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Research Article

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Multi-Year Evaluation of Cover Crop Intercropping in Sunflower (Helianthus annuus): Ecosystem Services, Climate Adaptation, and Yield Stability

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ABSTRACT
Climate change, soil degradation, and increasing biotic stress factors necessitate the development of new, sustainable cultivation technologies. This research evaluates the integration of cover crop intercropping in sunflower *(Helianthus annuus)* production based on field trials conducted between 2021 and 2025 across multiple European locations. The results highlight that while intercropped sunflowers can achieve yield surpluses in years with optimal precipitation (e.g., France, 2023), extreme drought and heat during the 2024 and 2025 seasons resulted in intense water competition, causing the main crop's yield to fall behind the traditional technology control. However, the intercropping system provides numerous ecosystem services: it improves soil quality, reduces weed pressure, eliminates pre-emergent herbicide phytotoxicity, and significantly increases pollinator activity. In alignment with recent international findings, the trials confirm that the appropriate species composition *(e.g., Phacelia and Trifolium species)* is critical for the phenotypic development of the sunflower and the overall success of the cultivation system.

Keywords: Crop, Sunflower, Climate Adaptation, Yield Stability, Ecosystem Services

Introduction

Climate Change, Biotic Stress, and the Expansion of Sunflower
According to climate model predictions, the mean annual temperature will rise by 1-2.5 °C in the 2021-2050 period, while warming could reach 2-5 °C by 2071-2100. Concurrently, summer precipitation is expected to decrease by 10-30%. These climate change trends are reshaping arable crop compositions. Because sunflower genetically tolerates drier and warmer conditions better, it is projected to become the second most widely cultivated arable crop in Hungary by 2025, potentially reaching an area of 740,000 hectares.

Introduction

The transition toward sustainable agricultural models necessitates the development of cropping systems that minimize synthetic fertilizer and pesticide use. While the agronomic benefits of cover crops—such as nitrogen fixation, soil structure improvement, weed suppression, and microclimate regulation—are well-documented, their simultaneous application with main crops remains a complex challenge.

A comprehensive literature review revealed that over 150 studies have investigated intercropping systems in maize, soybean, and cereal crops. The vast majority of these studies were conducted by researchers at universities in the United States. Consequently, the application of intercropping methodologies within European agricultural contexts is notably lacking. Because sunflower (Helianthus annuus) is predominantly cultivated on the European continent, simultaneous cover crop intercropping for this specific species has remained largely unexamined.

Data collection for this research trajectory began in 2020 with the objective of developing a specialized sunflower cultivation model utilizing a "living mulch". For such a system to be viable in commercial farming, it is imperative that the main crop's yield and quality do not deviate significantly in a negative direction compared to traditional cultivation methods. This paper details the 2025 field trials, evaluating the agronomic and ecological trade-offs of this system under severe environmental stress.

The Role of Intercropping and Recent Research

The agricultural sector is a primary driver of global land-use change (LUC), which accounts for nearly 18% of global greenhouse gas emissions. Approximately 15% of the Earth's

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non-ice-covered land surface shows signs of degradation. Intercropping is one of the most promising tools for sustainable intensification. Recent international trials across three locations demonstrated that cover crops sown between sunflower rows (such as buckwheat, clover, flax, oats, peas, and mustard) exert a strong weed-suppressive effect and provide habitats for beneficial pollinators. These studies showed that cover crops do not necessarily reduce sunflower yields or oil content (yielding approx. 2.8 t/ha in both covered and untreated controls), but they are expected to improve soil aggregate stability and root mass.

Furthermore, experiments by Langlade et al. in France highlighted that the phenotypic traits of sunflower varieties strongly depend on the composition of the cover crop mixture [1].

Mixtures with varying compositions affect soil moisture and nitrogen availability differently, fundamentally influencing the main crop's performance. Additionally, diverse systems, such as 12-species cover crop mixtures, can triple rhizosphere carbon sequestration compared to monocultures.

Materials and Methods

Experimental Setup and Application Technology

The research was conducted between 2021 and 2025. The 2022 technological investigations clearly proved that applying seeds via a broadcaster and cultivator is inefficient because the seeds do not reach the appropriate depth. Therefore, in subsequent years (2023-2025), cover crops were sown using a grain seed drill immediately after sowing the main crop. The sunflower was sown in the second half of April using a Wintersteiger Dynamic Disc precision planter, with a 75 cm row spacing and a density of 69,900 seeds/ha. The 2025 trials were set up in 21 m² plots with 36 replicates [2].

Evolution of Species Composition (2021-2025)

Based on previous years and international experiences (e.g., Langlade et al., 2024), species that caused excessive water competition or acted as weeds in the rotation (such as rapeseed, sorghum, peas, and alfalfa) were excluded from the final mixtures. The intercrop blend (MIX5) was formulated based on previous trials, specifically excluding flax and Persian clover, which failed to develop properly as intercrops in 2024 [3].

The MIX5 composition consisted of:

- *Trifolium alexandrinum: 35%*
- *Trifolium incarnatum: 30%*
- *Phacelia tanacetifolia: 30%*
- *Ornithopus sativus: 4%*
- *Vicia sativa: 1%*

The final mixture aimed at providing nitrogen fixation, weed suppression, and pollinator support.

Control plots received seed treatments and pre-emergent or post-emergent herbicides, whereas intercropped plots received no chemical weed control.

Results and Discussion

Plant Protection Effects and Phytotoxicity

The cornerstone of traditional sunflower cultivation remains pre-emergent weed control; however, this method carries significant risks under volatile weather conditions. In 2025, intense rainfall during the 2–4 leaf stage caused soil-borne herbicide residues to splash onto the young foliage, resulting in severe phytotoxicity [4].

This chemical stress significantly hindered initial crop development. In contrast, the intercropped plots remained unaffected by such stress, as evidenced by our drone-based Leaf Area Index (LAI) measurements. The radar chart (representing the average of 72 plots per treatment) clearly illustrates a consistent reduction in leaf area across the control plots compared to the chemically unstressed, biologically managed system (Figure 1).

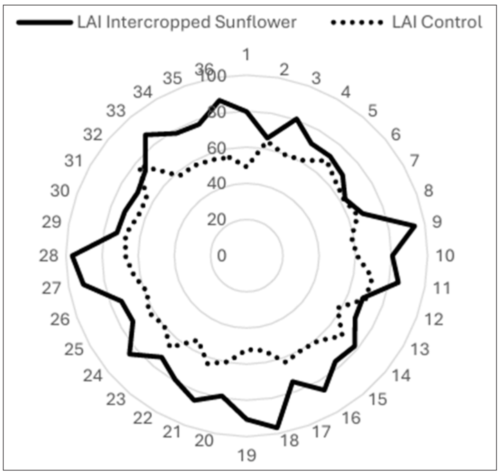

Figure 1: Average Leaf Area Index, Hungary 2025

Yield Results and the Dilemma of Water Competition

The results strongly correlated with the specific year's precipitation and sowing time.

- **Optimal Conditions (2023):** In Southern France (Alzonne), the grain yield was significantly higher in the intercropped plots compared to the control when sown at the optimal time (Figure 2).

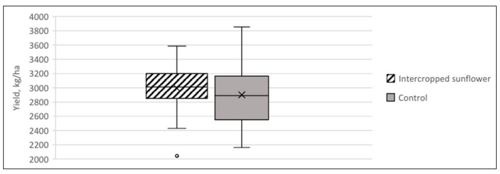

Figure 2: Results, 2023 Yield kg/ha, with 9% moisture content Alzonne (France)

Drought Years (2024-2025): In extremely dry and hot vegetative periods, intense water competition occurred. In 2024 at Szentlőrinc, the control yield (4332 kg/ha) significantly exceeded the intercropped yield (3097 kg/ha). This trend repeated in 2025, where control plots outperformed the intercropped ones by an average of 800-1500 kg/ha (Figure 3).

Quality Parameters and Soil Dynamics

While seed size (TKW) and protein content fell behind the control during the dry years, oil content was surprisingly 0.5-2% higher in the intercropped areas in 2025. This aligns with Langlade's (2024) findings on specific phenotypic effects of cover crops, combined with the lack of early-season phytotoxic stress on oil synthesis.

Soil sampling revealed that under intercropping, Cation Exchange Capacity (CEC) increased by 11%, potentially mineralizable nitrogen by 2.5%, and soil organic carbon by 3%, while these values decreased in the control. Furthermore, the Arany-type soil binding coefficient (KA) and magnesium content measurably increased by harvest time in 2025.

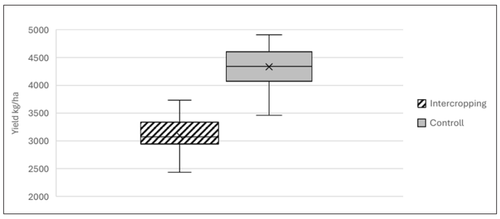

Figure 3: Yield kg/ha, with 9% moisture content Szentlőrinc (Hungary) 2024

Pollinator Activity

During the second day of anthesis, honeybee activity was monitored in Kozármisleny using two automated cameras. The devices recorded images of randomly selected flower heads at 60-second intervals over a 30-minute sampling period. Observational data exclusively confirmed the presence of honeybees (*Apis mellifera*); no bumblebee (*Bombus spp.*) visitations were documented. The significantly higher visitation rates observed in the intercropped plots (Figure 4) are likely attributable to the synchronous flowering of *Phacelia tanacetifolia,* which acted as a primary attractant within the floral mixture.

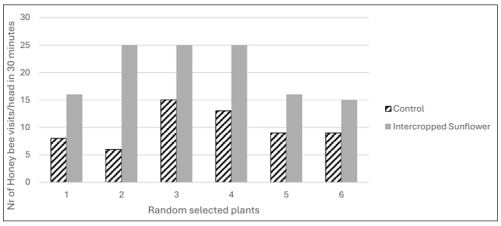

Figure 4: Number of floral visits per 30-minute observation period, recorded at 60-second intervals

Total Biological Output and Resource Allocation

To evaluate the total biological productivity of the two systems, biomass measurements were conducted at the Kozármisleny trial site in 2025. The data reveals a slight reduction in sunflower biomass within the intercropped plots decreasing from approximately 6.6 kg/m2 to 6.1 kg/m2. This marginal decline is a direct result of the interspecific competition for light, water, and nutrients between the sunflower crop and the companion species during the early vegetative stages. However, this is offset by the significant contribution of the cover crop, which produced roughly 1 kg/m2 of additional organic matter. Consequently, the total system biomass was higher in the intercropped plots.

Conclusions

The 2021-2025 trial series highlights that intercropping cover crops in sunflower cultivation offers immense potential for improving soil quality, increasing aggregate stability, and attracting pollinators. As international literature confirms, the technology can function without competition if precipitation conditions are adequate. However, during extremely dry years, the competition for water and nutrients causes an economic disadvantage compared to traditional technology. The primary task for future research—considering increasing biotic (e.g., fungal pathogens) and abiotic (drought) stress factors—is to optimize the termination timing of cover crops in semiarid regions to conserve moisture.

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