

Durum wheat-vetch intercropping in Mediterranean agroecological systems: Effects on yield, nitrogen balance, and farm profitability

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ABSTRACT

Cereal–legume intercropping offers a viable pathway for advancing the agroecological transition of Mediterranean farming systems from conventional monocultures to more diversified and sustainable agroecosystems. However, field-based evaluations, particularly involving underutilized species and contrasting input levels, remain limited. This study assessed the performance of a low-input intercropping system combining durum wheat and common vetch (*Vicia sativa* L.), compared to fertilized and unfertilized sole crops, over two growing seasons (2022–2024) in Southern Italy. Compared to the input-intensive monoculture, the intercropping system matched or exceeded grain yield in 2022–2023 (3.31 vs. 3.03 t ha⁻¹) and was comparable in 2023–2024 (2.67 vs. 2.79 t ha⁻¹), despite a sharp decline in rainfall (314.6 mm vs. 673.6 mm) and a rise in mean temperature (15.47 °C vs. 13.58 °C), which increased drought stress. Protein content was comparable or higher (13.9 % vs. 12.3 % in 2022–2023; 12.4 % vs. 12.3 % in 2023–2024), and nitrogen uptake increased by 15.2 kg ha⁻¹ (91.3 vs. 76.1 kg ha⁻¹) in 2022–2023 and 11.9 kg ha⁻¹ in 2023–2024 (66.6 vs. 54.7 kg ha⁻¹). Common vetch demonstrated the highest nitrogen accumulation and contributed up to 124.6 kg N ha⁻¹ via crop residues, enhancing nutrient cycling. Land Equivalent Ratios (1.62 and 1.35) confirmed superior land-use efficiency. Economically, intercropping achieved the highest contribution margin (€280.6 ha⁻¹), outperforming the fertilized wheat monoculture (€47.5 ha⁻¹), despite additional seed separation costs. While absolute performance declined under drought, intercropping remained competitive or superior to monocultures across all metrics, reinforcing its potential as a resilient, low-input solution for Mediterranean agriculture. Further research, supported by long-term field trials, should aim to validate these benefits, improve legume drought tolerance, and refine species combinations to enhance resilience and adaptability in dry Mediterranean environments.

1. Introduction

Food and environmental security, along with the efficient use of agricultural inputs, remain global priorities in agriculture (Maitra et al., 2021). These concerns are especially pressing in the Mediterranean region, where climate stressors and complex agri-food challenges hinder sustainable agricultural development (Antonelli et al., 2022). Cereal crops are the most widely consumed staple foods worldwide (Ahmad et al., 2024), and cereal farming remains a cornerstone of Mediterranean

agriculture (Savin et al., 2022). Yet, Mediterranean cereal systems are increasingly challenged by limited land availability, climate change, and declining input-use efficiency (Perniola et al., 2015). Agricultural intensification has increased cereal monocrop productivity but has also caused environmental trade-offs, necessitating crop diversification and alternative practices to redesign farming systems for sustainability (Di Bene et al., 2022). In this context, agroecology and ecological intensification have emerged as strategies to mitigate the negative impacts of cereal monocultures by promoting diversified cropping systems that

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enhance ecosystem services and sustainability (Bommarco et al., 2013; Kremen et al., 2012; Messéan et al., 2021).

Diversified intercropping systems, especially cereal–legume combinations, are among the most effective agroecological strategies. These systems improve the use efficiency of light, water, and nutrients, while also stabilizing yields under increasingly variable climatic conditions (Bedoussac et al., 2015; Justes et al., 2021). Defined as the simultaneous cultivation of two or more species in the same field, intercropping offers a practical and scalable path toward diversification in intensive systems (Huss et al., 2022; Landschoot et al., 2024). Intercropping can take various forms: row, mixed, strip, or relay, and enhances agroecosystem functioning through competitive, facilitative, and complementary plant interactions (Cardinale et al., 2002; Jensen, 1996). Cereal–legume intercropping, in particular, supports sustainable intensification by improving resource capture, boosting soil fertility, and reducing erosion (Tripathi et al., 2021). As an ecological intensification practice, intercropping increases food production while enhancing crop protection, climate resilience, and overall farm sustainability (Huss et al., 2022). It has also been recognized as improving land-use efficiency, optimizing nitrogen cycling, and reducing dependence on synthetic inputs (Li et al., 2009; Bedoussac et al., 2015; Tamburini et al., 2020; Yu et al., 2015). A synthesis of 24 meta-analyses by Huss et al. (2022) confirms its multiple advantages, including superior suppression of weeds, pests, and pathogens, alongside higher relative yields, and greater gross profitability than monocultures.

Cereal-legume intercropping has gained substantial attention due to its ability to enhance crop productivity, optimize N availability, and contribute to long-term soil fertility (Hauggaard-Nielsen et al., 2003; Jensen et al., 2010; Peoples et al., 2009). Legumes, through biological nitrogen fixation (BNF), reduce reliance on synthetic fertilizers, decrease greenhouse gas emissions, and enhance N availability for associated crops (Jensen et al., 2012; Parvin et al., 2023; Voisin et al., 2014). Beyond N benefits, legumes support biological pest control, pollination, and carbon sequestration (Blanco-Canqui et al., 2015; Gaba et al., 2015). Meta-analyses confirm cereal-legume intercropping improves land productivity by enhancing the utilization of soil-derived and fixed nitrogen, and it also reduces weed pressure and increases yield stability, especially in organic and low-input systems (Rodriguez et al., 2020; Tosti et al., 2023).

Intercropping research has expanded from yield and plant interaction studies to broader themes like microbial dynamics, climate adaptation, biodiversity, and long-term sustainability (Tang et al., 2025). Current research emphasizes the need to move beyond dominant maize–wheat–soybean systems and explore the potential of underutilized species in diverse agroecological contexts, particularly for their adaptability, yield stability, and multifunctional benefits (Landschoot et al., 2024; Todde et al., 2024). Underutilized legumes, in particular, offer strong potential to enhance food security under climate change due to their resilience to extreme conditions (e.g., drought, salinity, poor soils), high nitrogen-fixing capacity, disease resistance, weed suppression, and superior nutritional profiles (Ayilara et al., 2022). This is especially relevant for Mediterranean organic durum wheat (*Triticum durum* Desf.) systems, where tailored agronomic practices are essential to sustain productivity. Evidence shows that cereal–legume intercropping enhances system productivity, stabilizes gross margins, and contributes to soil health and weed suppression (Bedoussac et al., 2015; Guiducci et al., 2018; Louarn et al., 2021; Martin-Guay et al., 2018). Among legumes, vetch (*Vicia sativa* L.) is a particularly valuable companion crop due to its substantial biomass production and strong symbiotic nitrogen fixation (De la Rosa et al., 2021). Its capacity to improve soil nitrogen (N) availability, stimulate microbial activity, and support long-term fertility makes it a key component of sustainable intercropping strategies. The inclusion of legumes in wheat intercropping has been shown to increase the land equivalent ratio (LER), indicating more efficient land use compared to monocultures (Guiducci et al., 2018). Additionally, by reducing the need for synthetic fertilizers and improving nitrogen

availability, vetch can lower input costs and increase gross production value (GPV), thus enhancing overall economic sustainability. However, effective management is crucial to balance interspecific competition and fully optimize both the agronomic and economic benefits of vetch–wheat intercropping (Lauk and Lauk, 2009; Louarn et al., 2021; Parvin et al., 2023; Rose et al., 2024). Further research is needed to refine management practices and select suitable cultivars to maximize the multifunctional advantages of these systems.

This study, conducted in a Mediterranean environment, investigates the effects of a durum wheat–common vetch intercrop, sown and harvested concurrently under real farm conditions, on yield, nitrogen balance, and farm profitability. Specifically, it assesses: (i) agronomic performance, through grain yield and protein content, (ii) land-use efficiency, via the land equivalent ratio (LER), (iii) nitrogen dynamics within the system; and (iv) the contribution margin compared to monocultures. The findings aim to inform strategies for crop diversification and sustainable intensification in Mediterranean cereal systems.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at the La Generale cooperative in Genzano di Lucania, Italy (40.82460° N, 16.09348° E). The 12-hectare experimental site features a typical Mediterranean climate, characterized by annual temperatures of 15 °C and precipitation ranging from 500 to 700 mm. The region experiences characteristic Mediterranean seasonality, with dry summers and moderately distributed rainfall during autumn and winter. The soil at the experimental site exhibits textural variability, predominantly classified as clay loam, with moderate organic matter content and an alkaline pH (~8.2). The reported values represent average soil properties, derived from a spatial variability study conducted across different plots within the experimental area. The total N content is approximately 0.9 g kg⁻¹, with available phosphorus averaging 7.7 mg kg⁻¹ and exchangeable potassium around 0.8 meq 100 g⁻¹. The cation exchange capacity (CEC) is moderate (~21.3 meq 100 g⁻¹), indicating a good potential for nutrient retention. Although variations in soil texture and fertility exist across different zones, the area is characterized by a general cereal-growing vocation. This supports durum wheat cultivation under both continuous and rotational cropping systems, which are typically integrated with legumes or fallow periods to maintain soil health and productivity.

2.2. Definition of experimental plots

The 12-hectare experimental area was divided into five experimental plots, each measuring 2.4 ha, to evaluate different cropping systems under real farming conditions (Fig. 1):

- Plot A: Monocropping of durum wheat
- Plot B: Legume cultivation
- Plot C: Medicinal crop cultivation
- Plot D: Durum wheat rotation
- Plot E: Cereal-legume intercropping

This design allows for a comparative assessment of different agronomic practices, providing insights into their impact on productivity, soil health, and overall system sustainability.

This study focuses on a cereal-legume intercropping system, tested over two consecutive years within a rotational framework. To ensure uniform management and reliable comparisons, the subdivision of plots was designed independently of soil variability. However, a spatial variability analysis was conducted using soil electrical resistivity mapping, followed by a physical and chemical characterization of the homogeneous areas, according to the method of Denora et al. (2022b). This procedure enabled the delineation of homogeneous zones (HZs), within

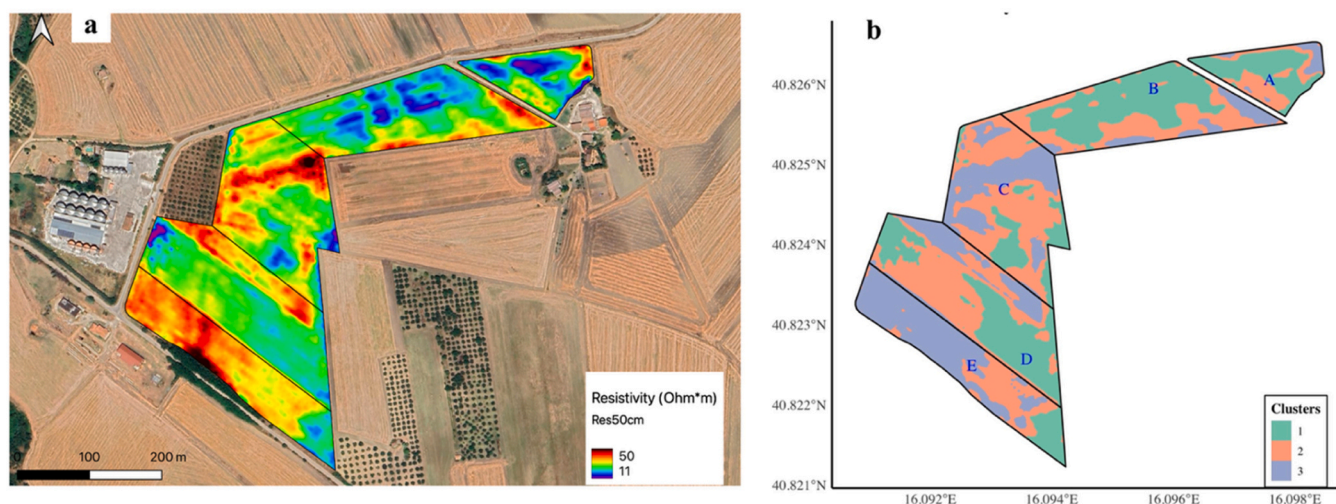


Fig. 1. Spatial characterization of the experimental area based on soil electrical resistivity. (a) Resistivity map (Ohm·m) at 50 cm depth, obtained via proximal sensing. (b) Geostatistical clustering of resistivity data, showing the delineation of three homogeneous zones (Clusters 1–3) and five experimental plots (A–E).

which all agronomic measurements were conducted, thereby improving the robustness of treatment comparisons despite the lack of formal plot replication.

The experiment followed an on-farm experimentation (OFE) approach, where treatments were fully integrated into the farmer's standard management practices. The layout was aligned with the operational widths of existing machinery (e.g., seed drill, sprayer boom, fertilizer spreader) to ensure compatibility with routine field operations. This design reflects the structural and logistical realities of commercial farming, thereby enhancing the practical relevance of the results (Giannini and Marraccini, 2023; Lacoste et al., 2021). Due to significant interannual differences in climatic conditions and crop management, data from each year were analyzed separately. This decision enabled a more accurate interpretation of treatment effects within each specific agronomic context, thereby avoiding confounding interactions that could arise from pooling temporally distinct data.

2.3. Experimental design

A strip-plot experimental design was implemented to align with the OFE framework, ensuring that treatment comparisons were conducted within homogeneous zones (HZs), as identified through spatial clustering analysis (Giannini et al., 2023). This approach enabled an accurate assessment of intercropping effects under specific soil conditions while maintaining farm-scale management practices (Cao et al., 2024). The experiment was conducted over two consecutive growing seasons (2022–2023 and 2023–2024), with the cereal-legume intercropping system rotated between plots:

- i. First year (Plot E, 2022–2023): Durum wheat (*Triticum durum* Desf.) and common vetch (*Vicia sativa* L.) were sown simultaneously on December 22, 2022, and harvested together on July 13, 2023. The preceding crop in Plot E was field pea (*Pisum sativum* L.), cultivated for grain and not incorporated into the soil as green manure.
- ii. Second year (Plot D, 2023–2024): Sowing occurred on December 9, 2023, with a simultaneous harvest on June 24, 2024. The preceding crop in Plot D was durum wheat (*Triticum durum* Desf.).

This setup enabled a comprehensive assessment of the intercropping system under commercial farming conditions, focusing on four key dimensions: crop productivity, land-use efficiency, N dynamics, and economic performance. A modified additive intercropping model was adopted, in which both durum wheat and common vetch were sown at reduced densities compared to their respective sole crops (Tosti et al.,

2023) to enhance functional complementarity and limit interspecific competition. Specifically, durum wheat seeding rate was reduced by approximately 35 %, and common vetch by about 33 %, with the latter intentionally maintained at a relatively high density to support BNF. In contrast to temporary intercropping systems, where the legume is often terminated early to reduce competition with the main crop (Parvin et al., 2023). This trial adopted a simultaneous intercropping approach, with both species sown and harvested concurrently, allowing them to complete their life cycles and contribute fully to the final yield.

The field experiment included four cropping treatments, applied within a strip-plot design to allow direct comparisons across distinct soil zones (Figs. 2–3). Treatments differed by crop composition and management regime, as detailed below:

- i. DW-SC-FM: Sole crop (SC) of durum wheat (*Triticum durum* Desf., cv. Tirex), sown at a rate of 230 kg ha⁻¹ and managed under full-input conditions (FM), including NPK fertilization, and chemical plant protection.
- ii. DW+CV-IC-NM: Intercrop (IC) of durum wheat (*T. durum*, cv. Tirex; 150 kg ha⁻¹) and common vetch (*Vicia sativa* L., cv. Ereica; 80 kg ha⁻¹), grown under a no-input management regime (NM), without fertilization or plant protection.
- iii. DW-SC-NM: Sole crop of durum wheat (*T. durum*, cv. Tirex; 150 kg ha⁻¹), managed under the same no-input conditions as the intercrop, enabling a direct comparison under a consistent agroecological framework.
- iv. CV-SC-FM: Sole crop of common vetch (*V. sativa*, cv. Ereica; 120 kg ha⁻¹), grown under full-input management (FM), including NPK fertilization and chemical plant protection.

The strip-plot design allowed for a structured evaluation of intercropping versus monocropping systems while maintaining homogeneity of soil resistivity within each treatment. This minimized the impact of spatial soil variability, ensuring a more accurate assessment of both the agronomic and economic performance of intercropping compared to monocropping (Marchant et al., 2019).

2.4. Data collection

2.4.1. Yield, quality, N dynamics, and LER assessment

Meteorological parameters, including daily precipitation and temperature, were recorded throughout the growing seasons using a weather station located at the experimental site. Grain and biomass yield were determined through sampling conducted in 2 × 2 m experimental

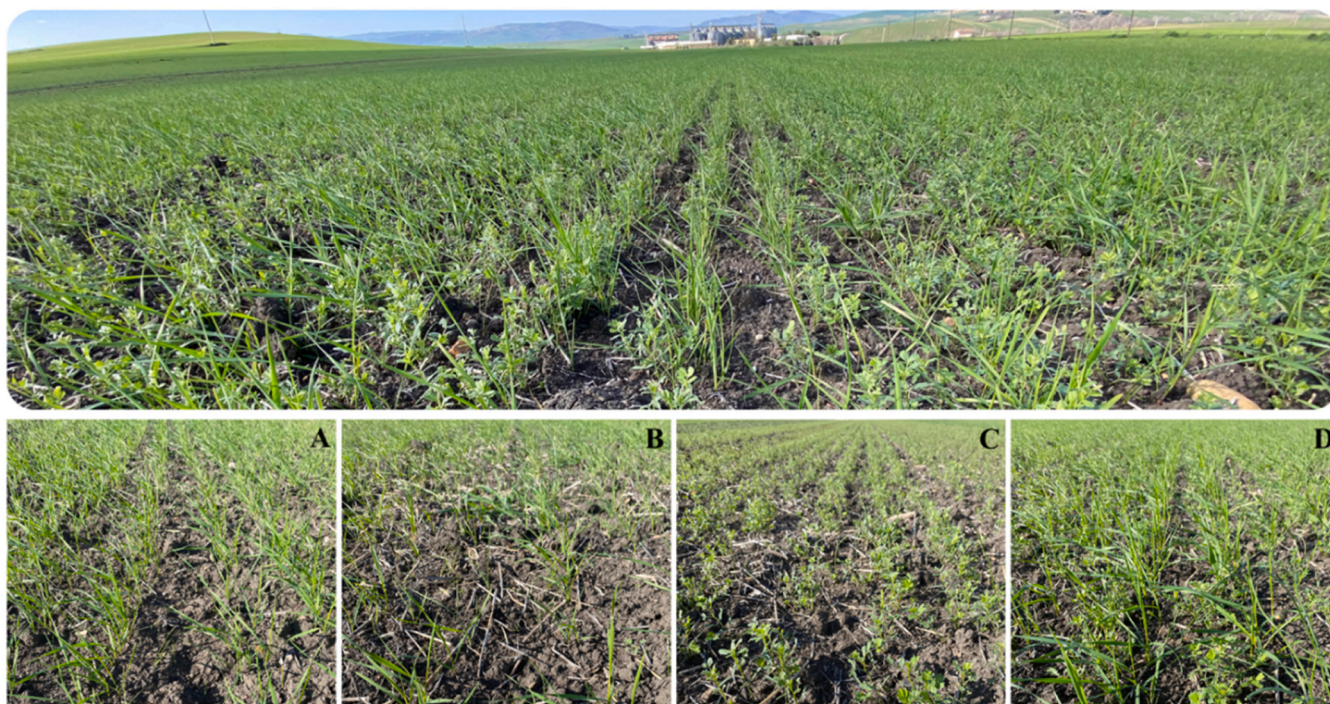


Fig. 2. Overview of the experimental design and details of the tested treatments. Top: General view of the experimental trial. Bottom: Close-up of the four tested combinations, from left to right: (A) DW-SC-FM, (B) DW-SC-NM, (C) CV-SC-FM, (D) DW+CV-IC-NM.

plots, with three replicates per treatment within the same HZ (Denora et al., 2022a).

Grain quality was assessed by determining the protein content of durum wheat using near-infrared spectroscopy (NIRS) with the Infratec 1241 Grain Analyzer (FOSS). At the time of sampling, the total N content (N, %) was determined using the Kjeldahl method (Bremner, 1960) across different crop fractions. Sampling was carried out at three representative points within a homogeneous field area to ensure consistency in the analysis of the various components. Total nitrogen (N) content was determined in the dry aboveground biomass of both common vetch and durum wheat, including direct measurements in the grain, to evaluate N distribution within the cropping system. At each sampling point, N concentration (%) was multiplied by the corresponding dry biomass (kg ha^{-1}) to calculate N uptake (kg N ha^{-1}). The analysis focused on comparing the intercrop treatment without nitrogen input (DW+CV-IC-NM) to the corresponding sole-cropped durum wheat under the same zero-input conditions (DW-SC-NM), both sown at equal seeding densities to maintain consistency within the agroecological framework. Additionally, a partial assessment of the vetch intercrop (CV-IC) was conducted to explore its potential contribution to ecosystem services, particularly in relation to residue management.

The land-use efficiency of the durum wheat–common vetch intercropping system was assessed using the LER, a widely adopted index for comparing the productivity of intercropping systems to their corresponding sole crops (Willey and Osiru, 1972). The LER expresses the theoretical land area required under sole cropping to match the yield obtained on one hectare of intercropping.

$$LER = \left(\frac{Y_{iw}}{Y_w} \right) + \left(\frac{Y_{iv}}{Y_v} \right) \quad (1)$$

where: Y_{iw} = (DW+CV-IC-NM) yield of durum wheat in intercropping (t ha^{-1}), Y_w = (DW-SC-FM) yield of durum wheat in sole cropping (t ha^{-1}), Y_{iv} = (CV-IC) yield of common vetch in intercropping (t ha^{-1}), Y_v = (CV-SC-FM) yield of common vetch in sole cropping (t ha^{-1}). Intercrop yields were derived from the DW+CV-IC-NM treatment, in which durum wheat and common vetch were sown at seeding rates of 150 and 80 kg ha^{-1} ,

respectively. The reference yields for the sole crops were obtained from plots managed with agronomically optimal seeding rates: 230 kg ha^{-1} for durum wheat and 120 kg ha^{-1} for common vetch. Despite the different seeding rates adopted in the intercropping (DW+CV-IC-NM) and sole crop treatments (DW-SC-FM for durum wheat and CV-SC-FM for common vetch), no correction was applied to the LER calculation. This methodological choice reflects the objective of assessing the land-use efficiency of intercropping under realistic agronomic conditions, where the intercrop is considered an autonomous cropping system and compared to sole crops managed at optimal seeding rates (Bedoussac and Justes, 2010). In this context, LER provides a valid basis for quantifying the overall productivity advantage per unit of cultivated area, even when differences in plant density are present between cropping systems (Justes et al., 2021). Partial LERw = $\left(\frac{Y_{iw}}{Y_w} \right)$ for durum wheat and pLERv = $\left(\frac{Y_{iv}}{Y_v} \right)$ for common vetch) were also calculated to determine the individual contribution of each species to the total LER. A total LER greater than 1 indicates a land-use advantage of intercropping, meaning that it achieves higher productivity per hectare than sole cropping systems.

2.4.2. Economic analysis

The economic analysis of the durum wheat–vetch intercropping system was performed by calculating Contribution Margin (CM), a key indicator that reflects the economic value of agricultural production by accounting for both gross production value (GPV) and production costs (C), excluding fixed overheads. This approach, consistent with the methodology of Leoni et al. (2024), enables the assessment of intercropping's economic performance relative to monoculture by analyzing the individual contributions of each species to the overall system.

To provide a detailed estimate, GPV and C were calculated separately for durum wheat and vetch. These values were then aggregated to determine the cumulative gross production value ($\text{GPV}_{(w+v)}$) and cumulative costs ($\text{C}_{(w+v)}$), thereby allowing a comprehensive evaluation of the net economic impact of intercropping compared to sole cropping systems.

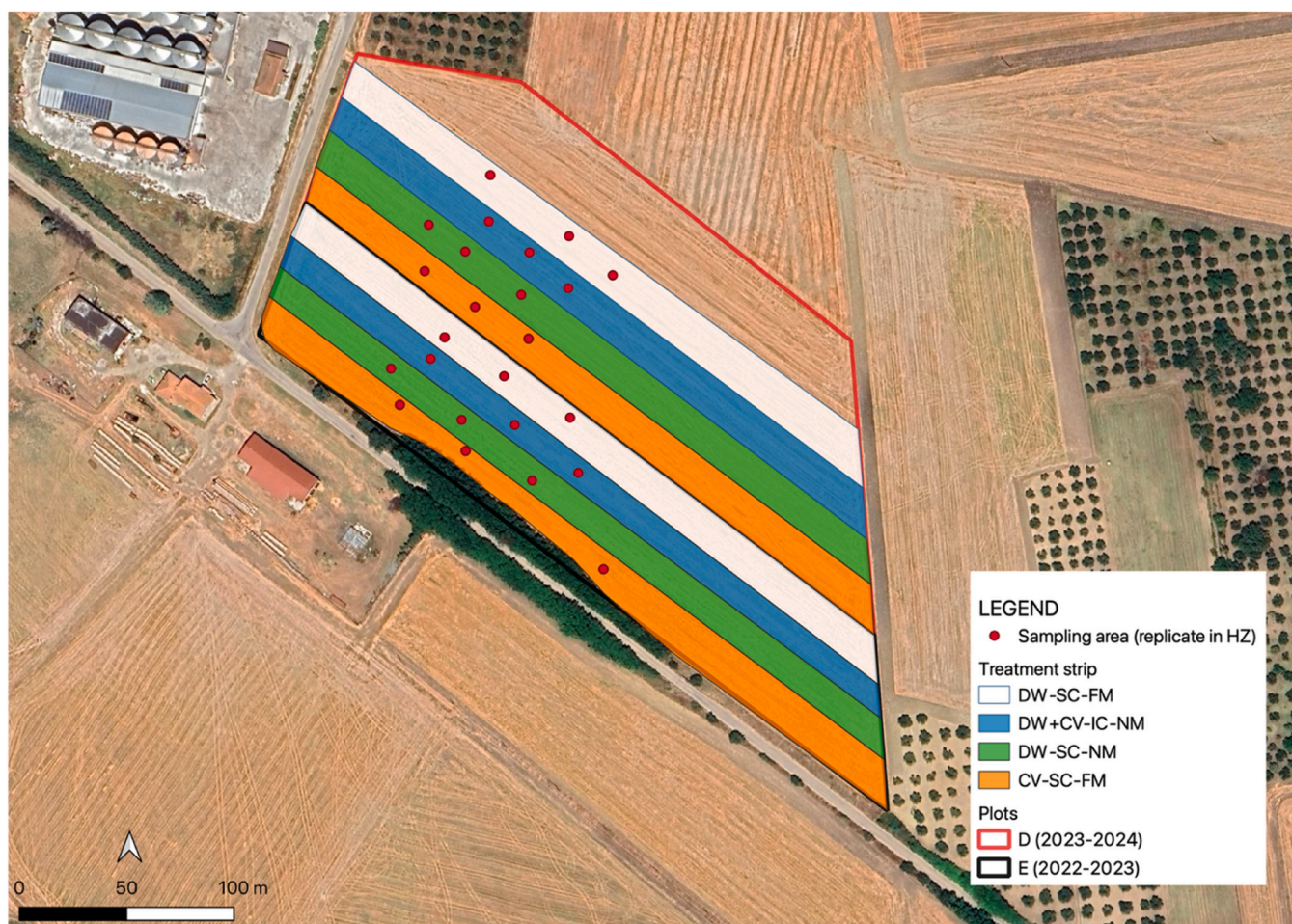


Fig. 3. Detailed experimental layout showing the distribution of treatment strips within Plots D and E, and the location of sampling points within homogeneous zones (HZs), specifically in Cluster 3 of Plot E and Cluster 2 of Plot D, as defined by soil spatial variability. The experimental design followed the OFE approach, aligning with the 24 m operational width of the contractor's equipment (seed drill, sprayer boom, and fertilizer spreader), to ensure full compatibility with standard farm operations and agronomic representativeness under field conditions.

GPV and C were calculated using the following equations:

$$GPV = Y \times P \quad (2)$$

where: Y = Crop yield ($t \text{ ha}^{-1}$), P = Market price (€ per ton).

To assess the overall efficiency of intercropping, the cumulative GPV was obtained by summing the values of the two crops:

$$GPV_{w+v} = GPV_w + GPV_v \quad (3)$$

Where: GPV_w : is the gross production value of durum wheat ($€ \text{ ha}^{-1}$), GPV_v : is the gross production value of vetch ($€ \text{ ha}^{-1}$).

The (C_{w+v}) was obtained by summing the individual costs of durum wheat (C_w) and vetch (C_v):

$$C_{w+v} = C_w + C_v \quad (4)$$

The CM of the intercropping system was calculated as the difference between the cumulative gross production value and the cumulative costs:

$$CM_{w+v} = GPV_{w+v} - C_{w+v} \quad (5)$$

The gross production value (GPV) was calculated excluding payments from the Common Agricultural Policy (CAP), ensuring an objective assessment of the system's economic potential without the influence of subsidies or incentives (Leoni et al., 2024). Yield data for both durum wheat and common vetch were obtained from field measurements described in this manuscript. For the economic analysis, it was assumed

that durum wheat would be marketed for pasta production, whereas common vetch for the forage or seed market. Official quotations from the Rome Commodity Exchange (2023, 2024) for cereals and legumes were used to determine market prices. The average prices adopted were as follows: in the 2022–2023 season, durum wheat was valued at $€380 \text{ t}^{-1}$ and common vetch at $€850 \text{ t}^{-1}$; in 2023–2024, the price of durum wheat declined to $€340 \text{ t}^{-1}$, while common vetch was valued at $€750 \text{ t}^{-1}$.

Production costs (C) included all variable expenses related to seed, soil preparation, sowing, harvesting, and pesticide applications, as well as additional operations such as mechanical weed control, seed separation, and post-harvest handling. In the intercropping system (C_{w+v}), costs were slightly higher than those of the sole crops, primarily due to the need for mechanical separation of wheat and vetch seeds after harvest. This separation required two cleaning steps using specialized equipment. Cost estimates were based on average rates charged by local agricultural contractors (see [Supplementary Material](#)). The comparison of contribution margin (CM) between the intercropping system and the respective sole cropping systems provides critical insights into the profitability and economic sustainability of combining durum wheat and common vetch in Mediterranean farming systems.

2.4.3. Statistical analysis

Statistical analyses were conducted using R software (R Core Team, 2024). The experiment was carried out over two consecutive cropping seasons (2022–2023 and 2023–2024), during which treatments were rotated between two distinct plots (Plot E and Plot D, respectively). A

linear mixed model was used to analyze grain yield and protein content, with the cropping system as a fixed factor and replication within homogeneous zones as a random factor. These variables were analyzed using the combined dataset from both years to evaluate the average agronomic performance of the cropping systems over the biennium. In contrast, for N balance variables, a one-way ANOVA was performed separately for each year. This choice was motivated by the spatial rotation of treatments across plots with different pedological characteristics and by the marked climatic differences between the two seasons, which could have affected N dynamics and compromised the interpretation of results in an aggregated analysis (Bates et al., 2015).

Before conducting ANOVA, model assumptions were checked: residual normality was assessed using QQ plots and the Shapiro–Wilk test, while homogeneity of variances was tested using Levene’s test. When assumptions were met, Tukey’s HSD test ($p \leq 0.05$) was used for post hoc pairwise comparisons, using the agricolae package in R (Christensen, 2020).

3. Results

3.1. Meteorological analysis

Fig. 4 shows the daily rainfall and average temperature trends for the 2022–2023 and 2023–2024 growing seasons, respectively, highlighting notable climatic differences that influenced the performance of the durum wheat–vetch intercrop.

In 2022–2023, total precipitation was 673.6 mm, with an average temperature of 13.58 °C, providing relatively favourable conditions for crop development. In contrast, the 2023–2024 season experienced a

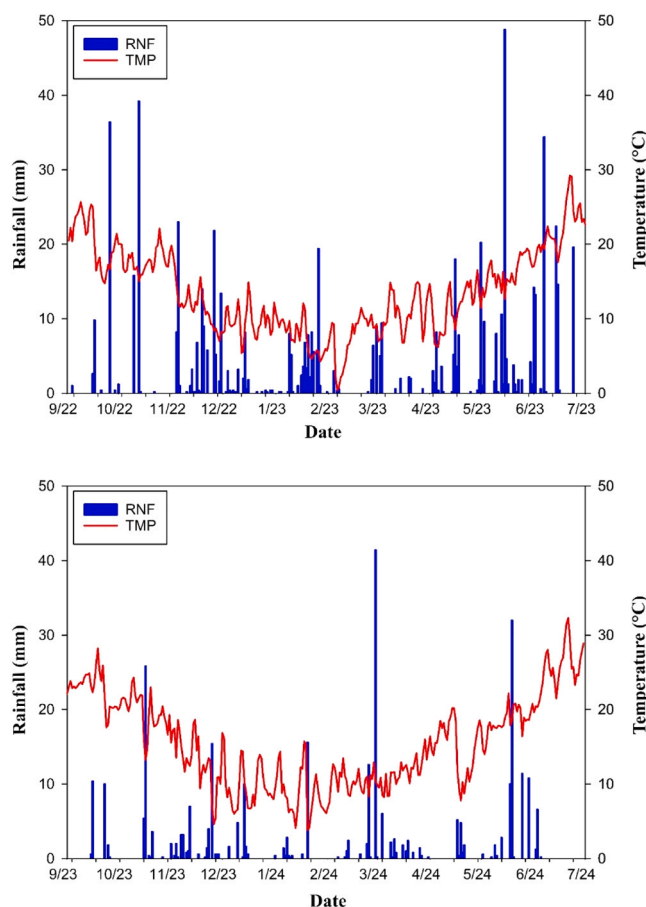


Fig. 4. Climographs for the 2022–2023 and 2023–2024 growing seasons. The blue bars indicate daily rainfall (mm), while the red line represents the daily average temperature (°C) for each season.

sharp reduction in rainfall to 314.6 mm and an increase in average temperature to 15.47 °C. These variations significantly affected water availability and increased thermal stress during key growth stages, ultimately impacting intercrop productivity.

3.2. Agronomic results

3.2.1. Crop yield

Fig. 5 illustrates the variability in grain yields among treatments and across the two cropping seasons. In the DW-SC-FM treatment, which received full agronomic inputs, durum wheat maintained high and relatively stable yields, recording 3.03 t ha⁻¹ in 2022–2023 and 2.79 t ha⁻¹ in 2023–2024. The year-to-year difference was not statistically significant. In contrast, the DW-SC-NM and DW-IC treatments—both conducted without fertilization or chemical protection—produced similar yields in the first year (2.57 and 2.60 t ha⁻¹, respectively), but experienced a significant decline in 2023–2024, with yields dropping to 1.96 t ha⁻¹ (DW-SC-NM) and 1.97 t ha⁻¹ (DW-IC) ($p < 0.05$). For common vetch, the CV-SC-FM treatment showed a modest increase in grain yield, from 0.93 t ha⁻¹ in 2022–2023 to 1.07 t ha⁻¹ in 2023–2024, although the difference was not statistically significant. A comparable trend was observed in the CV-IC treatment, with yields of 0.71 t ha⁻¹ and 0.70 t ha⁻¹, respectively. The intercropping system DW+CV-IC-NM, calculated as the sum of DW-IC and CV-IC grain yields, achieved a combined yield of 3.31 t ha⁻¹ in 2022–2023 and 2.67 t ha⁻¹ in 2023–2024. While the decline between years was statistically significant, the intercropping system maintained yields comparable to the input-intensive DW-SC-FM treatment, despite the absence of external inputs, demonstrating its potential as a low-input alternative in Mediterranean conditions.

3.2.2. Protein content

Fig. 6 shows the variation in grain protein content across cropping systems and between the two growing seasons. The data highlight significant differences both among treatments and across years. The highest grain protein content was recorded in the DW-IC-NM treatment during the 2022–2023 season, with a mean value of 13.9 %. This was followed by a significant decline to 12.4 % in 2023–2024. Despite this reduction, the DW-IC-NM system maintained a comparatively high quality relative to the other treatments. In the DW-SC-FM treatment, which was managed with full fertilization and chemical protection, protein content remained stable across both seasons at 12.3 %, indicating strong temporal consistency under high-input conditions. In contrast, the DW-SC-NM treatment exhibited the lowest protein levels among all systems. Starting at 12.0 % in the first year, protein content dropped significantly to 10.1 % in the second year, reflecting a notable decline under no-input management. Overall, the results underscore the combined influence of cropping system and growing season on wheat grain quality, with statistically significant reductions observed only in treatments lacking external inputs.

3.2.3. Land equivalent ratio analysis

Fig. 7 shows the partial Land Equivalent Ratios (pLER) for durum wheat (X-axis) and common vetch (Y-axis) in the intercropping system across the 2022–2023 and 2023–2024 growing seasons. The LER was used to quantify the productive efficiency of the durum wheat–common vetch intercrop relative to the corresponding sole cropping systems. Total LER was calculated as the sum of the partial contributions from each species (pLER_w for wheat and pLER_v for vetch) based on yields from sole crops managed at optimal seeding rates (DW-SC-FM for wheat and CV-SC-FM for vetch), while intercrop yields were obtained from the DW+CV-IC-NM treatment. In both seasons, total LER values exceeded unity, confirming a land-use advantage for the intercropping system: 1.62 in 2022–2023 and 1.35 in 2023–2024. Partial LERs indicate a consistently greater contribution from wheat. In 2022–2023, pLER_w was 0.86 and pLER_v was 0.76; in 2023–2024, values declined to 0.70

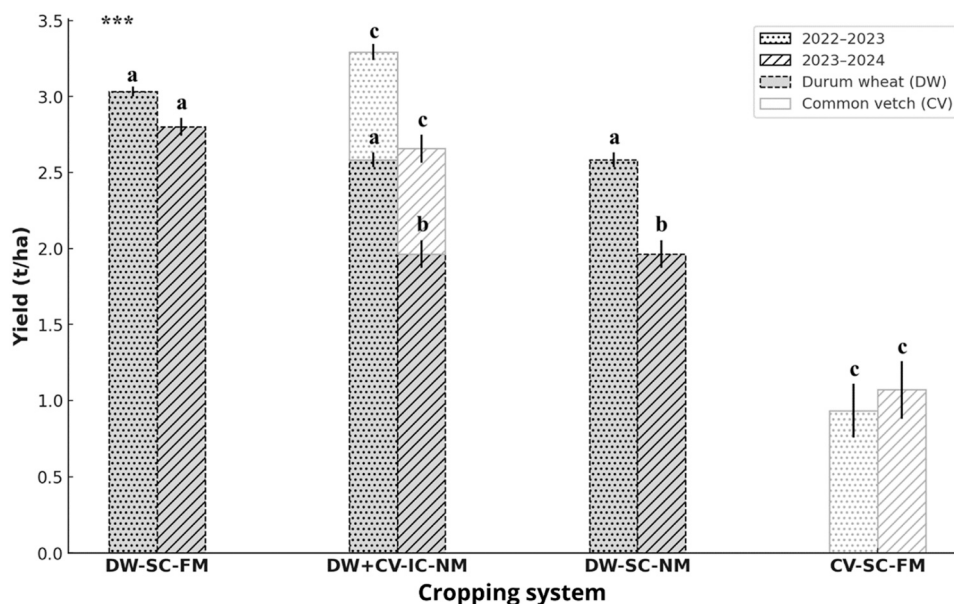


Fig. 5. Mean crop yield (t ha^{-1}) for each experimental treatment across the two growing seasons (2022–2023 and 2023–2024). Error bars represent standard deviation. Different letters above the bars indicate statistically significant differences among treatments, as determined by ANOVA ($p < 0.05$). Significance codes: 0 (***) ; 0.001 (**); 0.01 (*); 0.05 (.); 0.1 (.) ; ns = not significant). The analysis of variance revealed a highly significant treatment effect on yield ($F = 67.091$, $p < 0.001$), highlighting strong differences in productivity between cropping systems.

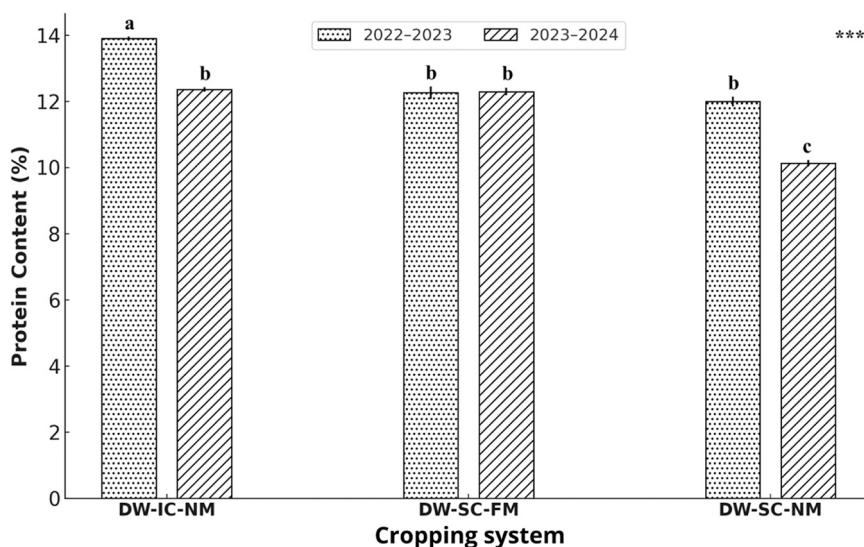


Fig. 6. Mean protein content (%) of durum wheat across different treatments in the 2022–2023 and 2023–2024 growing seasons. Error bars represent standard deviation. Different letters above the bars indicate statistically significant differences ($p < 0.05$) based on ANOVA results. Significance codes: 0 (***) ; 0.001 (**); 0.01 (*); 0.05 (.); 0.1 (.) ; ns = not significant). The analysis of variance confirmed a highly significant effect of treatment on protein content ($F = 561.27$, $p < 0.001$), highlighting strong differentiation in grain quality among cropping systems.

and 0.65, respectively. The distribution of points on the pLERw/pLERv plane further illustrates this trend, with the wheat component contributing more to overall system efficiency. Error bars represent the standard error from replicate plot yields, while dashed lines indicate theoretical thresholds: $\text{LER} = 1$ (intercropping advantage) and $\text{pLERw} = \text{pLERv}$ (equal contribution). These findings demonstrate that durum wheat–common vetch intercropping offers a stable, low-input strategy for enhancing land-use efficiency and resource productivity in Mediterranean cereal systems.

3.2.4. Economic performance and profitability of cropping systems

Table 1 presents the Contribution Margin (CM), Gross Production Value (GPV), and production costs (C) for each cropping system across

the 2022–2023 and 2023–2024 growing seasons. The data highlight the superior economic performance of the durum wheat–common vetch intercropping system (DW+CV-IC-NM) compared to the sole cropping systems, particularly under low-input conditions. In 2022–2023, DW+CV-IC-NM recorded the highest CM at $\text{€}407.5 \text{ ha}^{-1}$, with total costs ($C_{(w+v)}$) of $\text{€}1184 \text{ ha}^{-1}$, which included both standard agronomic operations and additional expenses related to mechanical seed separation. In comparison, the sole crop CV-SC-FM achieved a CM of $\text{€}114.5 \text{ ha}^{-1}$ ($C = \text{€}676 \text{ ha}^{-1}$), while DW-SC-FM had the lowest CM at $\text{€}47.4 \text{ ha}^{-1}$ ($C = \text{€}1104 \text{ ha}^{-1}$). In 2023–2024, CM values declined across all systems due to less favourable conditions. DW+CV-IC-NM remained the most profitable, yielding $\text{€}153.8 \text{ ha}^{-1}$ ($C_{(w+v)} = \text{€}1041 \text{ ha}^{-1}$), followed by CV-SC-FM at $\text{€}126.5 \text{ ha}^{-1}$ and DW-SC-FM at $\text{€}47.6 \text{ ha}^{-1}$.

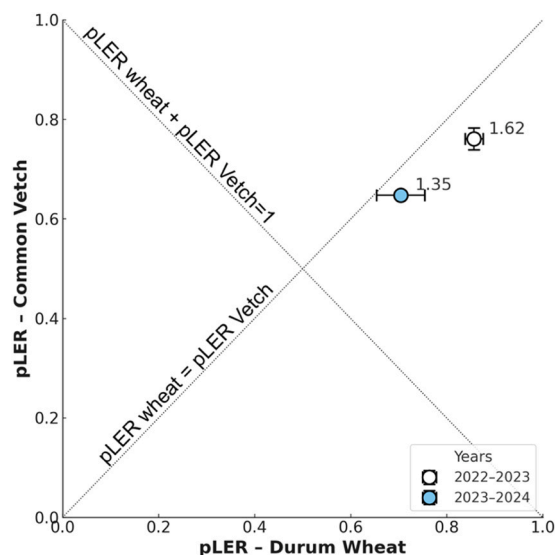


Fig. 7. Partial Land Equivalent Ratios (pLER) for durum wheat (X-axis) and common vetch (Y-axis) in the intercropping system during the 2022–2023 (white circles) and 2023–2024 (light blue circles) growing seasons. Numerical labels next to each point indicate total LER values. Dashed lines represent the efficiency threshold (LER = 1) and the line of equal contribution between species (pLER_w = pLER_v).

Table 1

GPV, production costs (C), and contribution margin (CM) for sole cropping treatments (DW-SC-FM, CV-SC-FM) and the intercropping system (DW+CV-IC-NM) during the 2022–2023 and 2023–2024 growing seasons. Production costs include sowing, soil preparation, harvesting, plant protection, and, for intercropping, additional expenses related to post-harvest mechanical separation of seeds. (°) Values for DW-IC and CV-IC are reported for descriptive purposes only and are already included in the cumulative GPV and CM of the intercropping system.

Season	Treatment	Yield (t ha ⁻¹)	Unit Price (€ t ⁻¹)	GPV (€ ha ⁻¹)	C (€ ha ⁻¹)	CM (€ ha ⁻¹)
22 –23	DW-SC-FM	30.3	380	1151.4	1104.0	47.4
	CV-SC-FM	9.3	850	790.5	676.0	114.5
	DW+CV-IC-NM	33.1		1591.5	1184.0	407.5
23 –24	DW-IC	26.0	380	988.0		
	CV-IC	7.1	850	603.5		
	DW-SC-FM	27.9	340	948.6	901.0	47.6
	CV-SC-FM	10.7	750	802.5	676.0	126.5
	DW+CV-IC-NM	26.7		1194.8	1041.0	153.8
	DW-IC [°]	19.7	340	669.8		
	CV-IC [°]	7.0	750	525.0		

Table 2

N uptake (kg ha⁻¹) in grain and straw for each cropping treatment during 2022–2023 and 2023–2024. The table reports nitrogen concentration, yield, and total N uptake. ΔN Uptake indicates variation compared to the DW-SC-NM reference. Different letters denote significant differences (p < 0.05, ANOVA). Significance: *** p < 0.001; ** p < 0.01; * p < 0.05; ns = not significant.

Season	Treatment	Grain			Straw			Total	Δ N
		N (g kg ⁻¹)	Yield (t ha ⁻¹)	Uptake (kg ha ⁻¹)	N (g kg ⁻¹)	Yield (t ha ⁻¹)	Uptake (kg ha ⁻¹)	Uptake (kg ha ⁻¹)	Uptake (kg ha ⁻¹)
22 –23	DW-SC-NM	20.6c	2.8 a	57.8 b	4.3 b	4.2	18.3c	76.1c	-
	DW-IC	24.5 b	2.6 a	63.7 a	6.0 b	4.6	27.6 b	91.3 b	+ 15.2
	CV-IC	40.3 a	0.7 b	28.2c	29.1 a	3.3	97.0 a	125.2 a	-
	Significance	**	***	*	**	ns	***	***	
23 –24	DW-SC-NM	17.3c	1.95 a	33.9 b	7.5 b	2.8	20.92c	54.7c	-
	DW-IC	21.1 b	1.97 a	41.6 a	8.6 b	2.9	25.03 b	66.59 b	+ 11.89
	CV-IC	30.0 a	0.7 b	21.0c	21.7 a	3.0	65.10 a	86.1 a	-
	Significance	*	**	*	**	ns	**	**	

Averaged over the two seasons, DW+CV-IC-NM consistently outperformed the sole cropping systems, recording a mean CM of €280.6 ha⁻¹, compared to €120.5 ha⁻¹ for CV-SC-FM and €47.5 ha⁻¹ for DW-SC-FM. A detailed breakdown of production costs and revenue components is provided in the supplementary materials.

3.2.5. Nitrogen uptake dynamics

Table 2 summarizes nitrogen (N) uptake across both cropping seasons, comparing sole-cropped durum wheat (DW-SC-NM) with the intercropping components—durum wheat (DW-IC) and common vetch (CV-IC)—all managed under zero-input conditions and sown at identical seeding rates. In 2022–2023, DW-SC-NM recorded a total N uptake of 76.1 kg N ha⁻¹, with 57.8 kg N ha⁻¹ in the grain and 18.3 kg N ha⁻¹ in the straw. In contrast, DW-IC absorbed 91.3 kg N ha⁻¹, including 63.7 kg N ha⁻¹ in the grain and 27.6 kg N ha⁻¹ in the straw—an increase of 15.2 kg N ha⁻¹ compared to the sole crop. The CV-IC treatment exhibited the highest total uptake at 125.2 kg N ha⁻¹, with 28.2 kg N ha⁻¹ in the grain and 97.0 kg N ha⁻¹ in the straw. In the 2023–2024 season, N uptake declined across all treatments due to climatic variability. DW-SC-NM absorbed 54.7 kg N ha⁻¹ (33.9 kg N ha⁻¹ in grain, 20.9 in straw), while DW-IC reached 66.6 kg N ha⁻¹ (41.6 kg N ha⁻¹ in grain, 25.0 kg N ha⁻¹ in straw), increasing to 11.9 kg N ha⁻¹ relative to the sole crop. CV-IC again recorded the highest uptake at 86.1 kg N ha⁻¹, including 21.0 kg N ha⁻¹ in the grain and 65.1 kg N ha⁻¹ in the straw. It should be noted that, due to the absence of a sole-cropped vetch treatment under identical conditions, N uptake by the CV-IC component is interpreted primarily in terms of its contribution to ecosystem services within the intercropping system, rather than direct comparison with monoculture performance.

4. Discussion

4.1. Effect of intercropping on durum wheat yield and quality

The two-year field trial confirmed that intercropping durum wheat with common vetch can enhance grain protein concentration under zero-input conditions. In DW-IC, protein content remained high across both years, suggesting improved N availability through legume association. However, grain yield comparisons revealed no significant advantage for intercropping relative to sole cropping at equivalent sowing densities. In both DW-IC and DW-SC-NM, grain yields declined significantly from 2022–2023 (2.60 and 2.57 t ha⁻¹, respectively) to 2023–2024 (1.97 and 1.95 t ha⁻¹), highlighting the vulnerability of low-input systems to climatic fluctuations. This trend is consistent with previous findings indicating greater environmental sensitivity at reduced plant densities, due to weaker canopy closure and increased weed pressure (Arduini et al., 2006; De Stefanis et al., 2017; Tosti and Guiducci, 2010). These outcomes reinforce the role of intercropping in agroecological Mediterranean systems, particularly for improving grain quality via biological N inputs, although resilience to abiotic stress

remains a key limitation.

Despite these fluctuations, intercropping maintained a LER greater than 1 in both seasons (1.62 in 2022–2023 and 1.35 in 2023–2024), indicating superior land-use efficiency compared to monocultures. This is in line with existing literature showing that cereal–legume intercropping can enhance resource-use efficiency, land productivity, and economic returns, especially when supported by appropriate management, species complementarity, and spatial arrangement (Rodriguez et al., 2020; Liu et al., 2023; Yadav et al., 2023; Raza et al., 2023). Our findings further align with a broad literature base highlighting the economic advantages of intercropping. For example, Sun et al. (2020) reported a 21.8 % increase in net income in maize–potato intercropping systems compared to monocultures, attributed to improved land-use efficiency and reduced input costs. Comparable LER values have also been documented in other cereal–legume systems, such as pea–barley and maize–cowpea, where total LERs typically range from 1.2 to 1.6, confirming the consistency of intercropping benefits across diverse agroecological contexts (Bedoussac et al., 2015; Bitew et al., 2022; Lithourgidis et al., 2011; Raza et al., 2023).

From a qualitative perspective, the DW+CV-IC-NM system exhibited significantly higher grain protein content compared to the DW-SC-NM monoculture (13.9 % vs. 12.0 % in 2022–2023), confirming the role of common vetch in enhancing N availability and supporting wheat N nutrition (Guiducci et al., 2018; Parvin et al., 2023). This improvement is consistent with findings from Hauggaard-Nielsen et al. (2003) and Jensen et al. (2010), who reported that intercropping with legumes facilitates nitrogen transfer and increases N-use efficiency in cereal partners. The qualitative advantage was maintained in the 2023–2024 season (12.37 % vs. 10.13 %), further indicating the greater susceptibility of unfertilized monocultures to nitrogen deficiency under fluctuating climatic conditions (Mosleth et al., 2020; Shewry et al., 2013; Gooding et al., 2003).

The DW-SC-FM monoculture, representative of conventional on-farm management with full inputs and standard sowing rates, showed greater yield stability across seasons (3.03–2.80 t ha⁻¹), but no corresponding improvement in protein content, which remained stable at 12.3 %. This pattern aligns with findings from Martre et al. (2006) and Triboi et al. (2000), who demonstrated that increased nitrogen inputs do not necessarily translate into enhanced grain protein under stable management regimes. In contrast, the DW+CV-IC-NM system (managed with reduced sowing density and without external inputs) achieved superior grain quality while maintaining total yields (DW-IC + CV-IC) comparable to the fully fertilized monoculture. These outcomes are consistent with Raza et al. (2023), Bedoussac et al. (2015), and Justes et al. (2021), who emphasized that interspecific facilitation in cereal–legume intercrops can enhance nitrogen-use efficiency, stabilize yields, and reduce input dependency. Similarly, Hauggaard-Nielsen et al. (2003) and Jensen et al. (2010) observed that legume intercropping can support cereal nutrient demands via biological nitrogen fixation and below-ground interactions, while improving the protein profile of the harvested grains. Peoples et al. (2009) also emphasized the agronomic advantage of legumes in low-input systems, citing their role in increasing system-level N availability and improving nitrogen recovery in cereals. Moreover, Liu et al. (2023) and Yadav et al. (2023) highlighted the broader ecological and economic sustainability of intercropping when spatial configuration and management practices are optimized.

4.2. N dynamics in intercropping systems

The nitrogen dynamics observed in this study indicate a consistent advantage of the durum wheat–vetch intercropping system over the unfertilized sole crop in terms of total N accumulation in aboveground biomass. The increase in total N uptake recorded under the DW-IC treatment compared to DW-SC-NM (+15.2 kg N ha⁻¹ in 2022–2023 and +11.9 kg N ha⁻¹ in 2023–2024) suggests an effective functional

complementarity between the two species. This interaction aligns with previous findings that, in cereal–legume intercrops, cereals predominantly capture soil mineral N, thereby stimulating enhanced BNF in the legume through competitive soil N depletion (Hauggaard-Nielsen et al., 2009; Raza et al., 2023; Zhang et al., 2021).

The CV-IC treatment exhibited the highest total N uptake across both seasons, largely concentrated in the straw fraction. Although BNF was not directly quantified in this study, the elevated N content in vetch biomass supports prior findings that legumes intercropped with cereals typically experience higher BNF rates due to reduced soil N access (Antichi et al., 2022; Bedoussac and Justes, 2010b; Li et al., 2024; Rodriguez et al., 2020).

Considering the straw residues of both species, the intercrop system potentially returned 124.6 kg N ha⁻¹ in 2022–2023 and 90.1 kg N ha⁻¹ in 2023–2024 as unharvested aboveground biomass. This underlines the system's role in internal nutrient recycling, particularly in low-input agroecological contexts where residues are retained. The rapid decomposition of legume residues, due to their favorable C/N ratio, facilitates the release of 60–80 % of N content within the following season (Monti et al., 2019; Tosti and Guiducci, 2010; Blesh and Drinkwater, 2013). This contributes significantly to organic matter inputs and soil fertility improvement in systems without synthetic fertilization (Amossé et al., 2014; Duchene et al., 2017; Hoang et al., 2024; Cong et al., 2015).

The reduced N uptake observed in 2023–2024 under drier conditions is consistent with the established sensitivity of legume BNF to moisture stress. This is supported by recent studies highlighting how water limitations suppress symbiotic N fixation and reduce nutrient transfer to companion cereals (Parvin et al., 2023; Rose et al., 2024; Fustec et al., 2010). Such inter-annual variability underscores the importance of evaluating intercropping systems not only for productivity but also for their resilience under increasing climatic uncertainty, particularly in Mediterranean environments.

4.3. Economic potential and limits of durum wheat–vetch intercropping

Cereal–legume intercropping is widely recognized for its potential to enhance agroecosystem performance, particularly by improving economic returns, nitrogen use efficiency, and system resilience under low-input conditions (Bedoussac et al., 2015; Lithourgidis et al., 2011; Liu et al., 2023). Our economic analysis confirms these benefits in the durum wheat–common vetch system, which consistently outperformed the sole crops in Gross Production Value (GPV) and Contribution Margin (CM) over both seasons, despite the absence of external inputs (Parvin et al., 2023; Hauggaard-Nielsen and Jensen, 2001; Raza et al., 2023). This economic advantage is attributed not only to reduced fertilizer and pesticide costs but also to the dual-output configuration of the system. Durum wheat and vetch are sown and harvested simultaneously, allowing for the joint valorization of wheat grain and vetch seed or forage, unlike temporary intercropping systems where the legume is often terminated before harvest (Stone et al., 2024; Justes et al., 2021). As emphasized by Stone et al. (2024), dual-purpose intercropping offers significant potential to increase plant-based protein production, contribute to the EU Farm to Fork Strategy, and support agroecological transitions.

These findings align with a broad literature base confirming the economic benefits of cereal–legume intercropping. Vlachostergios et al. (2018) reported improved forage quality and profitability in red pea–cereal systems, while Sun et al. (2020) documented a 34 % increase in net ecosystem economic budget from maize–potato intercropping. Bitew et al. (2019) and Lithourgidis et al. (2011) also observed enhanced gross returns and benefit–cost ratios in semi-arid, rainfed conditions. Recent studies reinforce these trends across diverse agroecological contexts: Sun et al. (2024) reported a 21.8 % higher net income from maize–potato systems; Pinto et al. (2022) highlighted profitability improvements in intermediate wheatgrass–legume mixtures; Yang et al.

(2018) demonstrated land and economic efficiency gains in maize–pea intercropping in arid China; and Sogoba et al. (2020) found that millet–cowpea systems in West Africa generated up to 48 % greater grain-related income with short-duration varieties.

European research adds further support, emphasizing the resilience of intercropping under variable economic conditions. Tzemi et al. (2025) observed that oat–pea systems increased net present value by 37 %, mainly due to nitrogen savings and rotational synergies. Manevska-Tasevska et al. (2024) noted that intercropping helped stabilize gross margins amid price volatility, particularly in mixed and strip cropping arrangements. However, the literature also highlights important constraints—such as fluctuating market prices, increased labor requirements, limited access to adapted harvesting technology, and institutional barriers to crop diversification—that can offset economic gains if not addressed.

However, the literature also highlights important constraints—such as fluctuating market prices, increased labor requirements, and limited access to adapted harvesting technology—that can offset economic gains if not addressed (Ronga et al., 2024; Kernecker et al., 2024). Taken together, these studies support the conclusion that cereal–legume intercropping is not only economically viable under Mediterranean low-input conditions, as demonstrated in our work, but also highly adaptable across varied environments, provided that crop choice, input management, and post-harvest logistics are well tailored to local constraints and market dynamics.

In terms of resource efficiency, the durum wheat–vetch intercrop exhibited superior land-use performance. Total LER values exceeded unity in both seasons, and the system fell within Sector J of the pLER framework, indicating a dominant cereal contribution with complementary legume support (Justes et al., 2021). This functional complementarity supports the 4C model for cereal–legume interactions and aligns with Mediterranean evidence demonstrating land productivity benefits even under climate variability (Tosti et al., 2023; Bedoussac and Justes, 2010; Li et al., 2024). However, the wider adoption of these systems still faces operational and structural challenges. The most critical limitation remains the post-harvest separation of mixed grains, which requires specialized equipment and increases processing costs (Leoni et al., 2024; Stone et al., 2024; Lithourgidis et al., 2011). Other barriers include the limited integration of intercrop products into commercial value chains and the absence of market incentives tailored to mixed-output systems (Stone et al., 2024; Salembier et al., 2023). Unlocking the full potential of intercropping will require targeted interventions at multiple levels, including breeding programs for intercrop-compatible cultivars (Kjær et al., 2022), investments in mechanization (Leoni et al., 2024), and the development of enabling policy frameworks that recognize ecosystem services and facilitate value chain development (Hauggaard-Nielsen et al., 2021; Salembier et al., 2023; Stone et al., 2024).

5. Conclusions

This study demonstrates that simultaneous intercropping of durum wheat and common vetch offers a practical and effective approach to enhancing the sustainability of Mediterranean cereal systems. Conducted under real-world, zero-input conditions, the intercropping system consistently outperformed unfertilized monocultures in key areas, including nitrogen uptake, grain protein content, and land-use efficiency. These results underscore the functional advantages of cereal–legume associations in improving agroecological performance without reliance on external inputs. However, despite these advantages, large-scale adoption of cereal–legume intercropping with cash legumes is still limited by post-harvest constraints, particularly the need for mechanical separation of mixed grains, which adds to costs and complexity. Addressing these barriers will require targeted innovations in farm machinery, improved supply chain logistics, and breeding of crop varieties specifically adapted for intercrop systems. Given these findings,

future research should further explore the integration of economically viable legumes rather than relying solely on cover crops to better balance environmental sustainability with farm-level profitability. The benefits of intercropping extend beyond increased contribution margin; they also include long-term agroecological gains such as improved soil structure, enhanced biodiversity, and reduced dependency on synthetic fertilizers. Vetch residues, in particular, act as a nitrogen reservoir that supports the nutrient demands of subsequent crops, contributing to internal nutrient cycling and soil regeneration.

Integrating intercropped cereal–legume systems into conventional crop rotations represents a scalable solution for diversifying Mediterranean agriculture. When supported by tailored agronomic practices, market incentives, and farmer training, this approach can contribute meaningfully to EU sustainability targets, such as reduced agrochemical input and improved nutrient use efficiency. In this context, intercropping stands out as a resilient and multifunctional strategy for transitioning toward more regenerative, productive, and climate-smart farming systems.

CRedit authorship contribution statement

Michele Perniola: Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Enrica De Falco:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Domenico Ronga:** Writing – review & editing, Visualization, Methodology. **Pierluigi Mazzei:** Writing – review & editing, Visualization, Methodology. **Loriana Cardone:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Domenico Mario Melone:** Writing – original draft, Resources, Investigation, Formal analysis, Conceptualization. **Pierluigi Casiero:** Writing – review & editing, Resources, Investigation, Formal analysis, Conceptualization. **Donato Casiello:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Andi Mehmeti:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Michele Denora:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT (OpenAI) solely to assist with language refinement, summarization, and formatting of non-scientific content. No generative AI tools were used to generate or interpret scientific data or to draw conclusions. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ijagro.2025.100045](https://doi.org/10.1016/j.ijagro.2025.100045).

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