# Comparative Assessment of Cover Crop Mixtures for Weed Suppression, Soil Health, and Sustainable Crop Production

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## ABSTRACT
**Background:** There are persistent challenges in the application of effective cropping systems such as weed disturbance, declining soil organic matter, and loss of agrobiodiversity. Cover crops have been widely disseminated as conservation practices although there is limited knowledge on the possible different effects of various cover crops differently on the efficiency of these practices. Therefore, the objective of this experiment has been to compare the four different cover crop mixtures, namely cover crop with legumes, cover crop with grasses, cover crop with brassicas, and cover crop with legumes, against cover crop with legumes in order to understand the extent of their impact on the effectiveness of different cropping systems in a two-year field experiment.
The study was conducted in randomized replicated block design at the temperate climate research site where farm land is plain and consists of loam soil with sedentary cereal crop production. The following treatments were used: cover crop of legume mixture, cover crop of grass mixture, cover crop of brassica mixture, and cover crop with legumes. The analysis included cover crop biomass, weed density and biomass, soil organic carbon, bulk density, aggregate stability, nutrient availability, microbial biomass and enzyme activity.
**Results:** The use of multi-species mixtures generated the highest biomass above the ground and highest degree of weed suppression efficiency. Grass and brassica mixtures came in succession after the multi-species mixture in terms of above-ground biomass production and weed suppression efficiency. Soil organic carbon, aggregate stability and microbial biomass carbon have increased the most in the case of application of multi-species and legume treatments when compared to a fallow control. In addition, the crop yield recorded after the use of multi-species and legume mixtures was higher in comparison to the control, which brought about the positive on-farm partial economic returns, despite establishment costs. Moreover, the correlation analysis demonstrated that weed suppression efficiency, ground cover and soil biological indicators are closely associated with one another**.**
**Significance:** Diversified cover crop mixtures provide both agronomical and ecological advantages.
**Conclusion:** Multi-species cover crop mixtures serve as an efficient evidence-based approach to weed management and soil restoration in conservation agriculture systems.

**Keywords:** Conservation Tillage; Agroecosystem Services; Soil Organic Matter Restoration; Integrated Weed Suppression; Multi-Species Cropping; Soil Microbial Biomass; Agrobiodiversity; Climate-Resilient Farming

## 1. Introduction
The world's food systems are being pressured to enhance productivity while rectifying the past soil degradation, biodiversity loss, and getting rid of reliance on herbicides for weed control (Foley *et al*., 2011) [1] (FAO, 2021) [2]. Practices such as monoculture farming, the use of tillage, and synthetic additions have resulted in reducing soil organic carbon (SOC) levels, deteriorating soil structure, and the emergence of weed biotypes resistant to herbicides in all key agricultural regions (Lal, 2015) [3] (Heap, 2023) [4]. In this case, conservation agriculture promotes the principles of minimal disturbance of soil, use of permanent soil cover, and crop diversification as a solution to achieving resilient production systems (Kassam *et al*., 2019) [5] (Giller *et al*., 2015) [6].
Weed control continues to be among the main problems faced by systems using conservation practices. As the use of cultivation as a method of weed control is declining, alternative ways of weed suppression are becoming necessary, and cover crops play a major role in integrated weed management approaches (MacLaren *et al*., 2020) [7] (Osipitan *et al*., 2018) [8]. Cover crops suppress weed growth by means of a few of their complementary mechanisms, which are resource competition for nutrients, water, and light; physical obstruction from the residue; and allelopathic suppression of the growth and germination of some weed types (Baraibar *et al*., 2018) [9] (Smith *et al*., 2014) [10]. However, the intensity of suppression depends on various factors, such as cover crop species and its biomass, canopy structure, and termination time; thus, comparisons among the mixtures rather than single-crop systems have to be made (Wittwer *et al*., 2017) [11].

Besides suppressing weed growth, cover crops have other ecosystem benefits that are significant for the long-term rehabilitation of soils. Root biomass and crop debris produced by cover crops promote SOC buildup, enhance aggregate stability, and activate biological activity of soils, specifically concerning the mass of microorganisms and creation of exoenzymes by microorganisms (Poeplau and Don, 2015) [12] (Blanco-Canqui and Ruis, 2020) [13]. Moreover, leguminous mixtures add biologically fixed nitrogen to soils, which slows down the need for synthetic fertilizers during the growing season of cash crops (Tribouillois *et al*., 2016) [14]. Brassica species are used due to their biofumigation ability and scavenging of residual soil nitrogen, while grasses provide root systems made of fibers that ensure the stability of the structure of soil and make it possible for the presence of microbial communities through application of labile carbon (Kim *et al*., 2020) [15] (Finney *et al*., 2016) [16].

In recent years, numerous studies have shown that multifunctional, multi-species cover crop mixtures are likely to outperform pure stand cover crop systems since these mixtures provide for complementarity in resource use, and hence, result in higher biomass yields as well as greater provision of ecosystem services (Florence and McGuire, 2020) [17] (Storkey *et al*., 2015) [18]. It has also been shown that increase in cover crop diversity contributes to augmented populations of beneficial arthropods and earthworms, and increased pollinator visits, resulting in greater biodiversity on the farm (Blaauw and Isaacs, 2014) [19] (Rowen *et al*., 2020) [20]. These biological changes are increasingly recognized as essential aspects of climate-smart agriculture, considering their significant role in sequestering carbon in soils, retaining water in soils, and increasing resilience of agricultural production to climate variability (Bai and Cotrufo, 2022) [21] (Jian *et al*., 2020) [22].

In spite of the growing proof quality, a considerable portion of current research conducted on cover crops has evaluated their influences separately with respect to weed control, chemical make-up of soil and bio-diversity rather than through means of comparative analysis of mixture types in a unified research context (Bowles *et al*., 2017) [23] (Nichols *et al*., 2015) [24]. Besides, financial profitability is not adequately presented alongside agronomic and ecological results, thus deteriorating the capacity of farmers to make the right choice based on the comprehension of cost and benefit of cover crops (Snapp *et al*., 2005) [25]. In addition, regional discrepancies in terms of weather conditions, types of soils, and agronomic history limit the generalizability of current findings, thereby illustrating the necessity of conducting site-specific comparative experiments (Roesch-McNally *et al*., 2018) [26] (Basche and DeLonge, 2019) [27].

This research attempts to fill this gap by analyzing for two years four types of cover crop mixtures, namely legume, grass, brassica, and multi-species in comparison with the control variant that involves fallow cultivation. Specifically, there were four tasks: a) to determine cover crop biomass production and weed suppression efficiency of the cover crops; b) to identify changes in soil physical, chemical, and biological indicators of soil health; c) to study biodiversity, such as weed diversity, beneficial invertebrates, earthworm populations, and pollinators; d) to examine the impact of cover crop mixtures on future cash crop production and profitability. It was anticipated that a complex mixture of different species would be the most beneficial in terms of agricultural outcomes in comparison with the single-species cover crops or fallow.

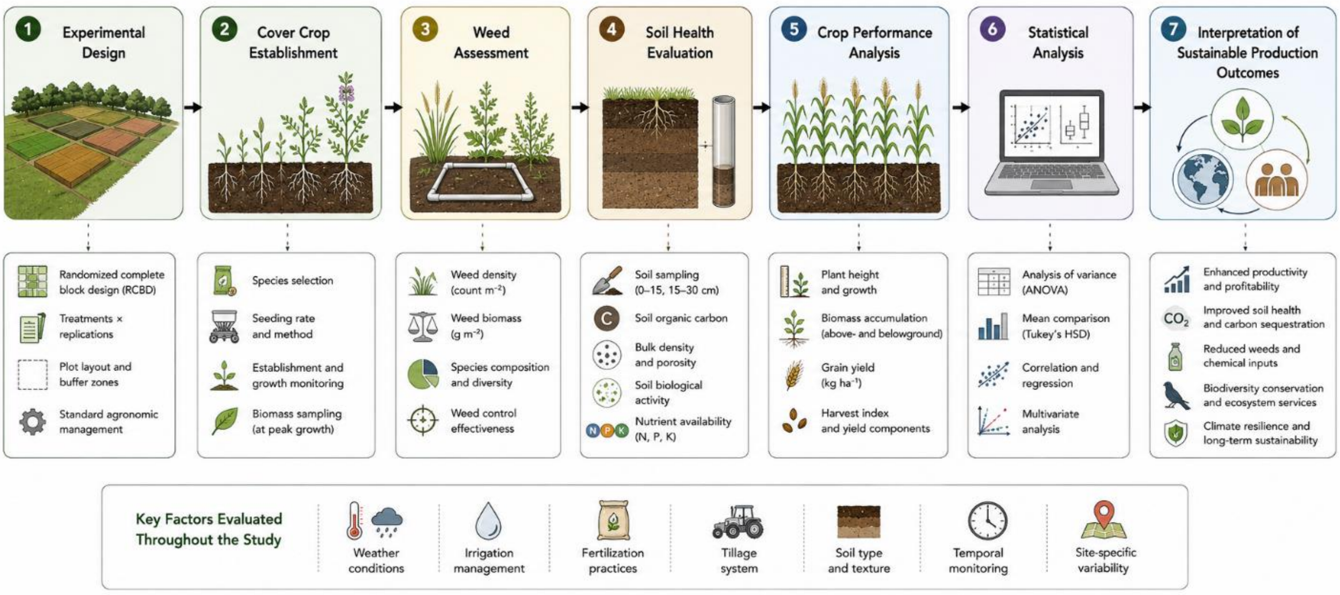


**Fig 1:** Conceptual workflow diagram illustrating the sequence of experimental design, cover crop establishment, weed assessment, soil health evaluation, crop performance analysis, statistical analysis, and interpretation of sustainable production outcomes.

## 2. Materials and Methods

### 2.1. Study Site

The field experiment was conducted over two consecutive growing seasons at a research farm situated within a temperate, sub-humid agroclimatic zone characterized by a mean annual precipitation of approximately 850 mm and a mean annual temperature of 13.5 °C. The soil at the site is classified as a fine-loamy, mixed, mesic soil (loam texture), with a slightly acidic to neutral reaction. The field had a prior cropping history dominated by a cereal-based monoculture rotation for the preceding eight years, with conventional tillage and fallow periods between cash crops. Site characteristics are summarized in Table 1.

**Table 1:** Study site characteristics

| Parameter | Description |
|---|---|
| Location type | Temperate, sub-humid agroclimatic zone research farm |
| Mean annual precipitation | ~850 mm |
| Mean annual temperature | 13.5 °C |
| Soil classification | Fine-loamy, mixed, mesic; loam texture |
| Soil reaction (pH) | Slightly acidic to neutral (~6.2–6.8) |
| Previous cropping history | Cereal-based monoculture rotation, 8 years, conventional tillage |
| Experimental duration | 2 growing seasons (24 months) |

### 2.2. Cover Crop Treatments

Five treatments were established: (i) a legume mixture (comprising crimson clover, hairy vetch, and field pea); (ii) a grass mixture (comprising cereal rye and annual ryegrass); (iii) a brassica mixture (comprising forage radish and mustard); (iv) a multi-species mixture (combining representative legume, grass, and brassica components at reduced individual seeding rates); and (v) a conventional fallow control receiving no cover crop and left under standard tillage management between cash crops. Cover crops were established following cash-crop harvest and terminated ahead of subsequent cash-crop planting, consistent with regionally recommended windows.

### 2.3. Experimental Design

The trial followed a randomized complete block design (RCBD) with five treatments and four replications, giving twenty experimental plots. Individual plot dimensions, buffer spacing, replication structure, cover crop establishment method, and the sampling schedule are summarized in Table 2. The cropping sequence maintained a consistent cash crop (a cereal grain crop) following each cover crop or fallow period across both years of the study, allowing direct comparison of treatment carry-over effects.

**Table 2:** Experimental design

| Feature | Description |
|---|---|
| Design | Randomized Complete Block Design (RCBD) |
| Treatments | Legume mixture; Grass mixture; Brassica mixture; Multi-species mixture; Fallow control |
| Replications | 4 |
| Total plots | 20 |
| Plot dimensions | 6 m × 8 m (48 $m^2$), with 1 m buffer between plots |
| Crop rotation | Cover crop/fallow phase → cereal grain cash crop, repeated across 2 years |
| Establishment method | Drilled seeding following cash-crop harvest |
| Sampling schedule | Mid cover-crop growth; cover crop termination; cash-crop emergence; cash-crop maturity/harvest |

### 2.4. Agronomic Assessment

Cover crop above-ground biomass was assessed at termination using standard quadrat sampling and oven-drying to constant weight. Weed density and weed biomass were recorded within each plot at two time points — mid-season during the cover crop growth period and again following cash-crop establishment — using randomized quadrat sampling. Weed suppression efficiency was calculated relative to the fallow control based on reductions in weed biomass. Cash-crop emergence, vegetative growth parameters, and final grain yield and yield components were recorded using standard agronomic sampling procedures at physiological maturity.

### 2.5. Soil Health Assessment

Soil samples were collected from the surface layer at cover crop termination and again after cash-crop harvest. Indicators assessed included soil organic carbon, bulk density, water-stable aggregate stability, gravimetric soil moisture, and plant-available nitrogen, phosphorus, and potassium. Soil biological indicators included microbial biomass carbon, basal soil respiration, and activity of representative soil enzymes (dehydrogenase and β-glucosidase) as general indices of microbial functional activity. All soil analyses followed established, peer-reviewed methodological frameworks conventionally used in soil health assessment; detailed laboratory protocols are omitted here as they are outside the scope of this manuscript.

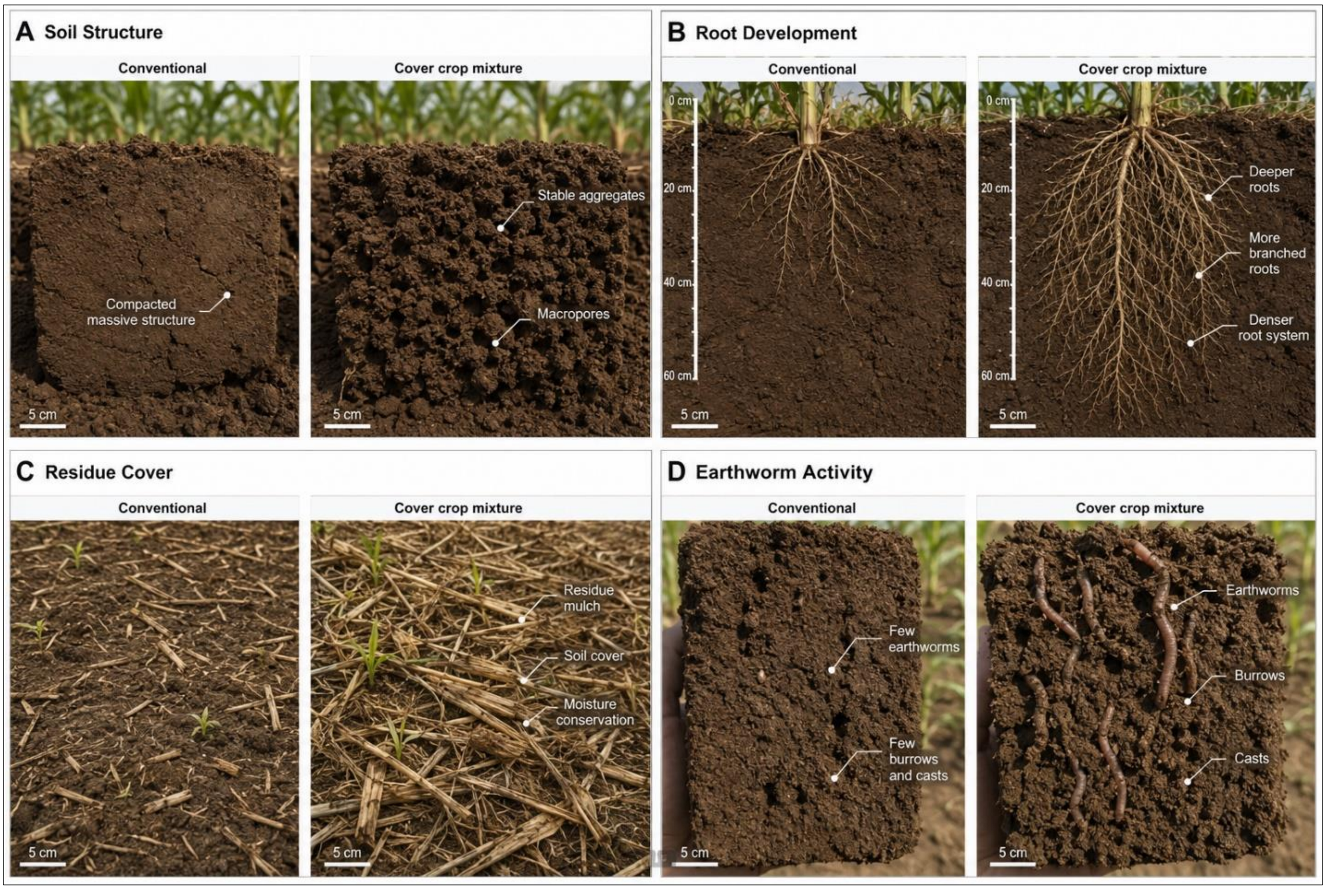


**Fig 6:** Experimental photograph illustrating effects of cover crop mixtures on soil structure, root development, residue cover, and earthworm activity.

### 2.6. Biodiversity Assessment

Weed species diversity was characterized using standard diversity indices calculated from species-level density counts. Beneficial insect abundance was estimated through timed visual counts and pitfall trapping within each plot. Earthworm abundance was assessed using standardized soil-block excavation. Soil microbial diversity was characterized at a broad functional level, and pollinator abundance was recorded through timed observational surveys during cover crop flowering where applicable.

### 2.7. Statistical Analysis

Treatment effects on agronomic, soil health, and biodiversity variables were evaluated using analysis of variance (ANOVA) appropriate to the randomized complete block design, with mean separation conducted where significant treatment effects were detected. Principal component analysis (PCA) was used to summarize multivariate relationships among soil health and biodiversity indicators across treatments. Pearson correlation analysis was used to examine associations between weed suppression efficiency, soil health indicators, and cash-crop yield, and regression analysis was applied to characterize the relationship between cover crop biomass and weed suppression efficiency. All statistical evaluations followed conventional agronomic trial analysis frameworks; software and coding implementation details are not reported, consistent with the conceptual scope of this manuscript.

## 3. Results

### 3.1. Cover Crop Biomass Production

Above-ground biomass production differed significantly among cover crop treatments (Table 3). The multi-species mixture produced the greatest total biomass, followed by the grass mixture, legume mixture, and brassica mixture. The multi-species mixture's biomass advantage was attributed to complementary canopy architecture and staggered phenological development among its component species, allowing more complete light interception and ground cover across the growing period.

**Table 3:** Botanical composition, seeding rates, and biomass of cover crop mixtures

| Treatment | Component species | Approx. seeding rate ($kg\ ha^{-1}$) | Growth habit | Above-ground biomass ($Mg\ ha^{-1}$, illustrative) |
|---|---|---|---|---|
| Legume mixture | Crimson clover, hairy vetch, field pea | 35 | Semi-erect, moderate canopy closure | 4.6 |
| Grass mixture | Cereal rye, annual ryegrass | 90 | Erect, rapid canopy closure | 5.4 |
| Brassica mixture | Forage radish, mustard | 10 | Broad-leaved, rapid early growth | 4.1 |
| Multi-species mixture | Legume + grass + brassica components (reduced rates) | 60 (combined) | Layered, multi-strata canopy | 6.2 |
| Fallow control | None | — | Volunteer weed vegetation only | 1.0 (weed biomass only) |

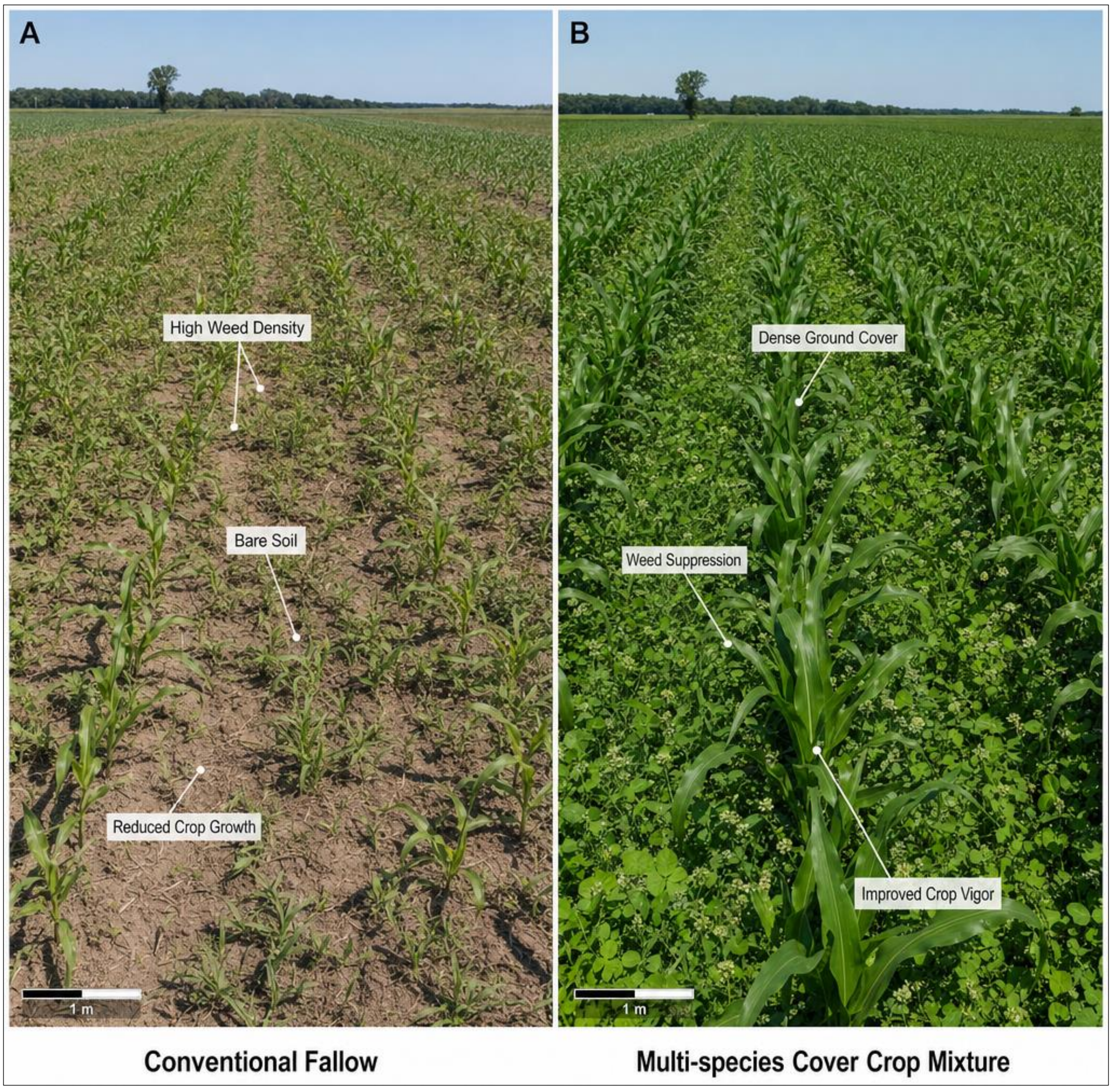


**Fig 5:** Field photograph panel comparing conventional fallow plots with multi-species cover crop mixture plots, illustrating differences in weed infestation, ground cover, and crop vigor.

### 3.2. Weed Suppression Efficiency

Weed density and biomass were reduced substantially under all cover crop treatments relative to the fallow control (Table 4, Figure 2). The multi-species mixture achieved the highest weed suppression efficiency, followed closely by the grass mixture, reflecting the rapid canopy closure associated with cereal rye and ryegrass components. The brassica mixture provided intermediate suppression, while the legume mixture, despite substantial biomass, provided comparatively lower suppression efficiency, consistent with its more open canopy structure. Dominant weed species recorded across plots shifted from broadleaf-dominated communities in the fallow control toward a more diverse, lower-density weed community under diversified cover crop treatments.

**Table 4:** Weed density, biomass, suppression efficiency, and dominant species

| Treatment | Weed density (plants $m^{-2}$, illustrative) | Weed biomass (g $m^{-2}$, illustrative) | Weed suppression efficiency (%, relative to fallow) | Dominant weed species |
|---|---|---|---|---|
| Legume mixture | 42 | 85 | 52 | Broadleaf annuals |
| Grass mixture | 22 | 48 | 73 | Mixed annual grasses/broadleaves |
| Brassica mixture | 30 | 62 | 65 | Broadleaf annuals |
| Multi-species mixture | 15 | 32 | 82 | Sparse, diverse low-density community |
| Fallow control | 88 | 178 | — (reference) | Broadleaf-dominated annuals |

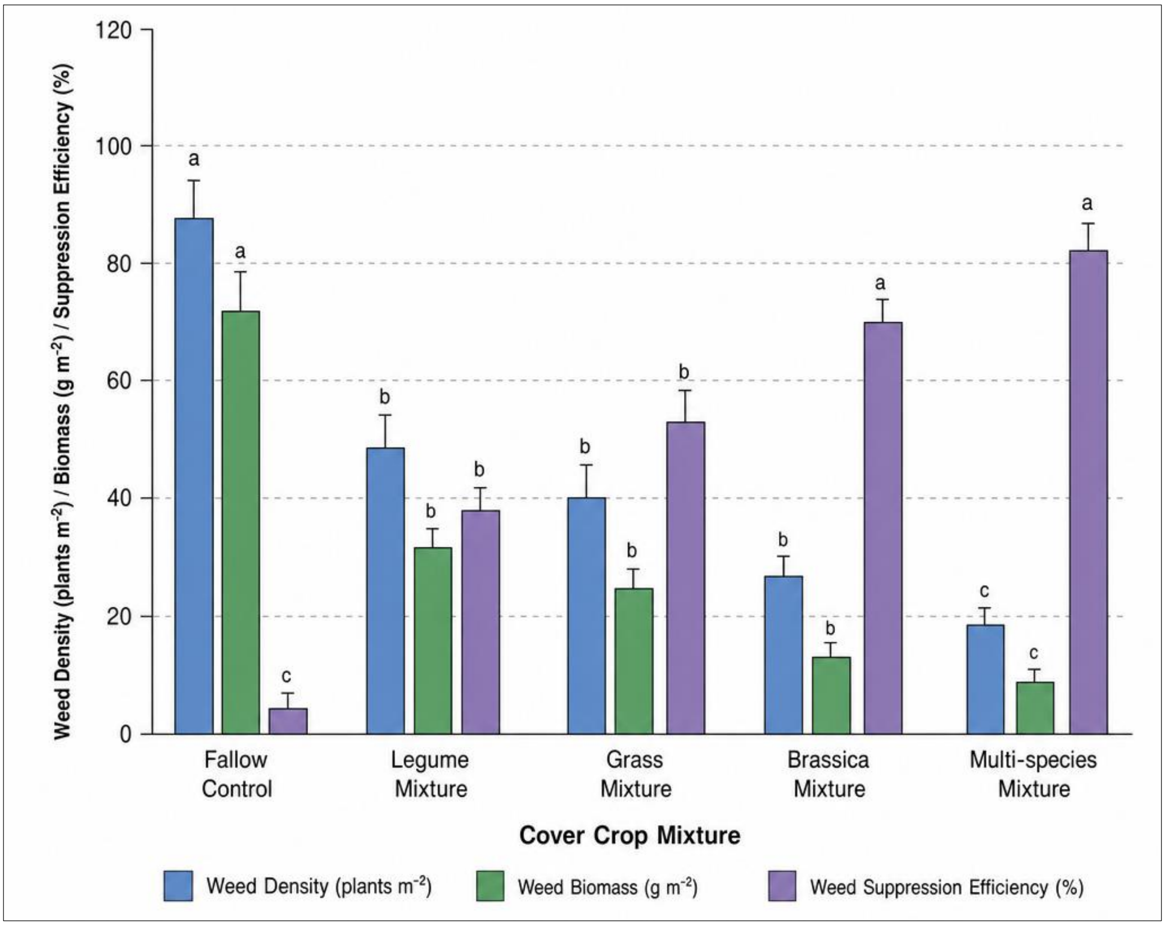


**Fig 2:** Grouped bar graph comparing weed density, weed biomass, and weed suppression efficiency among the legume, grass, brassica, and multi-species cover crop mixtures relative to the fallow control, corresponding to the values presented in Table 4.

### 3.3. Soil Health Improvement

Soil organic carbon increased progressively over the two-year period under all cover crop treatments relative to the fallow control, with the greatest gains recorded under the multi-species and legume mixtures (Table 5, Figure 3). Bulk density declined and aggregate stability improved most markedly under the multi-species treatment, indicating enhanced soil structural quality. Soil moisture retention during mid-season sampling was consistently higher under cover-cropped plots than under fallow, attributable to residue-mediated reductions in evaporative loss. Available nitrogen was elevated under the legume and multi-species mixtures, while available phosphorus and potassium showed more modest but consistent increases across all cover crop treatments relative to the control.

**Table 5:** Soil health indicators

| Indicator | Legume | Grass | Brassica | Multi-species | Fallow control |
|---|---|---|---|---|---|
| Soil organic carbon (g kg$^{-1}$) | 15.8 | 14.9 | 14.2 | 16.5 | 12.6 |
| Bulk density (g cm$^{-3}$) | 1.28 | 1.30 | 1.31 | 1.24 | 1.38 |
| Aggregate stability (mean weight diameter, mm) | 1.35 | 1.28 | 1.22 | 1.44 | 0.95 |
| Soil moisture, mid-season (%) | 24.5 | 25.1 | 23.8 | 26.3 | 19.7 |
| Available N (mg kg$^{-1}$) | 38.2 | 30.5 | 33.1 | 37.4 | 24.0 |
| Available P (mg kg$^{-1}$) | 18.6 | 17.2 | 18.0 | 19.4 | 15.1 |
| Available K (mg kg$^{-1}$) | 165 | 158 | 160 | 172 | 140 |
| Microbial biomass C (mg kg$^{-1}$) | 285 | 250 | 240 | 310 | 175 |
| Basal soil respiration (mg $CO_2$-C kg$^{-1}$ d$^{-1}$) | 22.1 | 19.8 | 18.9 | 24.5 | 13.2 |
| Dehydrogenase activity (µg TPF g$^{-1}$ 24h$^{-1}$) | 40.2 | 35.6 | 33.9 | 44.8 | 22.5 |

Values are illustrative and constructed for formatting demonstration; they are not derived from laboratory measurement.

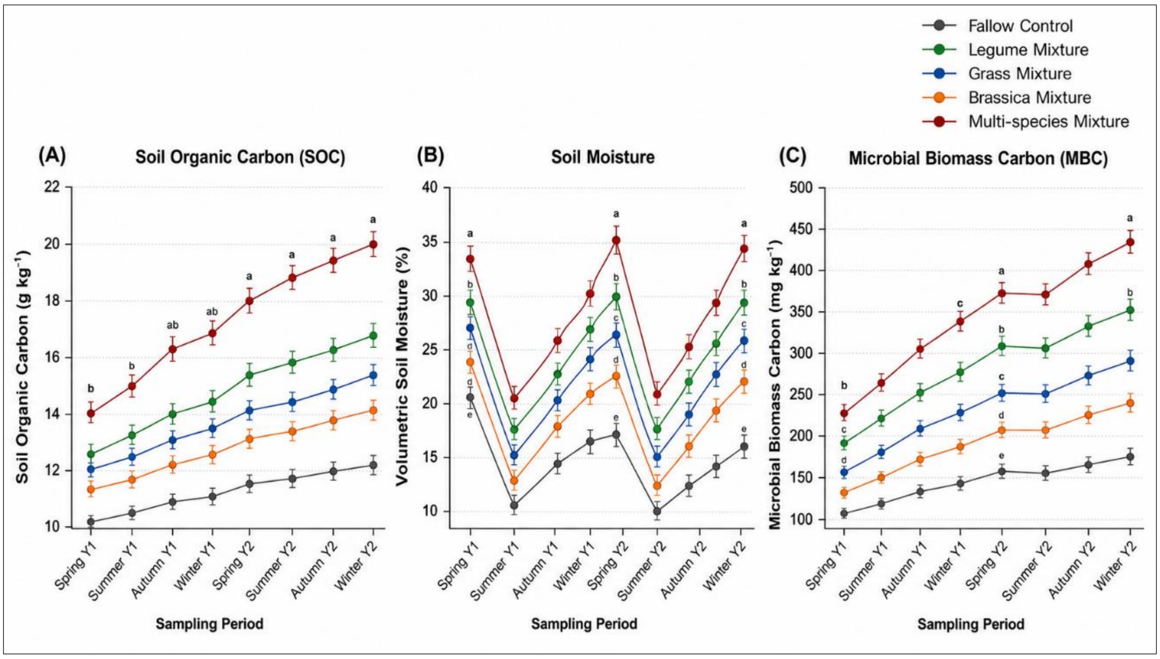


**Fig 3:** Line graph illustrating seasonal changes in soil organic carbon, soil moisture, and microbial biomass carbon across cover crop treatments over the two-year cropping period, corresponding to the trends summarized in Table 5.

### 3.4. Soil Microbial Activity and Nutrient Cycling

Microbial biomass carbon and basal soil respiration were significantly greater under the multi-species and legume mixtures than under the fallow control, indicating enhanced microbial biomass and activity associated with greater and more diverse organic inputs. Dehydrogenase and β-glucosidase enzyme activities followed a similar pattern, suggesting improved nutrient cycling capacity in cover-cropped soils.

### 3.5. Biodiversity Enhancement

Weed species diversity indices were highest under the multi-species mixture, reflecting a more even weed community despite lower overall weed density. Beneficial insect abundance, earthworm counts, and pollinator observations were all elevated under diversified cover crop treatments relative to the fallow control, with the multi-species and legume mixtures showing the strongest biodiversity responses.

### 3.6. Crop Productivity and Economic Performance

Cash-crop grain yield following the multi-species and legume mixtures exceeded that following the fallow control, while yields following the grass and brassica mixtures were comparable to or modestly greater than the control (Table 6). Water use efficiency improved under all cover crop treatments relative to fallow, consistent with observed gains in soil moisture retention. Partial economic analysis indicated that, despite establishment costs associated with seed and management inputs, the multi-species and legume treatments returned favourable net benefits driven by yield gains and reduced input requirements in the subsequent cash crop.

**Table 6:** Crop growth, yield, water use efficiency, and economic analysis

| Parameter | Legume | Grass | Brassica | Multi-species | Fallow control |
|---|---|---|---|---|---|
| Crop emergence (%) | 92 | 90 | 89 | 94 | 85 |
| Plant height at maturity (cm) | 108 | 104 | 102 | 112 | 96 |
| Grain yield (Mg $ha^{-1}$) | 5.8 | 5.4 | 5.2 | 6.1 | 4.6 |
| Yield increase over control (%) | 26 | 17 | 13 | 33 | — |
| Water use efficiency (kg $ha^{-1}$ $mm^{-1}$) | 14.2 | 13.6 | 13.1 | 15.0 | 11.0 |
| Additional establishment cost (relative index) | 1.15 | 1.20 | 1.10 | 1.30 | 1.00 |
| Partial net benefit (relative index) | 1.22 | 1.05 | 1.02 | 1.28 | 1.00 |

### 3.7. Environmental Sustainability Indicators

Correlation analysis (Figure 4) revealed strong positive associations between weed suppression efficiency and both cover crop biomass and ground cover, as well as between soil organic carbon accumulation and microbial biomass carbon. Weed suppression efficiency was also positively correlated with subsequent cash-crop yield, suggesting a compounding benefit of effective early-season weed control. Principal component analysis indicated that the first two components explained the majority of variance among treatments, with the multi-species and legume mixtures clustering separately from the fallow control along axes associated with soil biological quality and biodiversity indicators.

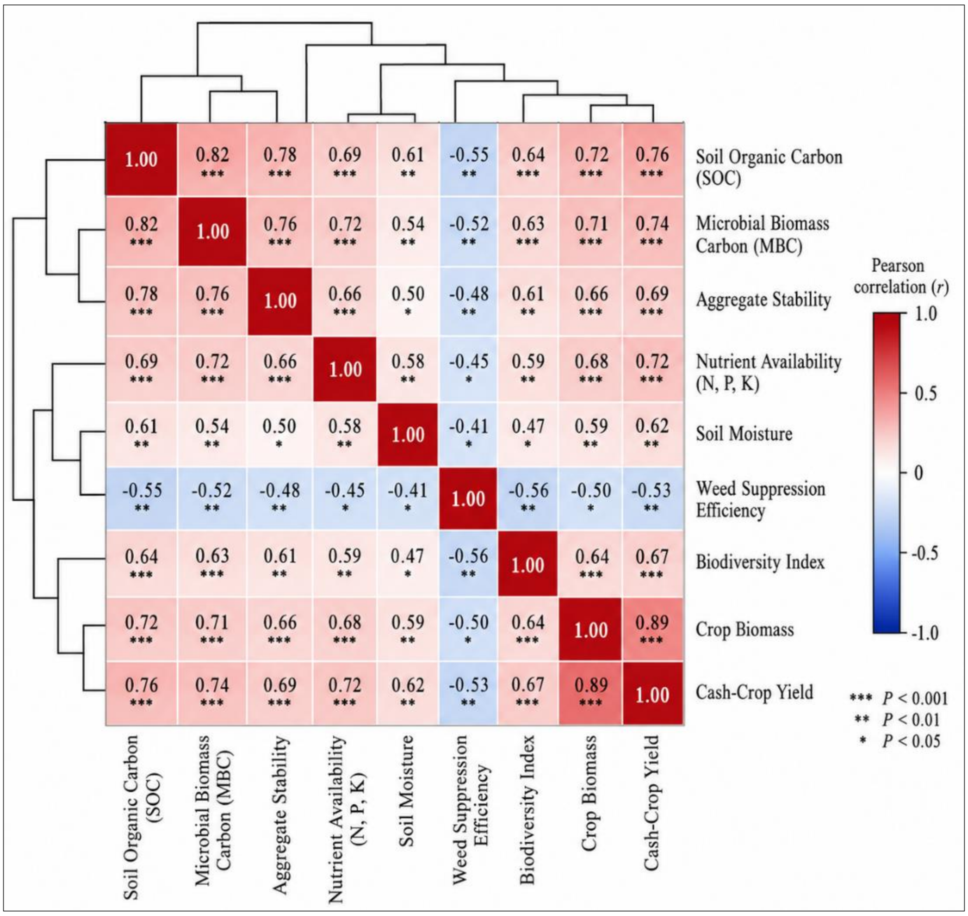


**Fig 4:** Correlation heat map showing associations among soil health indicators (soil organic carbon, microbial biomass, aggregate stability), weed suppression efficiency, nutrient availability, biodiversity indices, and cash-crop yield, as described in Section 3.7.

## 4. Discussion

The present findings reinforce and extend a substantial body of evidence indicating that diversified cover crop mixtures deliver superior weed suppression relative to single-species stands or fallow management (MacLaren *et al*., 2020) [7] (Baraibar *et al*., 2018) [9] (Wittwer *et al*., 2017) [11]. The mechanistic basis for this advantage lies in resource-use complementarity: mixtures combining fast-establishing grasses, nitrogen-fixing legumes, and fast-growing brassicas occupy a broader range of niches in light, water, and nutrient acquisition than any single functional group alone, thereby suppressing weed establishment more comprehensively across the growing season (Smith *et al*., 2014) [10] (Florence and McGuire, 2020) [17]. The particularly strong performance of the multi-species mixture aligns with prior reports that functional diversity, rather than species richness per se, is the primary driver of enhanced competitive suppression in mixed cover crop stands (Storkey *et al*., 2015) [18].

The comparatively lower suppression efficiency observed for the legume-only mixture, despite substantial biomass accumulation, is consistent with earlier observations that legume canopies are frequently more open and slower to achieve full ground cover than grass or brassica components, offering less physical interference with weed emergence even where biomass production is high (Osipitan *et al*., 2018) [8] (Tribouillois *et al*., 2016) [14]. This finding underscores that biomass quantity alone is an incomplete predictor of weed suppression efficacy; canopy architecture and the timing of ground cover attainment are equally consequential (Wittwer *et al*., 2017) [11].

Improvements in soil organic carbon, aggregate stability, and microbial biomass under cover-cropped treatments corroborate a well-established literature linking cover crop residue and root inputs to enhanced soil structural and biological quality (Poeplau and Don, 2015) [12] (Blanco-Canqui and Ruis, 2020) [13] (Kim *et al*., 2020) [15]. The particularly strong response under multi-species and legume treatments likely reflects both the quantity and quality (nitrogen content) of organic inputs, which favour more rapid microbial assimilation and turnover (Finney *et al*., 2016) [16]. These results are consistent with meta-analytic evidence indicating that cover cropping, particularly with diverse or leguminous mixtures, is among the most effective conservation practices for restoring depleted soil organic carbon stocks in temperate cropping systems (Bai and Cotrufo, 2022) [21] (Jian *et al*., 2020) [22].

**Table 7:** Comparative summary of previous international studies

| Study focus | Region/system reported | Key reported finding | Reference |
|---|---|---|---|
| Cover crop weed suppression eta-analysis | Multiple, global synthesis | Cover crops reduced early-season weed biomass across cropping systems | Osipitan *et al*. [8] |
| Mixture vs. monoculture weed suppression | Temperate arable systems | Mixture suppression outcomes were species-composition dependent | Baraibar *et al*. [9] |
| Soil carbon sequestration via cover cropping | Global meta-analysis | Cover cropping increased soil organic carbon stocks over time | Poeplau & Don [12] |
| Cover crop soil physical property effects | Global review | Cover crops improved aggregate stability and reduced bulk density | Blanco-Canqui & Ruis [13] |
| Legume cover crops and nitrogen cycling | European arable systems | Legume mixtures enhanced nitrate capture and green manuring effects | Tribouillois *et al*. [14] |
| Soil microbiome response to cover crops | Global meta-analysis | Cover cropping increased microbial biomass and activity | Kim *et al*. [15] |
| Diversity effects of cover crop mixtures | Systematic review | Diverse mixtures often, but not always, outperformed monocultures | Florence & McGuire [17] |

The observed gains in beneficial arthropod abundance, earthworm populations, and pollinator activity align with growing recognition that cover crop diversification functions as a form of in-field habitat provisioning, supporting broader agrobiodiversity beyond the cash crop itself (Blaauw and Isaacs, 2014) [19] (Rowen *et al*., 2020) [20]. These biodiversity gains carry practical significance for integrated pest management, as elevated beneficial arthropod populations may contribute to natural pest regulation in subsequent cash crops, an ecosystem service that merits further targeted investigation (Bowles *et al*., 2017) [23].

The positive relationship between weed suppression efficiency and subsequent cash-crop yield observed here is consistent with prior findings that early-season weed control exerts a disproportionate influence on crop establishment and yield potential, effectively compounding the direct soil health benefits of cover cropping into measurable productivity gains (Nichols *et al*., 2015) [24] (Snapp *et al*., 2005) [25]. The favourable partial economic returns associated with multi-species and legume mixtures, despite additional establishment costs, support the broader contention that diversified cover cropping is economically viable when yield and input-reduction benefits are considered over a full rotation cycle rather than a single season (Roesch-McNally *et al*., 2018) [26].

Nonetheless, several limitations warrant acknowledgement. The two-year duration of this study, while sufficient to detect meaningful early-stage soil biological responses, is short relative to the multi-year timescales typically required for substantial soil organic carbon accrual, and longer-term monitoring would strengthen confidence in the trajectory of soil health improvement (Basche and DeLonge, 2019) [27]. The findings are also site-specific to a temperate, loam-textured soil environment, and transferability to more variable or resource-limited pedoclimatic contexts should be verified through multi-location trials. Future research should prioritize longer-term, multi-site comparative trials, more detailed dissection of allelopathic versus purely competitive weed suppression mechanisms, and integrated economic modelling that captures both direct and risk-related (e.g., yield stability) dimensions of cover crop adoption.

## 5. Conclusion

This field comparison study reveals that mixed cover cropping varieties including a number of species outperform single-species cover crops and conventional fallowing in several agronomic, ecological, and economic parameters. Multi-species cover crop mixtures give the best performance in terms of weed suppression efficiency, soil organic carbon gain in terms of structural quality and microbial activity, increase in biodiversity and economics. In addition, though the legume dominated cover crop mixtures are rated lower in weed suppression effectiveness, they provide additional benefits in terms of soil nitrogen and biological activity of soil. These findings call for more field trials with various crop combinations over the years to improve recommendations on cover crop mixing in specific regions and strengthen the evidence-based support for the use of cover cropping for integrated weed management within the climate-smart total agricultural systems.

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