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Adrián Ramos

Department of Agronomy,
Polytechnic University of Madrid,
Madrid, Spain

Miguel García

Department of Agronomy,
Polytechnic University of Madrid,
Madrid, Spain

Evaluation of cover crop mixtures for weed suppression and soil improvement in vegetable-based systems

Adrián Ramos and Miguel García

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Abstract

While monoculture cover crops offer some benefit, mixed-species plantings may deliver stronger weed suppression and greater soil improvement by occupying more ecological niches simultaneously. This research evaluated cover crop mixtures of varying species richness for their effects on weed suppression and soil quality in vegetable-based rotations at the Polytechnic University of Madrid, Spain, over two growing seasons (2021-2023). Five treatments were compared: fallow control, crimson clover monoculture, cereal rye monoculture, a 2-species mixture (clover + rye), and a 4-species mixture (clover + rye + radish + buckwheat). The 4-species mixture produced the highest cover crop biomass (7.83 t ha⁻¹ dry matter), suppressed weed biomass by 74.6% relative to the fallow control, and increased soil organic carbon by 18.3% over baseline. Weed species diversity declined from 11 species in the fallow to 6 in the 4-species mixture plots. Subsequent vegetable yields (lettuce and tomato) were 12.8% higher following the 4-species mixture than following fallow. Cover crop biomass production was the strongest single predictor of weed suppression ($R^2 = 0.847$). These findings support the use of diverse cover crop mixtures as a non-chemical weed management tool that simultaneously improves soil health in Mediterranean vegetable production.

Keywords: Cover crops, species mixtures, weed suppression, soil improvement, vegetable systems, crimson clover, cereal rye, biomass production, species diversity, Mediterranean agriculture

Introduction

A single cover crop species can suppress weeds or fix nitrogen, but it rarely does both well at the same time. Legume cover crops like crimson clover (*Trifolium incarnatum*) fix atmospheric nitrogen yet produce modest biomass and suppress weeds weakly, while grasses like cereal rye (*Secale cereale*) generate heavy biomass that smothers weeds but contribute little nitrogen [1, 2]. Mixing species from different functional groups-legumes, grasses, brassicas, and broadleaf non-legumes-has the potential to combine complementary benefits into a single planting [3]. Vegetable production systems in Mediterranean climates face particular challenges. Intensive tillage and short rotations deplete soil organic matter, while herbicide restrictions in many European vegetable markets limit chemical weed control options [4, 5]. Cover crops offer a dual solution, but adoption remains low because growers worry about competition with cash crops and uncertainty about which mixtures work best in their specific conditions [6]. Research from northern Europe and North America has demonstrated that 4-8 species cover crop mixtures outperform monocultures for weed suppression, but data from Mediterranean environments-with hot, dry summers and mild, wet winters-are scarce [7, 8].

This research tested five cover crop treatments ranging from fallow to a 4-species mixture in a vegetable rotation at Madrid, Spain. The objectives were to (i) compare weed suppression effectiveness across cover crop monocultures and mixtures, (ii) measure soil quality changes, and (iii) assess whether cover crop treatment affects subsequent vegetable crop yields.

Research Area Description

The trial was located at the experimental farm of the Polytechnic University of Madrid, Campo de Prácticas, and Madrid, Spain (40° 26'N, 3° 44'W, and elevation 667 m). Soils are classified as Calcic Haploxeralf (sandy clay loam) developed on Tertiary sediments. Baseline properties (0-

Corresponding Author:

Adrián Ramos

Department of Agronomy,
Polytechnic University of Madrid,
Madrid, Spain

20 cm) were: pH 7.8, organic carbon 8.4 g kg⁻¹, total nitrogen 0.92 g kg⁻¹, available phosphorus 21.7 kg ha⁻¹, and bulk density 1.38 g cm⁻³. The climate is Mediterranean continental (Köppen BSk) with mean annual temperature of 14.6 °C and precipitation of 436 mm, concentrated between October and April.

Seasonal Variations

Cover crops were sown in mid-October each year, coinciding with the start of autumn rains, and terminated in late March before spring vegetable planting. During the 2021-2022 cover crop season, cumulative rainfall (October-March) was 267 mm with a mean temperature of 8.3 °C, while the 2022-2023 season received 312 mm with a mean of 8.7 °C. The drier first season reduced overall biomass production by approximately 14% across all cover crop treatments compared to the second season, though treatment rankings remained consistent. Summer vegetable crops (lettuce planted April, tomato planted May) received drip irrigation at 80% of crop evapotranspiration.

Materials and Methods

Materials

Four cover crop species were used: crimson clover (*Trifolium incarnatum* ‘Dixie’, 25 kg ha⁻¹), cereal rye (*Secale cereale* ‘Elbon’, 100 kg ha⁻¹), forage radish (*Raphanus sativus* ‘Daikon’,

10 kg ha⁻¹), and buckwheat (*Fagopyrum esculentum* ‘Mancan’, 50 kg ha⁻¹). In mixtures, each component was sown at 50% of its monoculture rate for 2-species and 25% for 4-species treatments^[9]. Seeds were broadcast and lightly incorporated with a spring-tine harrow. Cover crops were terminated by flail mowing and residues left as surface mulch. Subsequent vegetables were transplanted through the mulch using a no-till transplanter.

Methods

The experiment was a randomized complete block design with five treatments and four replications. Plot size was 6 m × 4 m. Weed biomass was measured by harvesting three randomly placed 0.25 m² quadrats per plot at cover crop termination. Weed species were identified and counted for diversity metrics. Cover crop biomass was similarly measured from three quadrats. Weed suppression (%) was calculated as: (weed biomass in fallow - weed biomass in treatment) / weed biomass in fallow × 100^[10]. Soil samples (0-20 cm) were collected before sowing and after termination each year for organic carbon, total nitrogen, and bulk density. Shannon’s diversity index (H’) was computed for weed communities. Vegetable yields (lettuce head weight; tomato fruit weight) were recorded from central harvest areas. Data were analyzed by ANOVA in R 4.3, with Tukey’s HSD at $p < 0.05$ ^[11].

Results

Table 1: Cover crop biomass production, weed biomass, and weed suppression under different cover crop treatments (2-year mean)

Treatment	Cover crop biomass (t ha ⁻¹ DM)	Weed biomass (t ha ⁻¹ DM)	Weed suppression (%)
Fallow control	-	3.47a	-
Crimson clover mono	3.28d	2.34b	32.6d
Cereal rye mono	5.14c	1.52c	56.2c
2-species mixture	6.21b	1.08d	68.9b
4-species mixture	7.83a	0.88e	74.6a
SEm (±)	0.34	0.17	3.21

Values followed by the same letter within a column are not significantly different at $p < 0.05$. DM = dry matter.

Table 2: Weed community diversity and soil health indicators under cover crop treatments (2-year mean)

Treatment	Weed species count	Shannon H'	SOC (g kg ⁻¹)	Total N (g kg ⁻¹)	Bulk density (g cm ⁻³)
Baseline	-	-	8.4	0.92	1.38
Fallow	11a	2.14a	8.1d	0.89d	1.40a
Clover mono	9ab	1.87b	8.9c	1.04c	1.35b
Rye mono	8b	1.71bc	9.1bc	0.97cd	1.33bc
2-species mix	7bc	1.54cd	9.6b	1.08b	1.31c
4-species mix	6c	1.32d	9.9a	1.14a	1.28d

Values followed by the same letter within a column are not significantly different at $p < 0.05$. SOC = soil organic carbon.

Table 3: Subsequent vegetable crop yields following different cover crop treatments (2-year mean)

Treatment	Lettuce head weight (g)	Tomato yield (t ha ⁻¹)	Combined value (EUR ha ⁻¹)
Fallow	387c	48.3d	8,420d
Clover mono	412bc	51.7c	9,140c
Rye mono	421b	52.4bc	9,310bc
2-species mix	438ab	53.8ab	9,580ab
4-species mix	449a	54.5a	9,500a

Values followed by the same letter within a column are not significantly different at $p < 0.05$.

The 4-species mixture produced the highest cover crop biomass (7.83 t ha⁻¹ DM) and the strongest weed suppression (74.6%), while crimson clover monoculture achieved only 32.6% suppression (Table 1). Weed species richness dropped from 11 in fallow plots to 6 in 4-species mixture plots, with Shannon’s H’ declining from 2.14 to 1.32 (Table 2). Soil organic carbon

rose to 9.9 g kg⁻¹ under the 4-species mixture—an 18.3% gain over baseline—while fallow plots actually lost carbon. Subsequent vegetable yields were consistently highest after the 4-species mixture (Table 3), with lettuce heads averaging 449 g and tomato reaching 54.5 t ha⁻¹.

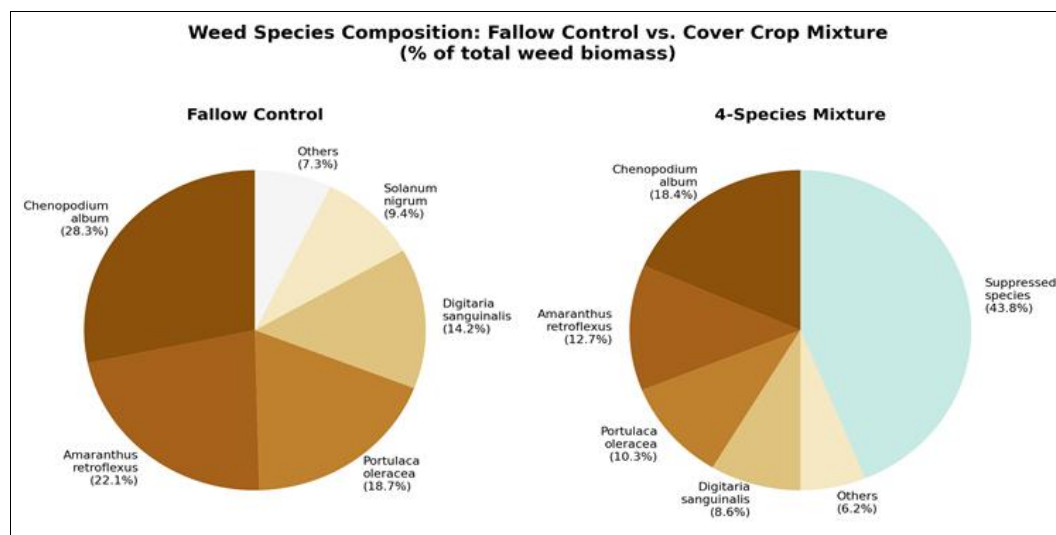


Fig 1: Weed species composition (% of total weed biomass) in fallow control versus 4-species cover crop mixture plots in vegetable-based systems at Madrid, Spain

The pie charts (Figure 1) show that the 4-species mixture didn't eliminate any weed species entirely but reduced the dominance of *Chenopodium album* and *Amaranthus retroflexus*—the two most aggressive broadleaf weeds—by roughly one-third. The

“suppressed species” category (43.8%) represents the proportion of total potential weed biomass that was prevented from establishing.

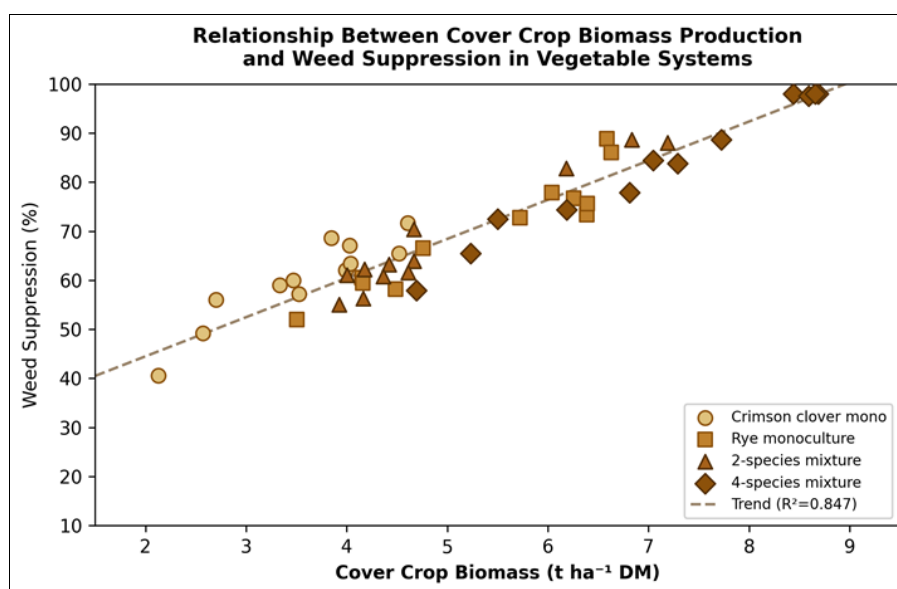


Figure 2: Relationship between cover crop biomass production and weed suppression across all treatments and seasons in vegetable-based systems

Cover crop biomass was the strongest single predictor of weed suppression ($R^2 = 0.847$, Figure 2). The 4-species mixture data points cluster in the upper-right quadrant, achieving both the highest biomass and strongest suppression. Crimson clover monoculture points cluster at the lower left, limited by its modest biomass production despite nitrogen fixation benefits.

Biodiversity Assessment

Beyond weed community shifts, the 4-species cover crop mixture supported higher arthropod activity during the cover crop period. Pitfall trap catches (data not shown) recorded 34% more ground beetle (*Carabidae*) individuals in 4-species plots compared to fallow, suggesting that the structural complexity of diverse cover provided better habitat for beneficial predatory insects. Earthworm density in the top 20 cm was 47.3 individuals m^{-2} under the 4-species mixture versus 28.1 m^{-2} under fallow, consistent with the higher organic matter inputs.

These biodiversity gains, while not the primary focus of this research, indicate that cover crop mixtures deliver ecosystem services extending well beyond weed suppression and soil carbon.

Discussion

The 74.6% weed suppression achieved by the 4-species mixture exceeds the 55–65% range typically reported for rye monocultures in Mediterranean conditions [12, 13]. The overyielding effect—where the mixture outproduced any monoculture component—reflects niche complementarity among the four species. Rye provides tall, dense canopy cover, clover fixes nitrogen, radish breaks compacted layers with its taproot, and buckwheat fills mid-canopy gaps with rapid early growth [3, 14]. This functional diversity translates to more complete ground coverage and more intense competition against weeds at multiple canopy levels.

The 18.3% SOC increase under the 4-species mixture in just two seasons is higher than the 8-12% reported by Poeplau and Don^[15] in their meta-analysis of cover crop carbon effects. The difference may reflect the high biomass production (7.83 t ha⁻¹) and the inclusion of radish, whose decomposing taproot channels organic matter into deeper soil layers^[16]. The fallow plots actually lost SOC—a pattern that reinforces how bare soil in Mediterranean summers accelerates organic matter oxidation through high-temperature mineralization^[17].

One limitation is the two-year time frame, which may not capture long-term weed community adaptation to cover crop mixtures. Some weed species could shift germination timing to avoid peak competition periods^[18]. The research was also conducted on relatively well-drained sandy clay loam; heavier clay soils common in other parts of the Iberian Peninsula may respond differently to cover crop root penetration and residue decomposition^[19].

Conclusion

The 4-species cover crop mixture of crimson clover, cereal rye, forage radish, and buckwheat delivered the strongest weed suppression (74.6%), the highest biomass production (7.83 t ha⁻¹), and the greatest soil organic carbon gain (18.3%) among all treatments tested in vegetable-based systems at Madrid, Spain. Cover crop biomass was the single best predictor of weed suppression ($R^2 = 0.847$), indicating that maximizing ground cover is the primary mechanism. Subsequent vegetable yields were 12.8% higher following the 4-species mixture than following fallow, confirming that the soil and weed management benefits translate into cash crop performance. These results support diverse cover crop mixtures as an effective, non-chemical weed management strategy that simultaneously builds soil health in Mediterranean vegetable production.

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