	2.97	B	0.16	F	9.30	A	0.71	B	9.63	4.95
	ORG2	B	A	1.17	B	3.64	F	2.15	A	0.47	B	3.46	F	0.37	1.61
	ORG3	B	B	1.79	F	0.17	A	3.90	B	0.10	F	5.99	A	1.13	2.78
P. rhoeas	NT	B	B	5.90	B	1.01	B	1.25	B	0.26	B	3.37	B	0.77	1.41
	MW1	B	A	0.74	B	4.57	A	0.52	B	0.33	A	3.67	B	2.18	1.67
	MW2	B	B	3.37	A	0.29	B	4.46	A	0.05	B	12.32	A	0.54	4.34
	ORG1	B	F	0.55	A	0.52	B	4.43	F	1.58	A	1.14	B	3.00	2.54
	ORG2	B	A	0.44	B	4.19	F	1.17	A	0.93	B	1.74	F	0.30	1.04
	ORG3	B	B	0.31	F	1.67	A	3.73	B	0.50	F	2.61	A	1.17	2.00
Total weeds	NT	B	B	3.93	B	0.61	B	0.93	B	0.19	B	2.90	B	1.28	1.32
	MW1	B	A	1.31	B	3.71	A	0.46	B	1.23	A	0.48	B	3.06	1.31
	MW2	B	B	3.07	A	0.41	B	1.64	A	0.12	B	2.68	A	1.46	1.47
	ORG1	B	F	0.50	A	4.53	B	0.38	F	2.76	A	0.86	B	6.35	2.59
	ORG2	B	A	0.94	B	3.48	F	1.41	A	0.54	B	2.96	F	0.43	1.34
	ORG3	B	B	1.17	F	0.34	A	2.62	B	0.45	F	2.53	A	1.78	1.84

[a]Crop codes: A, alternative crop (winter peas or false flax in the middle-way system; winter peas, vetch, or spring peas in the organic system); B, barley; F, fallow.
[b]MW1 and MW2: two different crop sequences within the middle-way system; NT: no-tillage (single sequence); ORG1, ORG2, and ORG3: three different crop sequences within the organic system.

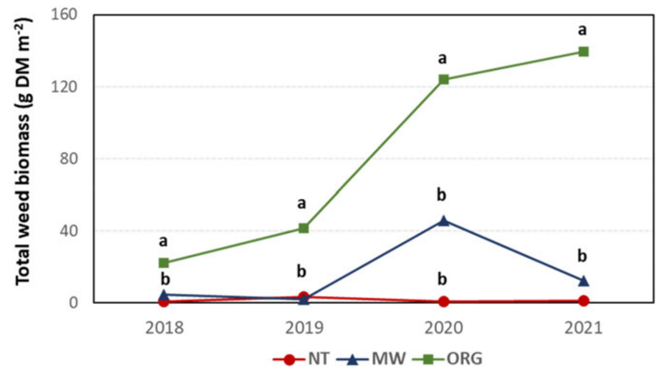

Figure 4. Total weed biomass (g dry matter m^{-2}) recorded in the spring samplings from 2018 to 2021. Cropping systems: MW, middle way (average of the two crop sequences); NT, no-tillage; ORG, organic (average of the three crop sequences). Values followed by the same letter in the same year are not significantly different according to Bonferroni test at $P \leq 0.05$.

date and the strong competitive ability of this crop contributed to effective weed suppression (Codina-Pascual et al. 2022; Rasmussen 2004). Overall, mean λ values for total weed populations in the MW system were comparable to those observed in the NT system, ranging from 1.31 in MW1 to 1.47 in MW2. In the ORG system, weed populations increased throughout the experimental period, especially in the last years. The highest weed densities—336 and 395 plants m^{-2} in 2020 and 2021, respectively—were recorded in barley crops following peas (Figure 3A; Supplementary Material). These results suggest that weed population dynamics tended to stabilize across cropping systems following the completion of the first full rotation cycle, indicating that data from 2019 onward—when the 3-yr rotation in the ORG system was completed—are more representative for evaluating the long-term effects of management practices.

To evaluate weed abundance at the end of the annual crop cycle and the effectiveness of control practices during the growing season, weed biomass was sampled in late spring (May) over the last 5 yr of the experiment. Herbicide treatments in NT barley plots were consistently effective, keeping weed biomass below 10 g dry matter m^{-2}—over 90% lower than the peak values in the ORG system (Figure 3B). Similarly, weed biomass in the MW plots remained low—typically under 15 g dry matter m^{-2}—indicating successful weed control in both barley and pea crops when compared with the substantially higher biomass levels recorded in ORG plots during the same years. An exception was observed in 2020, when the MW1 false flax crop had low February weed density but high weed biomass later in the season, likely due to poor crop emergence, which compromised its competitive ability. Weed biomass remained high in ORG plots, particularly in those sown with peas. The high weed biomass in barley plots in 2020 and 2021 was associated with high initial weed densities resulting from inadequate weed control in preceding pea crops.

As previously observed in winter weed density assessments, spring biomass sampling further confirmed the existence of two distinct phases following the adaptation of cropping systems up to 2018. During the initial 3-yr adaptation phase, no major differences in weed biomass were detected among cropping systems. However, from 2019 onward, a clear divergence emerged: weed biomass increased sharply in the ORG system, while both NT and MW maintained consistently low levels (Figure 4).

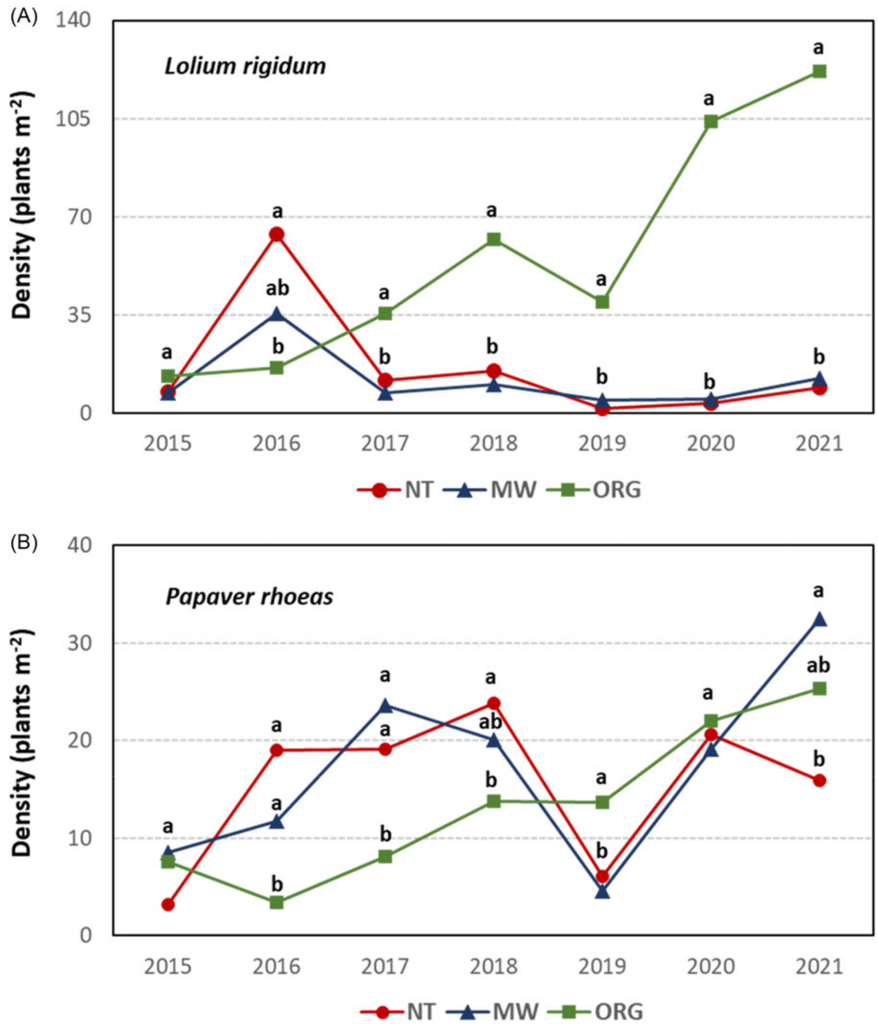

Figure 5. Densities (plants m^{-2}) of (A) *Lolium rigidum* and (B) *Papaver rhoeas*, recorded in the winter samplings from 2015 to 2021. Cropping systems: MW, middle way (average of the two crop sequences); NT, no-tillage; ORG, organic (average of the three crop sequences). Values followed by the same letter in the same year are not significantly different according to Bonferroni test at $P \leq 0.05$.

Effects on Individual Species Dynamics

In 2015, before the treatments began, the dominant species were *L. rigidum*, with densities ranging from 6.3 to 18.5 plants m^{-2}, and *P. rhoeas*, with densities between 3.2 and 12.9 plants m^{-2}. These two species were uniformly distributed throughout the experimental area.

Lolium rigidum populations, which were initially high in NT and MW (direct-drilled barley), declined after 2016 and remained low through the end of the study (Figure 5A). Conversely, populations in ORG steadily increased, reaching up to 278 plants m^{-2}. Annual growth rates varied depending on the cropping system and the preceding crop within each sequence. In NT and MW2, where no herbicide treatments were used in 2015, λ reached 8.51 and 6.99, respectively (Table 2). However, from 2018 onward, *L. rigidum* populations were more or less stable in NT (avg. $\lambda = 1.60$) and MW2 (avg. $\lambda < 1.87$), with occasional years of negative growth (e.g., 2019). In contrast, ORG plots showed increasing growth, with average λ values ranging from 1.61 to 4.95 across the different crop sequences during 2018 to 2021.

Lolium rigidum is a difficult to control weed in grain systems, particularly in Mediterranean climates (Holm et al. 1991). In our study, continuous no-till barley treated with the same herbicides for six consecutive years effectively controlled this species, with no apparent signs of resistance. However, international experience—such as in Australia, where conservation tillage systems and repeated use of single herbicide modes of action have led to severe resistance problems—serves as an important warning for similar agroecosystems (Bajwa et al. 2021). This underscores the need for integrated management strategies, including crop rotation and diversified herbicide programs, to sustain long-term control of *L. rigidum* and avoid the development of resistance, even in regions where it is not currently a problem (Kleemann et al. 2017). In our case, implementing a 2-yr rotation with tilled peas or false flax alongside targeted herbicide use also proved successful in managing this species. However, in organic systems, *L. rigidum* control was challenging. Although pre-sowing tillage destroyed early cohorts, late-emerging individuals were poorly controlled by tine harrows. This species roots effectively after shallow tillage, especially under moist conditions. Fallow phases, expected to reduce *L. rigidum* populations, failed due to incomplete weed control, allowing substantial seed production in the absence of crop competition. Although a moldboard plow could effectively bury these weeds, this operation was avoided, being used only in a

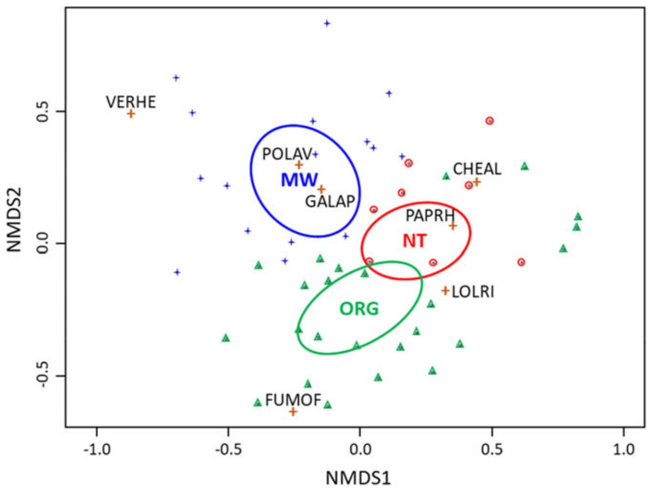

Figure 6. Nonmetric multidimensional scaling (NMDS) ordination of weed community composition in barley crops under three cropping systems: no-till (NT), middle way (MW), and organic (ORG), based on winter weed density data from 2018 to 2021. Weed species are identified by their EPPO codes: CHEAL, *Chenopodium album*; FUMOF, *Fumaria officinalis*; GALAP, *Galium aparine*; LOLRI, *Lolium rigidum*; PAPRH, *Papaver rhoeas*; POLAV, *Polygonum aviculare*; VERHE, *Veronica hederifolia*. Points represent yearly averages per plot in each cropping system: MW, blue crosses; NT, red circles; ORG, green triangles. Ellipses show the confidence regions for the locations of group centroids (with 95% confidence). Stress value = 0.210.

few cases. These findings in the ORG system highlight the adaptability and resilience of *L. rigidum* in tilled systems where seeds are incorporated into the soil profile, thereby preventing surface predation and decomposition (Goggin et al. 2012).

Papaver rhoeas populations increased across all cropping systems during the first 3 yr (Figure 5B), but declined sharply in 2019. This decline coincided with a severe drought from January to March (Figure 1), which likely affected either the survival of emerged seedlings or the persistence of the seedbank. Notably, peak emergence for this species in the region typically occurs earlier in the season, during autumn (October to December) when most germination events take place (Cirujeda et al. 2008). Populations recovered rapidly in ORG and MW systems, while NT showed a marked decline by 2021 (15.9 plants m^{-2} in NT compared with 26.9 in MW and 25.8 in ORG). Growth rates varied across crop sequences, systems and years (Table 2). In 2016, high λ values (3.37 to 5.90) were observed in MW2 and NT following barley sown without herbicides. In MW, growth rates were crop dependent, with consistently higher λ values in barley plots compared with alternative pea or false flax crops. ORG showed no clear pattern, although *P. rhoeas* growth tended to decrease in peas after fallow and increase in barley after peas. In 2019, drought led to a marked decline in growth rates across all systems and crop sequences ($\lambda = 0.11$ to 1.58), followed by a recovery in 2020 ($\lambda = 1.14$ to 5.90).

Papaver rhoeas is the most prevalent dicot weed in Spanish winter cereals. Its persistence is due to a long-lived seedbank, extended germination, and high fecundity (Cirujeda et al. 2006; Torra and Recasens 2008). Control of this species has become more difficult in recent years with the appearance of herbicide-resistant biotypes. The responses of this species to the different cropping systems are more difficult to explain than those of *L. rigidum.* While it is adapted to tillage-based systems (Gill 1996), other studies suggest it thrives under no-till due to the shallow distribution of seeds in the 0- to 5-cm soil layer (Dorado and López-Fando 2006; Recasens et al. 2020). In our study, *P. rhoeas* populations generally increased across all cropping systems, with the extent of these increases varying annually in response to the specific meteorological conditions.

Weed Community Composition

Eleven weed species were regularly observed across crop sequences within cropping systems (Supplementary Material): yellow gromwell [*Amsinckia calycina* (Moris) Chater], *B. diandrus*, common lambsquarters (*Chenopodium album* L.), flixweed [*Descurainia sophia* (L.) Webb ex Prantl], fumitory (*Fumaria officinalis* L.), catchweed bedstraw (*Galium aparine* L.), *L. rigidum*, *P. rhoeas*, prostrate knotweed (*Polygonum aviculare* L.), common saltwort (*Salsola kali* L.) and ivyleaf speedwell (*Veronica hederifolia* L.).

Species composition varied significantly across cropping systems and their associated crop sequences. By the end of the experimental period, *G. aparine* dominated in MW1 (46.5 plants m^{-2}), followed by *P. aviculare*, *V. hederifolia*, *A. calycina*, and *D. sophia* (13.2, 9.8, 8.3, and 5.8 plants m^{-2}, respectively). In contrast, *C. album* was predominant in ORG2 (65.2 plants m^{-2}), while *F. officinalis* reached notable densities in ORG1 (10.0 plants m^{-2}). These species occurred at minimal densities in the NT system. No-till practices are well documented as modifying soil and micro-environmental conditions such as temperature, moisture, and residue cover, which in turn influence weed seed germination, emergence, and survival in a species-specific manner (Cordeau et al. 2015; Nichols et al. 2015). For instance, small-seeded species such as *C. album* or *G. aparine* may benefit from surface seed retention under no-till, whereas larger-seeded species tend to decline, because their greater seed reserves support emergence from deeper soil layers—an advantage primarily realized when the soil is disturbed (Chauhan et al. 2006). Over time, these shifts can lead to dominance of adapted species, reducing overall diversity, a pattern consistent with the observed dominance of *C. album* in ORG and *G. aparine* in MW.

The lower prevalence of winter weeds under NT was associated with reduced diversity, as mean species richness declined by 34% to 39% relative to the ORG system and by 13% to 17% relative to the MW system during 2019 to 2021 (Table 3). Other studies have also reported reduced weed diversity under no-till, with species richness decreasing by approximately 15% compared with conventional tillage due to environmental homogenization and consistent herbicide pressure (Scursoni et al. 2014). In contrast, crop rotation exerts variable selective pressures that can sustain weed diversity, irrespective of herbicide use (Weisberger et al. 2019). Although previous research has shown that diverse crop rotations alter weed life cycles and reduce weed pressure over time (Derksen et al. 2002), Weisberger et al. (2019) demonstrated that monoculture has minimal impact on weed diversification. Additionally, legume crops such as peas may promote certain species by altering soil fertility (Corre-Hellou et al. 2011). These findings may help explain our results, which showed lower weed diversity in the structurally simplified NT system (single crop sequence) compared with ORG and MW systems, both of which incorporate diversified crop sequences within their respective rotations.

The PERMANOVA analysis indicated that the weed community composition differed significantly among cropping systems ($P \leq 0.001$), and this pattern was confirmed by the NMDS visualization technique (Figure 6), which showed clear associations between specific cropping systems and distinct weed species. Pairwise comparisons revealed significant differences ($P \leq 0.05$) in

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Table 3. Diversity indices from 2015 to 2021 for different crop sequences within each cropping system.

Diversity index[a]	Cropping system[b]	Year[c]						
		2015	2016	2017	2018	2019	2020	2021
S	NT	8.5 ± 1.6^{a}	7.0 ± 0.8^{a}	10.8 ± 0.5^{b}	7.8 ± 1.0^{b}	4.8 ± 0.8^{b}	4.8 ± 0.8^{b}	6.3 ± 1.3^{b}
	MW1	10.0 ± 1.4^{a}	8.3 ± 0.9^{a}	13.3 ± 0.5^{a}	9.3 ± 0.8^{a}	9.0 ± 1.1^{a}	6.5 ± 1.2ab	9.5 ± 1.0^{a}
	MW2	10.3 ± 0.9^{a}	6.5 ± 1.0^{a}	10.5 ± 1.0^{b}	6.8 ± 1.3^{b}	3.5 ± 0.6^{b}	6.8 ± 1.0ab	6.8 ± 0.9^{b}
	ORG1	8.8 ± 2.1^{a}	6.9 ± 1.0^{a}	9.5 ± 0.6^{b}	7.0 ± 1.3^{b}	8.5 ± 0.9^{a}	8.3 ± 1.0^{a}	9.3 ± 1.0^{a}
	ORG2	8.8 ± 1.0^{a}	6.5 ± 1.0^{a}	10.5 ± 0.9^{b}	8.5 ± 0.6^{a}	7.0 ± 1.9ab	7.8 ± 1.4^{a}	10.5 ± 0.9^{a}
	ORG3	8.3 ± 1.7^{a}	6.8 ± 1.3^{a}	10.0 ± 0.8^{b}	5.5 ± 0.5^{b}	6.0 ± 0.6ab	7.3 ± 0.3^{a}	9.8 ± 1.0^{a}
SEI	NT	1.6 ± 0.2^{a}	1.0 ± 0.1^{a}	1.9 ± 0.1^{a}	1.4 ± 0.1^{a}	1.1 ± 0.1^{b}	0.9 ± 0.0^{b}	1.2 ± 0.2^{b}
	MW1	1.8 ± 0.2^{a}	1.5 ± 0.1^{a}	1.6 ± 0.1^{a}	1.6 ± 0.1^{a}	1.3 ± 0.2ab	1.2 ± 0.3ab	1.4 ± 0.1ab
	MW2	1.9 ± 0.2^{a}	1.1 ± 0.1^{a}	1.7 ± 0.2^{a}	1.4 ± 0.2^{a}	0.9 ± 0.2^{b}	1.3 ± 0.2ab	1.6 ± 0.2^{a}
	ORG1	1.5 ± 0.3^{a}	1.1 ± 0.1^{a}	1.6 ± 0.0^{a}	1.4 ± 0.1^{a}	1.3 ± 0.1ab	1.4 ± 0.1^{a}	0.9 ± 0.2^{b}
	ORG2	1.2 ± 0.3^{a}	1.2 ± 0.2^{a}	1.4 ± 0.1^{a}	1.0 ± 0.2^{a}	0.9 ± 0.1^{b}	0.6 ± 0.1^{b}	1.1 ± 0.1^{b}
	ORG3	1.4 ± 0.2^{a}	1.2 ± 0.1^{a}	1.5 ± 0.1^{a}	1.3 ± 0.1^{a}	1.5 ± 0.1^{a}	1.6 ± 0.1^{a}	1.7 ± 0.1^{a}
SDI	NT	3.7 ± 0.8^{a}	2.0 ± 0.1^{a}	5.1 ± 0.5^{a}	3.1 ± 0.4^{a}	2.4 ± 0.1^{b}	2.0 ± 0.1^{b}	2.8 ± 0.4^{b}
	MW1	4.9 ± 0.9^{a}	3.6 ± 0.5^{a}	3.4 ± 0.3^{a}	4.1 ± 0.6^{a}	2.9 ± 0.6ab	3.0 ± 0.9ab	3.1 ± 0.6ab
	MW2	5.4 ± 1.0^{a}	2.3 ± 0.2^{a}	4.2 ± 1.1^{a}	3.3 ± 0.5^{a}	2.3 ± 0.4^{b}	2.6 ± 0.3ab	4.3 ± 0.8^{a}
	ORG1	3.6 ± 0.8^{a}	2.4 ± 0.2^{a}	3.7 ± 0.1^{a}	3.4 ± 0.4^{a}	2.8 ± 0.4ab	3.3 ± 0.5^{a}	1.9 ± 0.3^{b}
	ORG2	2.6 ± 1.0^{a}	2.8 ± 0.7^{a}	2.8 ± 0.2^{a}	2.8 ± 0.4^{a}	1.9 ± 0.2^{b}	1.5 ± 0.2^{b}	2.0 ± 0.2^{b}
	ORG3	3.3 ± 0.8^{a}	2.7 ± 0.3^{a}	3.2 ± 0.1^{a}	3.2 ± 0.4^{a}	3.5 ± 0.3^{a}	4.0 ± 0.5^{a}	4.2 ± 0.7^{a}

[a]S, mean species richness; SDI, Simpson's diversity index; SEI, Shannon's evenness index.
[b]MW1 and MW2: two different crop sequences within the middle-way system; NT: no-tillage (single sequence); ORG1, ORG2, and ORG3: three different crop sequences within the organic system.
[c]Means followed by the same letter within a column and for the diversity index are not different (Bonferroni test at $P \leq 0.05$).

Table 4. Economic analysis from 2016 to 2021 of different crop sequences within each cropping system[a].

Cropping system[b]		Year						Average
		2016	2017	2018	2019	2020	2021	
		€ ha^{-1}						
NT	Products sold	1,013	416	882	325	831	789	
	CAP[a] contributions	0	0	0	0	0	0	
	Variable costs	459	480	389	262	316	316	
	Gross profit	554	−64	493	64	515	473	339
MW1	Products sold	742	442	653	330	427	674	
	CAP contributions	205	145	145	145	145	145	
	Variable costs	497	377	378	315	402	502	
	Gross profit	451	210	420	160	170	318	288
MW2	Products sold	972	304	829	468	860	719	
	CAP contributions	145	205	145	145	145	145	
	Variable costs	416	557	426	240	388	232	
	Gross profit	701	−47	548	373	617	633	471
ORG1	Products sold	0	38	1,117	0	243	700	
	CAP contributions	145	205	145	145	205	145	
	Variable costs	181	467	334	179	522	443	
	Gross profit	−35	−224	929	−34	−73	402	161
ORG2	Products sold	504	398	0	47	685	0	
	CAP contributions	205	145	145	205	145	145	
	Variable costs	38	465	248	489	438	207	
	Gross profit	671	79	−103	−237	392	−62	123
ORG3	Products sold	1,129	0	863	493	0	479	
	CAP contributions	145	145	145	145	145	205	
	Variable costs	468	240	356	418	163	467	
	Gross profit	806	−95	652	221	−18	217	297

[a]Gross profit = (Products sold + subsidies of the European Union's Common Agricultural Policy [CAP]) − variable costs.
[b]MW1 and MW2: two different crop sequences within the middle-way system; NT: no-tillage (single sequence); ORG1, ORG2, and ORG3: three different crop sequences within the organic system.

weed communities among all cropping systems, except between NT and MW, where the adjusted P-value was only marginally significant. This suggest that the weed communities in NT and MW systems are more similar to each other than to those in the ORG system. Indicator species analysis identified *L. rigidum* and *F. officinalis* as characteristic of the ORG system, while *V. hederifolia* and *G. aparine* were indicative of MW. Identification of *L. rigidum* as an indicator species for the ORG system in this study contrasts with previous reports of its association with no-till or conservation tillage systems rather than with organic or intensive tillage systems (Bajwa et al. 2021; Borger et al. 2024; Chauhan et al. 2006; Dorado and López-Fando 2006). However, in this study, although *L. rigidum* was the second most abundant species in NT after *P. rhoeas*, the herbicide program proved effective, and its abundance declined rapidly after 2016 in both MW and NT systems (Figure 5A). Other species such as *P. rhoeas*, *P. aviculare*, and *C. album*, while prevalent in the experimental area, were not indicative of any particular cropping system. This suggests these species are well adapted to a range of management practices and crop rotations, and they could pose a significant threat if they develop herbicide resistance.

Economic Profitability

The economic analysis, which accounts for the production of all crop sequences within each cropping system, reveals that ORG consistently generated lower gross profits compared with NT and MW (Table 4). Across crop sequences, average gross profits in ORG ranged from €161 to €297 ha^{-1}, while MW achieved higher and more consistent returns (€288 to €471 ha^{-1}), and NT averaged €339 ha^{-1}. Although organic products (e.g., peas) benefited from premium prices and subsidies, the inclusion of a fallow phase within the crop rotation significantly reduced overall output. While fallow is widely used in rainfed cereal systems in central Spain for weed suppression and water conservation (Monzon et al. 2006), it represents an economic trade-off due to lost production.

The NT system consistently produced barley yields similar to or higher than those of the other systems. However, as a monoculture, NT did not meet CAP requirements for crop diversification, resulting in lower total subsidies and, consequently, lower gross profits compared with MW. Under rainfed cereal production conditions typical of the European Union, the MW system—characterized by crop rotation and selective herbicide use—proved to be the most economically advantageous, with an average gross profit of €380 ha^{-1}, exceeding both NT (€339 ha^{-1}) and ORG (€194 ha^{-1} on average).

These findings underscore the importance of balancing agronomic effectiveness and economic returns when selecting cropping systems. Organic systems often face yield penalties from high weed pressure, limiting the financial benefit of organic premiums (Seufert and Ramankutty 2017). In contrast, NT and MW systems combine effective weed control with stable productivity and profitability (Pannell et al. 2014).

Management Implications

The consistently low weed densities observed in NT demonstrate the effectiveness of no-till combined with systematic herbicide use in the absence of herbicide resistance. Comparable weed control in MW suggests that optimized integration of tillage, herbicide use, and crop rotation can also ensure long-term weed suppression and contribute to delaying the development of herbicide resistance. In contrast, organic systems pose greater challenges for weed management, particularly due to the proliferation of *L. rigidum* and the limited efficacy of tillage-based control strategies.

From both agronomic and economic perspectives, the MW system represents the most advantageous strategy for rainfed cereal production in the European Union, combining effective weed control with increased gross profits. These findings are crucial for the development of resilient and sustainable cropping systems in Mediterranean agroecosystems. They underscore the importance of integrated weed management approaches that balance ecological sustainability with economic viability through practices such as crop rotation and targeted herbicide use.

Moreover, some of the most meaningful effects on weed dynamics and overall system performance may only become evident after a full crop rotation cycle is completed and restarted. Therefore, evaluating outcomes at the rotation level is essential to accurately capture long-term impacts. Clarifying whether each cropping system returns to its original starting crop at the end of the rotation would further enhance the interpretation of these long-term results and strengthen conclusions regarding the sustainability of each rotation strategy.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2025.10052

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Competing interests. The authors declare no conflicts of interest.

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