Intercropping in conservation agriculture: A path towards more resilient and sustainable agroecosystems

Bojana Brozović, Irena Jug, Boris Đurđević, Vedran Lederer, Danijel Jug

Faculty of Agrobiotechnical Sciences Osijek, University of Josip Juraj Strossmayer in Osijek, Vladimira Preloga 1, Osijek, Croatia (bojana.brozovic@fazos.hr)

Abstract

Intercropping represents an important agroecological practice that can contribute to the sustainability and resilience of agricultural production. The cultivation of two or more plant species on the same production area enables more efficient use of light, water and nutrients due to differences in plant morphology, growth dynamics and resource requirements. Within conservation agriculture, intercropping contributes to increased crop diversity, improved soil cover and more efficient use of natural resources. Greater diversity of plant residues and root systems can improve soil biological activity, nutrient cycling, soil structure and water use efficiency, while increased biomass inputs may contribute to the preservation of soil organic carbon. Intercropping can also improve the resilience of production systems to adverse environmental conditions and contribute to climate change adaptation. However, its effectiveness depends on plant species selection, agroecological conditions and management practices. Further long-term research is needed to evaluate changes in soil health and to develop intercropping systems adapted to different production conditions.

Key words: climate resilience, crop diversification, soil health, sustainable agriculture

Introduction

Agricultural production today faces the challenge of ensuring stable food production while preserving natural resources and adapting to increasingly pronounced climate change. Increasing average air temperatures, changes in the distribution and intensity of precipitation, and the increasing frequency of extreme weather events negatively affect crop productivity, water availability, and soil quality, particularly in systems that rely on intensive tillage and simplified crop rotations (Altieri et al., 2015; IPCC, 2023). At the same time, the long-term use of intensive production systems has contributed to the reduction of organic matter content, soil structure degradation, increased erosion, and biodiversity loss, which threatens the long-term sustainability of agricultural production (Lal, 2015; FAO, 2022).

Increasing attention is being paid to sustainable crop production systems that enable the conservation of natural resources while reducing dependence on external inputs. In this context, conservation agriculture represents one of the most significant sustainable approaches in plant production, and is based on minimal soil disturbance, permanent soil cover and proper crop rotation (FAO, 2017; Jug et al., 2018). The adoption of conservation agriculture principles contributes to the preservation of soil fertility, more efficient use of water and nutrients, and increasing the resistance of agroecosystems to abiotic and biotic stresses (Pittelkow et al., 2015). A greater variety of crops in crop rotations is one of the fundamental principles of conservation agriculture, with intercropping occupying an increasingly important place both in scientific research and in agricultural practice. Intercropping, unlike sole cropping, in which plants use the same resources at approximately the same time and in a similar way, allows for more efficient use of light, water, nutrients and vegetation space (Lithourgidis et al., 2011; Brooker et al., 2015;

Martin-Guay et al., 2018). Intercropping can increase the efficiency of natural resource use and contribute to greater stability and sustainability of crop production in changing agro-ecological conditions (Martin-Guay et al., 2018; Glaze-Corcoran et al., 2020). In addition to its effects on productivity, intercropping also plays an important role in preserving the functionality of agro-ecosystems. Increased crop rotation diversity has a positive effect on the dynamics of organic matter, microbial activity and nutrient cycling, which contributes to the improvement of the chemical, physical and biological properties of the soil (Bünemann et al., 2018; Tamburini et al., 2020). At the same time, intercropping systems create more favorable conditions for the development of beneficial organisms, while increasing the resistance of production systems to abiotic and biotic stresses and contributing to the long-term sustainability of agricultural production (Tamburini et al., 2020; Glaze-Corcoran et al., 2020). Therefore, intercropping is now considered one of the important agroecological strategies for increasing the resilience of production systems in the present climate change conditions (Beillouin et al., 2019; Burgess et al., 2022). The aim of this review paper is to present current knowledge on the role of intercropping in conservation agriculture, with a particular emphasis on its contribution to agroecosystem functionality, soil health, more efficient use of natural resources, and increasing the resilience of agricultural production in the face of climate change.

Intercropping as a component of conservation agriculture

Conservation agriculture is based on principles that aim to support sustainable agricultural production while preserving natural soil processes and ecosystem functions (Pittelkow et al., 2015; FAO, 2017). Its effectiveness is based on the combined benefits of minimal soil disturbance, permanent soil cover, and increased crop diversity. Intercropping involves the simultaneous cultivation of two or more plant species on the same production area during entire or part of the growing season (Lithourgidis et al., 2011). Such production systems are based on the functional complementarity of plant species, whose differences in morphological, physiological and phenological properties allow more efficient use of light, water, nutrients and vegetation space (Brooker et al., 2015; Li et al., 2014). Differences in root system morphology, growth dynamics and resource requirements reduce competition between plants and increase the overall efficiency of the production system (Hauggaard-Nielsen and Jensen, 2005; Brooker et al., 2015).The success of intercropping largely depends on the proper selection of plant species (Brooker et al., 2015). Combinations of legumes and non-legumes are particularly important, in which biological fixation of atmospheric nitrogen contributes to a better supply of this nutrient, while different dynamics of water and nutrient uptake enable their more efficient use during the growing season (Duchene et al., 2017; Hauggaard-Nielsen et al., 2001). Such complementarity often results in higher total biomass production, more efficient use of production area, and more stable yields compared to sole cropping (Willey, 1979; Martin-Guay et al., 2018; Glaze-Corcoran et al., 2020). In addition to increasing productivity, intercropping contributes to the achievement of the fundamental goals of conservation agriculture. Greater diversity of plant species increases the amount and variety of plant residues entering the soil, promotes the development of more diverse microbial communities and more intensive nutrient cycling, and contributes to the preservation of favorable soil structure (Duchene et al., 2017; Tamburini et al., 2020). At the same time, better soil coverage during the growing season reduces the risk of erosion, mitigates temperature fluctuations, and reduces water loss through evaporation (Glaze-Corcoran et al., 2020). When intercropping is combined with other principles of conservation agriculture, its positive effects on soil health and the resilience of the production system are further enhanced (Pittelkow et al., 2015; Beillouin et al., 2019; Tamburini et al., 2020).

Effects of intercropping on soil health and natural resource use

The effects of intercropping cannot be considered only through the achieved yield of individual crops. Its role in enhancing the long-term productivity and resilience of cropping systems is increasingly recognized, particularly through its contribution to soil health, nutrient cycling, biological activity, and water use efficiency (Glaze-Corcoran et al., 2020; Tamburini et al., 2020). Intercropping is therefore considered as an agroecological practice that influences the functioning of the entire agroecosystem. Many of its benefits develop gradually and may become more pronounced with long-term implementation (Beillouin et al., 2019). One of the most important effects of intercropping is the increased quantity and diversity of plant residues and root exudates entering the soil (Duchene et al., 2017).

Different plant species produce organic inputs with different chemical compositions, thereby increasing the diversity of organic substrates available to soil microorganisms. Such conditions encourage the development of more diverse microbial communities that participate in the decomposition of organic matter, the transformation of nutrients and the formation of a more stable soil structure (Duchene et al., 2017; Bünemann et al., 2018). Although changes in total organic matter content are generally observed only after several years of application, increased plant biomass input is an important factor in the gradual improvement of soil health (Lal, 2015; Lehmann et al., 2020). Increased soil biological activity is closely linked to more intensive nutrient cycling. More diverse microbial communities participate more effectively in the decomposition of plant residues and mineralization of organic compounds, thereby increasing nutrient availability during the growing season (Duchene et al., 2017). Combinations of legumes and non-legumes are particularly important, as biological fixation of atmospheric nitrogen contributes to an increase in the total amount of available nitrogen in the production system and reduces the need for mineral fertilization (Hauggaard-Nielsen et al., 2001; Duchene et al., 2017). At the same time, different dynamics in nutrient uptake from different soil depths improve nutrient use efficiency and reduce losses through leaching and denitrification (Hauggaard-Nielsen and Jensen, 2005; Brooker et al., 2015). Intercropping also has a beneficial effect on soil physical properties. Diverse root systems contribute to the formation and stabilization of soil aggregates and may increase soil porosity and improve water infiltration and retention (Mapa, 1995; Xiao et al., 2026). Increased soil cover during the growing season reduces the negative impact of raindrops, limits crust formation and decreases surface runoff, thereby mitigating the risk of erosion (Gregar et al., 2024). Intercropping can also improve water use efficiency, although these effects depend on climatic conditions, soil properties and crop management (Liu et al., 2025). In combination with minimal tillage, these effects may further contribute to the preservation of soil structure and improved soil water management.

Intercropping can also have an important role in the preservation of soil organic carbon. Increased production of aboveground and belowground biomass provides greater organic inputs to the soil, contributing to the formation of different soil organic matter fractions (Cotrufo et al., 2013; Li et al., 2023). Although changes in total soil organic carbon stocks require long-term application of such systems, research shows that increased inputs of plant residues can stimulate the accumulation of more active carbon fractions involved in nutrient cycling and gradually contribute to the formation of more stable carbon forms associated with the soil mineral fraction. Thus, intercropping can contribute to the preservation of soil fertility and long-term carbon sequestration (Li et al., 2023). Intercropping also increases the efficiency of using available natural resources. The complementary use of light, water and nutrients can increase overall productivity compared to sole cropping (Li et al., 2014; Yu et al., 2015). The efficiency of intercropping systems is often assessed by the Land Equivalent Ratio (LER), with values greater than 1 indicating more efficient

use of production area compared to sole cropping (Willey, 1979). Numerous studies and meta-analyses confirm that properly selected combinations of plant species achieve such values, although the results depend on agroecological conditions and management practices (Yu et al., 2015; Martin-Guay et al., 2018). Increased plant diversity in intercropping systems can support the biological regulation of pests, diseases and weeds by creating favorable conditions for beneficial organisms and limiting the spread of harmful organisms (Beillouin et al., 2019; Tamburini et al., 2020). Through the interaction of physical, chemical and biological processes, intercropping contributes to soil health, more efficient use of natural resources and greater resilience of agroecosystems (Glaze-Corcoran et al., 2020).

Intercropping as a component of more climate-resilient agroecosystems

Intercropping can improve the resilience of production systems by increasing the functional diversity of plant communities (Glaze-Corcoran et al., 2020; Burgess et al., 2022). Different plant species respond differently to changes in environmental conditions, which is why intercropping often achieves more stable yields in years marked by adverse weather conditions (Martin-Guay et al., 2018; Burgess et al., 2022). The complementary use of water, nutrients and light allows more efficient use of available resources during the growing season, especially in periodic droughts conditions, when different root system depths enable better water use from different soil depths (Hauggaard-Nielsen and Jensen, 2005; Brooker et al., 2015; Liu et al., 2025). Intercropping contributes to climate change adaptation primarily by improving the processes that determine soil health (Glaze-Corcoran et al., 2020; Burgess et al., 2022). It can also contribute to climate change mitigation by increasing plant biomass and organic matter inputs to the soil. The use of legumes can additionally reduce the dependence on mineral nitrogen fertilizers, while greater organic inputs may support the long-term maintenance of soil organic carbon stocks (Li et al., 2023; Duchene et al., 2017).

The effects of intercropping on the resilience of production systems depend on agroecological conditions and management practices (Brooker et al., 2015; Burgess et al., 2022). Therefore, the selection of plant species and cultivation practices should take into account climatic conditions, soil type and production goals. Adaptation to local conditions is one of the key factors for the successful application of intercropping in modern agriculture.

Limitations of application and future perspectives

Despite its numerous advantages, the wider application of intercropping in agricultural production is still limited by technological and economic factors (Brooker et al., 2015; Glaze-Corcoran et al., 2020). Successful planning of such production systems requires an understanding of the plant species interaction, resource requirements and growth dynamics, as well as the adjustment of agrotechnical measures during the growing season (Brooker et al., 2015). Future research should be focused on the development of production systems adapted to different agroecological conditions and on a better understanding of the long-term changes that intercropping causes in the soil. Long term experiments that allow monitoring of changes in soil health, nutrient cycling and the efficiency of natural resource use are particularly important (Beillouin et al., 2019; Glaze-Corcoran et al., 2020). At the same time, it is necessary to explore the synergistic effects of intercropping in combination with other agroecological practices, such as conservation tillage, cover crops, and diverse crop rotation (Beillouin et al., 2019; Tamburini et al., 2020).

Conclusion

Intercropping is an agroecological practice that naturally fits into the principles of conservation agriculture and contributes to more sustainable management of production systems. By increasing plant diversity, it enables more efficient use of natural resources, improves the physical, chemical and biological soil properties and contributes to preserving soil health. At the same time, it promotes more efficient nutrient cycling, increases production stability and contributes to the resilience of agroecosystems to climate change.

Although the effectiveness of intercropping depends on the choice of plant species, agroecological conditions and management methods, current knowledge confirms its significant potential as a component of sustainable agricultural production. Future research should focus on long-term trials and the development of production systems adapted to different production conditions in order to fully exploit the benefits of intercropping in preserving soil health, using natural resources more efficiently, and adapting agriculture to climate change.

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