Evaluating the Effect of Intercropping on Arthropod Abundance, Weed Suppression and Crop Performance

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Foreword

Having lived in Ethiopia, where most people directly rely on agriculture, I always had a strong sense of the close connection on food production and soil conservation. Additionally, I also saw how the farmers are affected by poor agricultural practices, soil depletions due to limited knowledge of integrated agronomic practices, and unwise use of synthetic chemicals. This made me interested in learning about farming, that can enable me to advise and support farmers to produce their food without affecting the environment, it also enhances livelihoods, by implementing resilient and sustainable production systems. For this mission I got agroecology would be the right program to make my dream real. Therefore, the opportunity of studying my Master's in Agroecology at the Swedish University of Agricultural Sciences will be a turning point along my future journey. The course offered depth in looking beyond food production, however it is a system interlinked through a science, a set of practices and a social movement as Stephen Gliessman described. I am most grateful for the lectures, field visits, and experiential learning they had to offer from studying organic farms committed to biodiversity to observing conventional systems committed to efficiency. These site visits had critical lessons on farming and the need for changing methods to conditions.

My thesis research on intercropping utilizes this experience. It addresses how small-scale farmers can improve beneficial insects that can help to reduce pesticides by biological pest control, weed control mechanism, and land-use efficiency through low-input, and easy-to-use methods. The aim is to be able to contribute to farming systems that are both productive resilient to climate change, environmental effects and assuring sustainable production systems. I am grateful to my teachers, supervisor and entire agroecology program members who taught me. They have been my arguers, advisors, and motivators, which have immensely helped me to grow both scholastically and as an individual. In the future, I intend to continue advisory and research roles serving agroecological food system producers. I think the strength of agriculture lies not only in what we are growing, but also how we grow it and for what values we do it in the process. My vision is to contribute to building robust, just, and sustainable farming systems for the future

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Abstract

Sustainable agriculture requires farming systems that promote biodiversity, resources use effectively and reduce external input usage. Intercropping has been proposed as a strategy to increase ecological resilience while maintaining productivity. The intercropping effect of winter wheat-winter pea (W+P) and winter oilseed rape-winter pea (R+P) on above ground dwelling arthropod abundance, suppressing weeds, enhancing crop biomass, and sustaining grain yield was evaluated compared to their sole strip cropping (SSC), and with their large field reference sole cropping plots (Ref). Field experiments were conducted in the 2023/2024 crop production season at SITES Lönnstorp Research Station, Skåne, southern Sweden. Abundance of aboveground dwelling arthropods was quantified by using pitfall traps and analysed with Generalized Linear Mixed Models (GLMM), while weed biomass, crop biomass, and grain yield were quantified with Linear Mixed Models (LMM). Tukey-adjusted pair-wise comparisons of estimated marginal means were used for treatment comparisons. Land Equivalent Ratio (LER) was computed for land-use efficiency comparison and correlation analysis was performed to examine the relationships these variables. Intercropping had a major positive impact on arthropod abundance, with intercropped cropping system showing about 27% and 69.2% higher than sole strip cropping (SSC) and sole cropping (Ref) plots, respectively. Significant weed suppression was also observed in winter pea treatment when intercropped with winter wheat. Similarly, both intercrop systems showed strong land-use advantages (LER > 1). In winter wheat-winter pea intercrops, where both crops were sown at 50% seeding density, winter pea contributed most (partial LER = 2.40), giving the highest total LER of 3.15. In winter oilseed rape- winter pea intercrops, where both crops were fully seeded, winter pea again dominated (partial LER = 1.95), with a total LER of 2.47. Thus, intercropping improved land-use efficiency, especially for winter wheat-winter pea IC cropping system. In conclusion intercropping increased land-use efficiency and biodiversity mainly in cereal-legume combination without compromising grain yield. Therefore, intercropping is a promising agroecological innovation that increasing biodiversity, weed control, and resource use efficiency while supporting sustainable intensification and enhancing ecological resilience in temperate agroecosystems.

Key words: arthropods abundance, crop biomass, intercropping, sole strip-cropping, weed suppression, winter wheat,

Table of contents

List of tables

List of figures

Abbreviations

Abbreviation	**Description**
IC	Strip intercropping
SIC	Strip intercropping
SSC	Sole strip cropping
Ref	Reference plots (Controle)
LER	Land Equivalent Ratio
W	Winter wheat
P	Winter pea
R	Winter oilseed rape
W+P	Winter wheat intercrop with Winte pea
P_(W+P)	Value of winter pea at winter wheat intercrop with pea
P+R	Winter pea intercrop with winter oilseed rape
P_(R+P)	Value of winter pea at winter oilseed rape intercrop with pea
R_(R+P)	Value of winter oilseed rape at winter oilseed rape intercrop with winter pea
SDGs	Sustainable Development Goals
RCBD	Randomized Complete Block Design
GLMM	Generalized Linear Mixed Model
LMM	Linear Mixed Model
SITES	Infrastructure for Terrestrial Ecosystem Science
QGIS	Quantum Geographic Information System
DIVA-GIS	Diversity Variables – Geographic Information System

1. Introduction

Agriculture is one of the pillars that sustained human existence and the global economy by providing the world with vital commodities such as food, raw materials, and energy. Plus, in developing countries it contributes to national economic progress, livelihood food security, and social stability (FAO 2021). Currently, global agriculture hosts approximately eight billion people and provides other services such as employment, cultural values, and ecosystem services (Power 2010). Furthermore, the agricultural sector has the principal responsibility of feeding an estimated world population of 9 billion by the year 2050, and therefore sustainable, resilient, climate change shock-resistant food production system without compromising yield are required (Tilman et al. 2011). But, as Suchithkumar et al. (2024) highlight, the present agricultural production system is facing twin challenges. Those are: ensuring food security and environmental conservation. While intensive sole cropping supported by high synthetic external inputs is in use, it often increases the cost of production, causes ecological degradation, reduces soil fertility, and increases vulnerability to pests, climate extremes, and decline in biodiversity (Altieri 1999; Tilman et al. 2002).

According to Hussain et al. (2025) finding the synthetic nitrogen fertilizer supply chain was responsible for estimated emissions of 1.13 billion tons of CO_2 in 2018, representing 10.6% of agricultural emissions. Another thing, due to the intensive synthetic fertilizer application on sole cropping system, nutrients leach from agricultural fields into water bodies, causing eutrophication (Menegat et al. 2022). This process reduces biodiversity in aquatic ecosystems and disrupts species diversity in terrestrial habitats.

The same problems are seen in Europe, mainly in Western European regions, that are heavily farmed. The over-reliance on synthetic agricultural inputs has resulted in a decline of soil organic matter and microbial diversity as well as a depletion in soil fertility (Virto et al. 2015). In area like Skåne, Sweden, there are few main crops like winter wheat, barley, oats, and oilseed rape, which together occupy the majority of arable land (Hösel 2019;Reumaux et al. 2023). These crops are mainly grown in smaller rotation systems or even in sole farming schemes, as per Börjesson et al. (2018) studied. Although such systems secure high yields, they are highly dependent on external inputs such as mineral fertilizers and chemical plant protection products (Ulfbecker 2018). Reliance on mono-cropping and input-intensive management reflects the negative trend observed globally (Meynard 2012;Jacobs et al. 2020). This situation raises concerns about the long-term sustainability and resilience of current cropping systems and highlights the need for diversified systems that can reduce dependence on external inputs while maintaining productivity. One of the promising practices to reduce the negative impact of sole cropping is intercropping (IC). Because adopting of crop diversification farming systems improves nutrient cycling, enhances biological pest control, and strengthens ecological resilience, thereby supporting sustainable crop production systems (Brooker et al. 2015(Landis et al. 2000; Rusch et al. 2016; Altieri 2018; Tamburini et al. 2020).

Similarly, Mason et al. (2020) documented that, in addition to biodiversity values, intercropping (IC) increases resource-use efficiency through spatial and temporal complementarity among crops. For example legumes such as pea can fix atmospheric nitrogen, reducing the use of synthetic nitrogen fertilizers, while cereals such as wheat offer structural canopy by covering the nearby ground can suppresses weeds and encourages beneficial arthropods, and physical supports to peas (Jensen et al. 2020). In addition to this, Crops like oilseed rape, having deep and strong root systems, break up compacted soil layers, improving topsoil structure, increasing nutrient availability (Kupcsik et al. 2021). Another point, oilseed rape uses as a bio fumigation that can reduce soil-borne pests, diseases, and weeds due to the capacity of releasing isothiocyanates, improving soil health and crop yields (Matthiessen & Kirkegaard 2006; Gimsing & Kirkegaard 2009).

While winter wheat, winter Peas and winter oilseed rape are important crops not only in Swedish but in global context, they are grown as sole crops with high external inputs (especially agrochemicals) leading to negative environmental consequences such as on biodiversity, soil depletion and water pollutions (Hossard et al. 2014 ; Reckling et al. 2016). There are few studies on intercropping in Europe (Luuk Croijmans et al.2024; Cadoux et al.2015) however, these studies focus on comparing sole crops when grown in strips. To my knowledge there is no study done yet on the implications of strip intercropping system of IC winter wheat-winter pea and winter pea-winter oilseed rape on biodiversity and crop performance.

1.1 Research aim, questions and hypothesis

Aim:

The aim of this study was to quantify and compare the agroecological performance of intercropping (IC) with sole strip cropping (SSC), by evaluating its effects on aboveground-dwelling beneficial arthropod abundance, weed suppression, crop biomass, and grain yield, with consideration of its potential contribution to reducing reliance on external inputs.

Research questions

To achieve the above research aim, four different questions were addressed. These are:

1. Does intercropping (IC) increase above ground dwelling arthropod abundance compared with its sole strip cropping (SSC)?
2. Does intercropping (IC) effectively suppress weeds relative to its sole strip cropping (SSC)?
3. Does intercropping (IC) enhance crop biomass accumulation compared with its sole strip cropping (SSC)? and
4. Does intercropping (IC) increase or sustain grain yield relative to its sole strip cropping (SSC)?

Hypothesis

Null Hypothesis (H_0): Intercropping (IC) has no significant effect on above ground dwelling arthropod abundance, weed suppression, crop biomass accumulation and grain yields compared with sole strip cropping (SSC).

Alternative Hypothesis (H_1): Intercropping (IC) significantly increases above ground dwelling arthropod abundance, suppresses weed, increases crop biomass and crop grain yields compared with sole strip cropping (SSC).

1.2. Scope and limitations of the study

This research was conducted in the 2024 crop production year at SITES Lönnstorp experimental farm, Skåne, Sweden, on three winter crops: winter wheat (W), winter oilseed rape (R), and winter pea (P). The field experiment had intercropping (IC) vs. sole strip cropping (SSC) systems, and Sole cropping (Ref) used as a baseline. Data were analyzed on above-ground dwelling arthropod abundance, weed dry matter biomass, crop dry matter biomass, and grain yield. The research had limited generality, as it was conducted in a single season on the basis of data from a specific experimental location that would limit geographical as well as seasonal variations. Furthermore, aboveground arthropod indicator groups of insect abundance were collected, these were identified to the group and not the species level, and only their total sum was analyzed, which might have reduced the taxonomic resolution of the ecological analysis. Winter pea and oilseed rape were over-mature, which caused some grain shattering during harvest and transport; therefore, productivity may likely underestimate. Despite these limitations, the present research offers significant empirical evidence of the effects of intercropping systems in increasing weed suppression, enhancing crop biomass, and increasing grain yield in temperate agroecosystems.

1.3. Significance of the study

This research contributes to crop production effort to apply ecological intensification to temperate agroecosystems, like biodiversity conservation, biological pest control, nutrient cycling, and the reduction of external synthetic inputs (Kremen & Miles 2012; Bommarco et al. 2013). The evaluation of intercropping (IC) effects on aboveground arthropod abundance, weed suppression, and crop performance provides empirical evidence for the design of sustainable cropping systems and the EU Green Deal strategy of biodiversity and agroecological transition. Plus, it contributes to the achievements of the United Nations Sustainable Development Goals (SDGs, 2015): like, SDG 13 (Climate Action) by building increased resilience and reducing external synthetic inputs; SDG 15 (Life on Land) by improving on-farm biodiversity; and SDG 12 (Responsible Consumption and Production) by maximizing the use of resources. Furthermore, it contributes to improve habitat quality, increase species diversity, and strengthen the ecological processes of agro-landscapes; the findings support Sweden's Environmental Quality Objective of "A Rich Diversity of Plant and Animal Life" (Tscharntke, Klein and Kruess, 2005).

2. Background

2.1. Definition and historical development of intercropping (IC)

2.1.1. Definition of intercropping (IC)

Several cropping arrangements that are employed on a farm during a specific production year are referred to as cropping systems (Ofori & Stern 1987b). These cropping systems' structure and efficiency are determined by how they interact with farm resources, and available technology. Some of the cropping systems are sole cropping, mixed cropping and intercropping (Willey 1979; Lithourgidis et al. 2011).

Intercropping is defined as the technique of growing two or more crops in the same farmland at the same crop production time (Willey 1979a). There are different types of intercropping production systems. Row intercropping is one of the intercropping crop production systems where two or more crops are cultivated simultaneously in a definite row pattern. Planting in rows makes applying fertilizer, weeding and harvesting easier (Brooker et al. 2015; Singh et al.2018). On the other hand, mixed intercropping is growing of two or more crops simultaneously with no definite row pattern; the seeds are mixed and sown in the field either by dibbling at random or by broadcast (Vandermeer 1992;Francis 1986). Another form of intercropping is Strip intercropping which is defined as growing of two or more crops simultaneously in different strips wide enough to permit for independent cultivation of crops but narrow enough for the crops to interact ecologically (L Bedoussac et al.2015; Lithourgidis et al. 2011; Duchene, Vian and Celette 2017; Martin-Guay et al. 2018). The underlying assumptions of intercropping are drawn from the ecological theory of Nitch, complementarity, facilitation, and resource partitioning with the aim of achieving a "land equivalent ratio" (LER) of greater than one, which will indicate greater land use efficiency than in sole cropping (Willey 1979).

2.1.2. The development and adaptation of intercropping (IC)

The conceptual roots of intercropping (IC) lie in historical agriculture production systems that date back centuries prior to the onset of industrial agriculture (Altieri 1995; Vandermeer 1995; Trenbath 1999). Traditional indigenous farmers and smallholder producers of most farms, from the "milpa" cropping systems of Mesoamerica (maize, beans, squash) to Asian and African traditional polycultures, naturally fostered many systems of intercropping as a means to enhance food security, improve dietary diversity, and reduce agricultural risks inherent in farming (Altieri 1994; Netting 1993).

As Novotny et al.(2021) specified that, despite milpa practices having their merits, they are diminishing because of socio-economic transformations and increasing labor demands, yet Fonteyne et al. (2023) added that milpa agronomy research had been scarce, with most focusing predominantly on maize. And he recommended that, for the sake of preserving and improving these old systems, research on crop types, soil fertility management, weeds, and general productivity-keeping in mind reducing labor needs-should continue. Such traditional systems possessed spatial arrangements similar to intercropping, on the basis of empirical observations of useful crop associations and local agroecology (Letourneau et al. 2011). As Altieri

(2002) emphasis is given to land use efficiency, building an enduring food base, and design of the system which is able to adapt to environmental fluctuations and low rates of external inputs were some of the key priorities. The scientific justification behind intercropping, under which the cropping system is operating, came into critical attention in middle decades of 20th century as scientists increasingly acknowledged its ability to lead towards more sustainable and efficient agriculture (Willey 1979a; Francis 1986).

Pioneering scientific investigation measured the yield benefit of intercropping with indices like Land Equivalent Ratio (LER) and unraveled the intricate competitive and facilitative relationships among component crops (Trenbath 1976; Vandermeer & Cunningham 1989). According to (Snapp et al. 2005), intercropping systems, such as strip planting, are still prevalent in the most developing nations and are a key way for resource-poor farmers to maximize land use, and diversify their income streams. To assess the advantages of intercropping scientifically, theoretical frameworks and experimental techniques were also used during this study. Globally, different policy regimes, agroclimatic factors, and socioeconomic traits all have an impact on the adoption of intercropping. Large-scale industrialized farming regions have tended to favor sole cropping, because of its apparent ease of management, mechanization, and reliance on synthetic inputs that contribute to ecological simplification, though intercropping's low input requirements and risk-reducing qualities are highly desirable in such contexts (Snapp et al., 2005; Gliessman et al., 2007).

However, Boliko (2019) argues that, awareness creation about biodiversity loss, ecological degradation, and the economic vulnerabilities of sole cropping has reversed this and promoted the use of diversified crop production in the developed regions. Similarly, Levidow (2018) notes that, changes in policy that support ecological intensification, agroecological transition, and ongoing studies showing the economic and environmental advantages of intercropping have helped it gradually re-grow and regain traction in many regions of the world, including Northern Europe.

Technological innovation in precision agricultural machines and equipment dedicated to intercropping is also overcoming some of the historical barriers to the adoption of intercropping on a larger scale (Gurr et al. 2016; Raseduzzaman & Jensen 2017). For example, in Europe during the 1990s, there was renewed interest in intercropping as a response to the environmental weaknesses of intensive sole cropping, with experiments conducted in France, Germany, and the Netherlands indicated that cereal-legume intercropping production systems could maintain or even increase yields while reducing nitrogen leaching and pesticide application (L Bedoussac et al., 2015). This is in parallel with the EU Green Deal and renewal of the Common Agricultural Policy (CAP) in sustainability and biodiversity directions (Silander 2019). That promotes sustainable and biodiversity-friendly agriculture production system by giving financial support to those who are engaged in diversifying cropping systems.

2.2. Agroecological outcomes of intercropping (IC)

Compared to sole strip cropping (SSC) systems, intercropping (IC) systems of leguminous crops possess several ecological benefits. A research done by Hauggaard-Nielsen et al. (2016) demonstrated that, IC reduces external input costs, maintains the total yield across rotation, and reduces the carbon footprint through improved root biomass, biological nitrogen fixation, and soil carbon and nitrogen sequestration. Also, as per Ali et al. (2024), IC also helps to suppress weeds by providing cover to soil, reducing solar radiation for weeds but increasing light interception and water use efficiency for its companion crop. As Mousavi and Eskandari (2011) also mentioned that, IC systems are less affected by pests and diseases due to enhacing of natural enemies.Crop diversification production systems generally promote sustainable agriculture via ecologic balance, better resource use efficiency, and increased productivity of land as described by Ali et al. (2024) and Mousavi & Eskandari (2011). This enable lowering the environmental impact of agricultural production. Besides that, IC produces more varied conditions with different canopy structures and microclimates, favoring greater diversity and density of beneficial insects, including aboveground-living arthropods (Rusch et al. 2016; D'adamo & Sassanelli 2022).

2.2.1.Arthropods abundance

According to Puliga et al. (2024), wheat-pea intercropping increases arthropod abundance and activity in the aboveground space compared with sole cropping of wheat. Similarly, Alarcón-Segura et al. (2022) indicated that strip intercropping using oilseed rape and wheat gives ecological benefits through enhanced populations of arthropods in the aboveground space and also natural pest control compared to sole cropping. The above evidence shows that crop-interaction systems, as opposed to single monocropping, give conditions for favoring beneficial insects. Intercropping, for instance, enhances habitat heterogeneity and microclimate by various canopy structures, organic ground litter, and flowering patterns, all of which are highly developed to sustain greater arthropod diversity of useful species (Sunderland & Samu 2000). As described by Symondson et al. (2002) and Schmidt & Tscharntke (2005) that, Carabidae (ground beetles), Staphylinidae (rove beetles), and spiders (Araneae) are the important aboveground arthropod families commonly used as indicators of insect diversity in agroecosystems. Equally, research by Finch and Collier (2000) and Tscharntke et al. (2005) suggests that above-ground arthropod diversity is often positively related to structural and compositional complexity of agricultural habitats, confirming their status as key indicators of the ecological benefits of intercropping. Ther functional describtion is described as follows:

2.2.1.1. Carabidae (ground beetles)

Carabidae are one of the ecologically sensitive indicators and major predators of agroecosystems (Makwela et al. 2023). Plus, Makwela et al. (2023) described as bioindicators of biodiversity balance due to their sensitivity to ecological disturbances such as pesticides, herbicides, and fungicides. Whereas cropping systems and agronomic practices could have an effect on their abundance.

Therefore, among the various cropping systems, IC mainly enhances them with higher structural complexity and greater prey abundance. For example, as per Rakotomalala et al. (2023) research conducted in France reported that, intercropping (IC) of wheat and maize resulted in a 30% increase in Carabid activity and a 15% higher species abundance compared than sole cropping under organic farming. And, in the Netherlands, Rusch et al.(2010) showed that, 1.4-fold higher in wheat-rapeseed IC compared with sole cropping, suggesting higher predation pressure, presumably caused by spatial segregation between crops with refuge and greater richness of food items. Similar benefits have been observed in Finland, where carabid abundance was higher in cabbage-faba bean IC than in sole-cropping cabbage (Holland & Luff 2000). Therefore, these research findings indicate that, in IC production system in different crop types, the abundance of Carabidae may vary, but overall, they still show an increase with the crop diversity compared to sole cropping systems.

2.2.1.2. Staphylinidae (rove beetles)

Staphylinidae are generalist predators that are well worth their cost in the biological control of insect pests such as aphids and fly larvae, whose effectiveness is strongly linked with structurally heterogeneous crop canopies and microhabitats of high organic matter content (Dennis & Wratten 1991). In cereal-legume rotations as per Gagic et al. (2011) reported that, pea-barley intercropping increased staphylinid populations by 32% compared to sole cropping. However, their population in the intercropping (IC) system can vary as it depends on conditions of the habitat as well as on some crop combinations (Sunderland and Samu, 2000). Experimentation done in Kenya also revealed that populations of staphylinids increased in the systems where there was minimal external input and maximum plant diversity (Devine et al. 2022). Also, Häfner et al.(2024) documented a non-significant but moderate increase in the density of staphylinid beetles in pea-wheat IC, which suggested that their populations strongly depend on the abundance of prey and the structure of vegetation. Additional studies supports for diversified crop production systems, such as IC and organic farming (free of chemical spray), are likely to increase staphylinid activity with increased habitat heterogeneity and secure prey resources as described by (Schmidt & Tscharntke 2005).

2.2.1.3. Spiders (araneae)

Spiders are generalist predators with extensive prey spectra and are particularly sensitive to habitat structure. As per Sunderland & Samu (2000) documented spider abundance increased under agricultural diversification in 63% of the studies they reviewed. Inline to this finding, Samu et al. (1999) described that, spider abundance and crop diversity correlates positively. That means at multiple spatial scales, with interspersed habitat diversifications proving more effective than segregated approaches for increasing spider abundance in agricultural systems. This is due to better ground cover and microclimatic buffering (Symondson et al. 2002). Moreover those findings, wheat-pea intercropping has also indicated that, an abundance of generalist predators, including spiders, compared to their sole cropping system (Langellotto & Denno 2004).

2.2.2. Impacts of intercropping (IC) on crop agronomic performance

Intercropping (IC) is a promising approach to improve the agronomic performance of cropping systems. Due to its interspecific interactions and spatial diversifications as compared to sole cropping system. Because, IC allows growing crops with different functional traits together, which promotes ecological synergy and more efficient use of environmental resources. Such increased crop complementarity is demonstrated in practical advantages such as reduced weeds, increased crop biomass accumulation, and improved grain yields. In addition, IC may result in >1 land equivalent ratio (LER) values, which reflects better land-use efficiency. Each of these agronomic outcomes is discussed below.

2.2.2.1. Weed density suppression

Weeds are commonly described as plants that appear in a place and in a time where and when they are not wanted (Harlan & deWet 1965). Weeds affect plant growth due to their high competitiveness of light, water, and nutrients. This leads to a reduction in crop yield quantity and quality (Radosevich et al. 2007; Zimdahl 2018). But, intercropping (IC) provides a sustainable way of weed management by enhancing natural suppression mechanisms which are less effective in sole cropping systems (Liebman and Dyck 1993; Harker and O'Donovan 2013). Therefore IC production system promotes weed control through spatial complementarity, high canopy cover, and niche occupation, by reducing resource availability for weeds (Brooker et al. 2015; Lithourgidis et al.2011). Evidence from Europe experiments by Laurent Bedoussac et al. (2015) indicates that, wheat with peas, barley and clover IC reduces weed density compared to sole cropping.

Like findings by Cadoux et al. (2015) also demonstrated that intercropping of legumes like faba bean with oilseed rape reduced herbicide needs. Therfore biological way of weed control can be attained with other benefits like an increase of nitrogen use efficiency and reduced insect damage by reducing competition and host plants of pest and disease. Additionally, according to Dayoub et al. (2022), intercropping oilseed rape with frost-sensitive legumes such as faba beans results significantly less weed dry biomass up to 41% compared to sole oilseed rape. Furthermore, Cadoux et al. (2015) documented that, these kinds of crop combinations reduces insect damage and improve the efficiency of nitrogen use, giving stringent evidence as IC adoption as a sustainable crop production systems substitute for the common conventional agricultural crop production systems.

2.2.2.2. Crop dry biomass accumulation

Aboveground crop dry biomass is described as being all the living components of crops such as stems, leaves, flowers, and reproductive structures, are critical indicators of crop yield and ecosystem processes (Zhu et al. 2019); Scurlock et al. 2003). It reflects a system's ability to direct solar energy, nutrients, and water into plant growth in varying environmental conditions (Kay et al. 2022). Intercropping (IC), it enhances dry biomass accumulation that is normally attributed to complementarity of resources and interspecific facilitation whereby crops utilize exclusive spatial and temporal niches for acquisition of light, water, and nutrients

(Brooker et al. 2015). Cereal-legume intercropping results indicate increased biomass production (Samu et al. 1999).

Also, Bedoussac and Justes (2010), argued that legumes add to nitrogen content of soil, while cereals benefit from earlier canopy closure and stronger roots, resulting in interdependence benefits. In addition, Blanc et al. (2024) further quoted other studies saying that, when winter oilseed rape intercropped with legumes contributes to dry biomass increments by rapid occupation of the surface, shading of weeds, and release of allelopathic compounds deterring competitor growth. Winter oilseed rape also improves soil structure by means of greater aeration and water infiltration as a result of the depth of its taproot (Liu 2009). In contrast to sole strips, evidence shows IC has experienced notable dry biomass increases (Lowry & Brainard 2016). For example, inter-cropping of peas with wheat increases wheat dry biomass due to the enhanced capture of light and reduced shading among the wheat plants. Furthermore, they get nutrients in a complementary way, there is less competition, and nitrogen fixation is an additional benefit from pea (Lithourgidis et al. 2011b). Intercropping legumes such as winter pea with oilseed rape increases system productivity, especially under low nitrogen application and further row spacings, due to greater nitrogen-use efficiency and spatial complementarity (Stahl et al. 2016).

2.2.2.3. Grain yield increase

Grain yield refers to the dry weight of grain per unit area, typically expressed in tons or kilograms per hectare, and is defined to be the main economic yield of cereal crops (Fischer 2015. Grain yield is one of the most reliable measures of cropping system performance and a primary determinant of farm profitability and food security (Albahri et al. 2023). However, it is influenced by different factors. Such as, genetic potential of the crop, climate condition of the production area, and cropping system (Peltonen-Sainio et al. 2007). As per Lithourgidis et al.(2011) study, IC has the potential to increase grain yield due to complementary interaction between crop species. Because of their canopy architecture, root development, and synergistic nutrient acquisition, cereal and legume crops or oilseeds with intercropping systems of oilseeds and legumes also experienced a yield advantage in comparison to monocropping (Raza et al. 2023). Additionally, by excluding the intraspecies competition and also profiting from the nitrogen fixed by the legume crop, wheat-pea mixtures improve wheat grain yield (Bedoussac et al. 2015b). Also, Su et al. (2015) found that oilseed rape sown with legumes has been effective in terms of acquiring pod yield and nitrogen due to enhanced belowground soil architecture for better utilization of nutrient resources.

Apart from this, Yu et al. (2016) also inferred that intercropping production systems demonstrated the potential to attain higher grain yield than sole cropping, low-input (organic farm) production systems. In order to quantify the yield advantage of intercropping, land equivalent ratio (LER) is commonly used, which demonstrates whether intercropping produces more per hectare than sole cropping (Yu et al. 2016).

2.2.2.4. Land equivalent ratio (LER)

Land use efficiency, measured by the LER, is a critical parameter for assessing the efficiency of sole cropping compared with intercropped systems (Willey 1979). LER result, if greater than one, shows better intercropping efficiency. LER more than one is achieved normally with combination crops such as cereal crops with legume crops (Lithourgidis et al. 2011). The benefits are based on complementarity between weed-suppressing, nutrient-use-efficient cereals and nitrogen-fixing legumes (Rodriguez et al. 2020). Land-use efficiency is important for ensuring food requirements while minimizing environmental negative impacts. Which is in line with the FAO objectives and global sustainability goals (Lan et al. 2023). Adoption of intercropping is not only increasing productivity, but it is also contributed to the conservation of natural resources and leads to enhanced environmental integrity. This cropping system can contribute towards solving extensive farming systems and improve sustainable production system (Lithourgidis et al. 2011a). Given these global perspectives on land-use efficiency and the sustainability benefits of intercropping, the following section describes the crop production system of Skåne region, Sweden, where the research site for this study is located.

2.3. Crop production system in Skåne, Sweden

Sweden covers about 45 million hectares, around 70% forested, and 3.2 million hectares are cultivated land (Petridou et al., 2024). Agricultural production is mainly in the south part. Skåne is the country's most productive agricultural region. With fertile soils, the longest growing season in Sweden, and nearly 60% of the country's arable land (Skärbäck & Grahn 2012). Despite its potential, crop production, Skåne has become highly specialized. Sole cropping of cereals, sugar beet, and oilseed rape dominates the landscape, and crop diversity has become declined (Yang 2020). This specialization is started in post-war agricultural modernization driven by mechanization, synthetic fertilizers, and pesticides and was further reinforced by Sweden's entry into the European Union in 1995.The Common Agricultural Policy (CAP) also has its role due giving a promotion on large scape productivity-based cereal and oilseed rape sole cropping system (Haberzettl et al. 2021).

While such production systems secure more production in the short term, they also create long-term environmental and agronomic problems. Continuous sole cropping, depletes soil nutrients, reduces organic matter, and causes biodiversity loss by limiting habitats for beneficial insects (Raderschall et al. 2021). These production systems are also dependent on external inputs. These external inputs may increase production costs while also posing environmental issues such as fertilizer leaching and pesticide contamination (Atapattu et al. 2025). To address these challenges and ensure long-term farming practices is important. Therefore, diversified cropping practices mainly intercropping, offer a promising alternative by enhancing biodiversity, suppressing weeds, improving crop performance, and increasing overall resilience and sustainability.

In this regard, the Lönnstorp Research Center is an appropriate experimental site for assessing such possibilities. Lönnstorp long-term field trials allow long term field experiments of diverse practices like strip intercropping under realistic farming conditions. This provides valuable insights into whether crop diversification can address ecological and agronomic challenges in Skåne's and other locations having similar agroecological zones.

3. Materials and methods

This part explains the method followed to achieve the research aim, and the material used during the process. Quantitative approach was selected to achieve both scientific standards and practical requirements in order to keep the data collected and subsequent analysis valid as relevant to the scope of the study.

3.1. Schematic approach

This study looked at the impact of intercropping (IC) on important agroecosystem components such as aboveground arthropod abundance, and agronomic practices like weed suppression, dry biomass accumulation, grain yield, and land use efficiency. The experiment took place during the 2023/2024 winter crop production season and conducted at the SITES Lönnstorp Research Station in Skåne, southern Sweden. Three cropping systems were evaluated: (1) IC of winter wheat with winter pea (W+P) and winter oilseed rape with winter pea (R+P); (2) sole strip cropping of winter wheat (W), sole strip cropping winter oilseed rape (R), and sole strip cropping of winter pea (P); and (3) Reference plots of winter wheat (W), Reference plots winter oilseed rape (R), and Reference plot of winter pea (P).

Grain yield was evaluated after threshing and weighing, weed and crop dry biomass were collected from 0.5 m^2 quadrats, arthropod abundance was sampled using pitfall traps, and LER was computed using yields from sole-cropped and intercropped treatments. Generalized linear mixed models (GLMMs) were used to assess arthropod data, while linear mixed models (LMMs) were used to examine grain yield, crop dry biomass, and weed dry biomass. Tukey-adjusted pairwise comparisons of estimated marginal means were employed for individual treatment comparisons of weed, crop biomass and grain yield, while Tukey-adjusted pairwise comparisons were used for arthropod abundances. A land-use advantage for intercropping was indicated by LER values. Diagrammatic representation is illustrated in Figure 1 below.

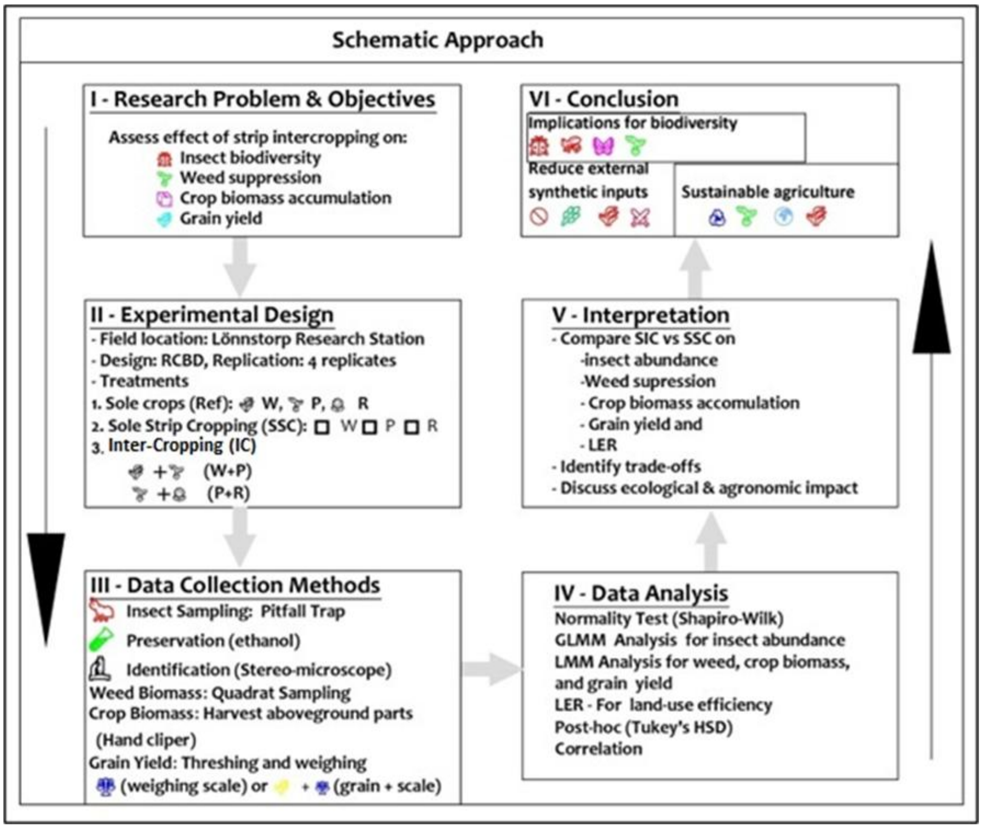

Figure 1. Schematic representation of the research framework of the experiment.

3.2. Description of the study site

The research was conducted during the 2023/2024 winter crop production season at the SITES Lönnstorp research station. This research center is located in Skåne region, southern Sweden, at the coordination of 55.67°N, 13.11°E. According to Lan et al. (2023) characterizes the site's climate zone is a temperate climate. Having an annual temperature of 5.5°C and mean annual precipitation of approximately 550 mm. The soil texture in the SITES Lönnstorp study area is loam with a clay content of around 15% and an organic content of 3% (SITES, 2015). The field site was mapped and georeferenced using Google Earth and QGIS, and administrative boundaries were obtained from DIVA-GIS and downloaded as a shapefile from https://diva-gis.org/.

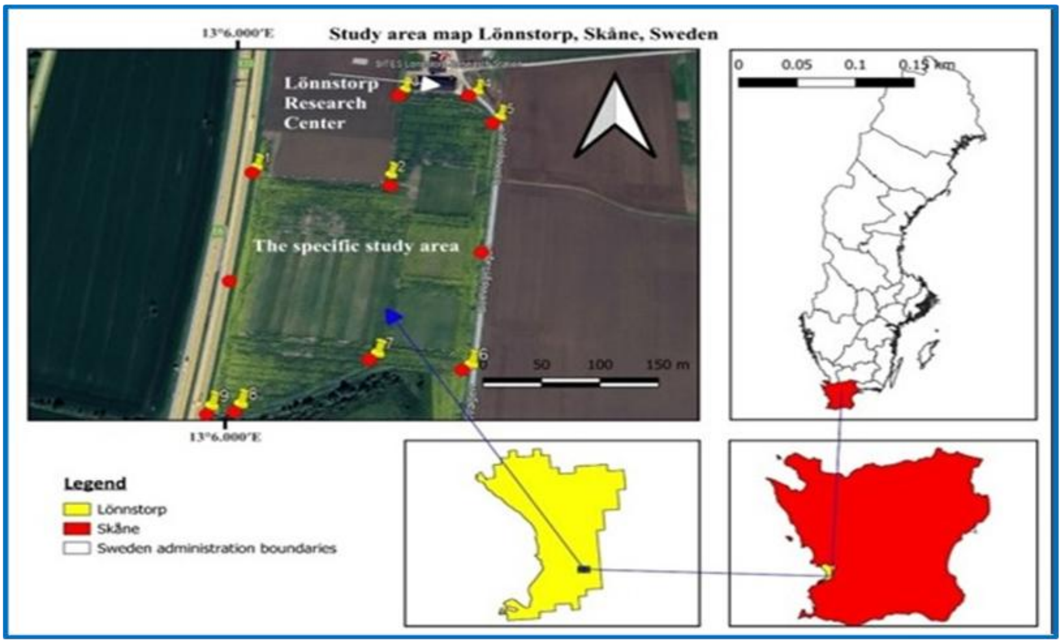

Figure 2. Study area site map of the Lönnstorp Research Station.

3.3. Experimental design

Randomized complete block design (RCBD) with four replications was used to account for spatial heterogeneity in soil properties. All the five treatments, i.e., winter wheat (W), winter oil seed rape (R) and winter pea (P), intercrop of winter wheat and winter pea (W+P), and intercrop of winter oilseed rape and winter pea (R+P), were individually allocated to a block. Three reference plots, reference of winter wheat (Ref_W), Reference of winter oilseed rape (Ref_R), and reference of winter pea (Ref_P), were established for comparison. Ref plots were 50 × 50 m while intercropped (IC) and the sole strip crops (SSC) strips were 100 × 6 m wide.

Following the 2023 harvest, soil was shallow tilled to a 20 cm deep and 50 kg N ha^{-1} Biofer (containing 10:3:1 of N:P: K) fertilizer were applied at sowing time to all treatments. Treatment, R was sowed around 26-27th august, to allow sufficient autumn growth for winter survival. While treatments, W and P were sowed simultaneously at around 28th September, 30 days later to reduce early competition, as well to arrange the maturity time.

The row spacing was 50 cm in treatment R and 12.5 cm in treatments, W and P. And the seeding density were 50 seeds m^{-2} for R, 300 seeds m^{-2} for W, and 60 seeds m^{-2} for P in both sole strip cropping (SSC) and reference plots of Ref _P, Ref _W and Ref _R. However, in intercropping (IC) system, W and P seeding density were at 50% reduction (150 and 30 seeds) m^{-2} respectively, whereas R was kept constant at 50 seeds m^{-2}. This was because the inter-row spacing of oilseed rape is sufficiently wide to enable successful intercropping with winter pea without compromising crop establishment. The layout of the field experiment indicated below in Figure 3.

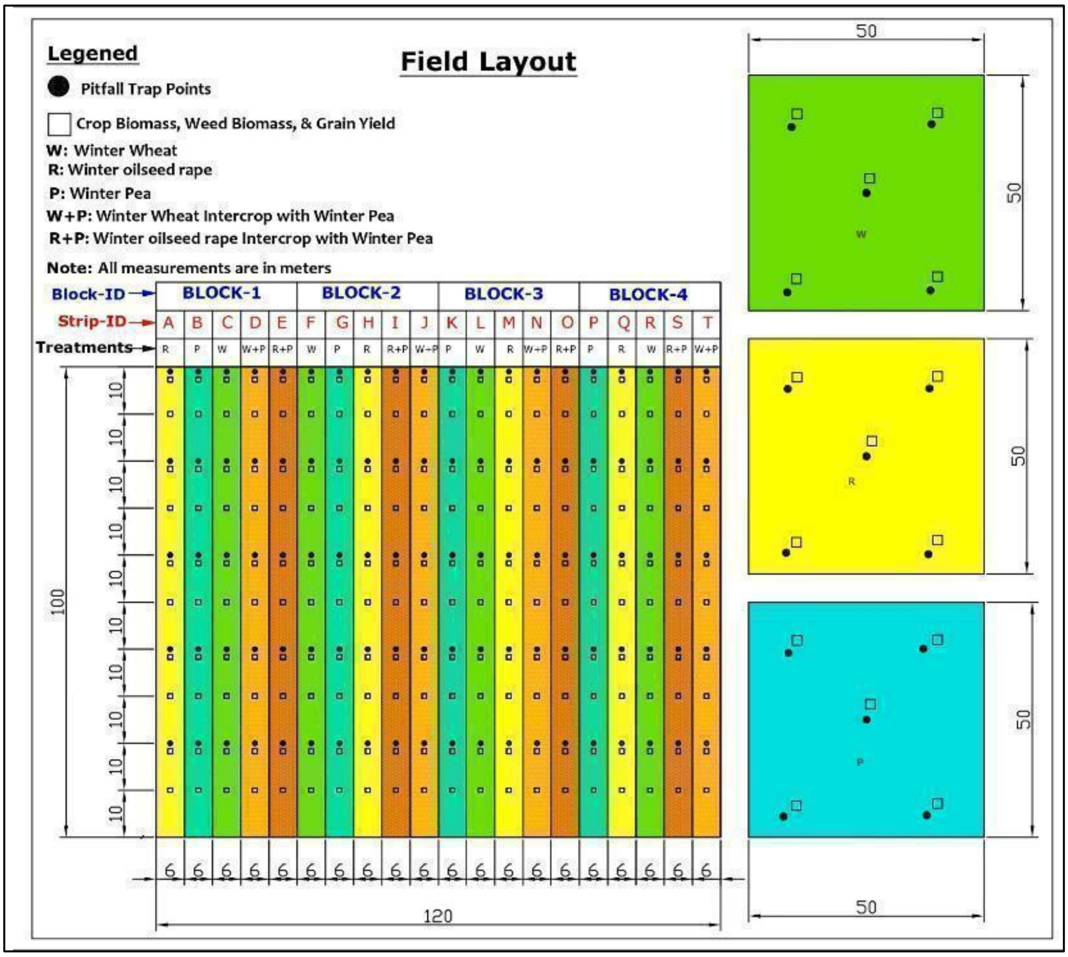

Figure 3 field layout of the experimental design at Lönnstorp research station.

The above Figure 3 illustrates the spatial arrangement of treatments in the intercropping (IC), sole strip cropping (SSC), and reference plots (Ref) plots of the experiment. The field was designed as strips having a total of 20 strips (Strip-ID, A–T), which were divided into four replicated blocks (BLOCK1-4). Each block contained five strips, and each strip was assigned to one of the five cropping treatments: winter wheat (W), winter oilseed rape (R), winter pea (P), intercrop of winter wheat with winter pea (W+P), and intercrop of winter oilseed rape with winter pea (R+P). Commonly placed sampling points for pitfall traps are indicated by black circular (●) symbols, while crop dry biomass, weed dry biomass, and grain yield are represented by rectangular (□) symbol on each treatment strip. The design allows the sampling to be uniformly distributed in the field. Treatment W is indicated in green, R in yellow, and P in cyan. And, W+P and R+P are represented in golden yellow and dark orange colors, respectively. Similarly, the reference plots represented by W, R and P, however they are placed in the center of the plots. The actual filed experiment's aerial photo was illustrated in figure 4 below.

Figure 4. The aerial view of the actual experimental site of this study.
Photo credit: Ryan Davidson (2023)

3.4. Sample collection

3.4.1. Above ground dwelling arthropod

The above ground-dwelling arthropods Carabidae (ground beetles), Staphylinidae (rove beetles), and spiders (order Araneae) sampled with pitfall traps. Because pitfall trapping is efficient in sampling ground-active arthropods (Pearce & Venier 2006). In total, 115 traps made of hard white polypropylene were used. All traps followed a nested cup design: a detachable inner cut cup, slit on the rim for ease of removal, was inserted into an uncut cup, stationary un slit outer cup anchored at ground level for the sampling period. The uncut cup was measured 12 cm in height, 11 cm in diameter wide at the rim, 8 cm in diameter at the base. These dimensions were designed to allow for a large enough opening to successfully trap surface-active arthropods (Luff 1975). The inside cup contained 250 ml of a 1:1 combination of water and Propylene glycol. Ethylene glycol was chosen due to its low evaporation rate and ability to fix both hard and soft-bodied specimens with negligible deterioration over lengthy trapping durations (Høisæter et al. 2024). Five traps were placed at 20 m intervals along the 100 m transect in each strip. In sole-cropped reference plots, one trap was placed at the center, and the remaining four traps were placed 2 m inwards from each corner to give even spatial coverage and reduce sampling bias. Samplings were done twice, at seven-day intervals on 25th June and 2nd July 2024. Figure 5. Materials used in Pitfall trap installation figure 5 below illustrates trap deployment:

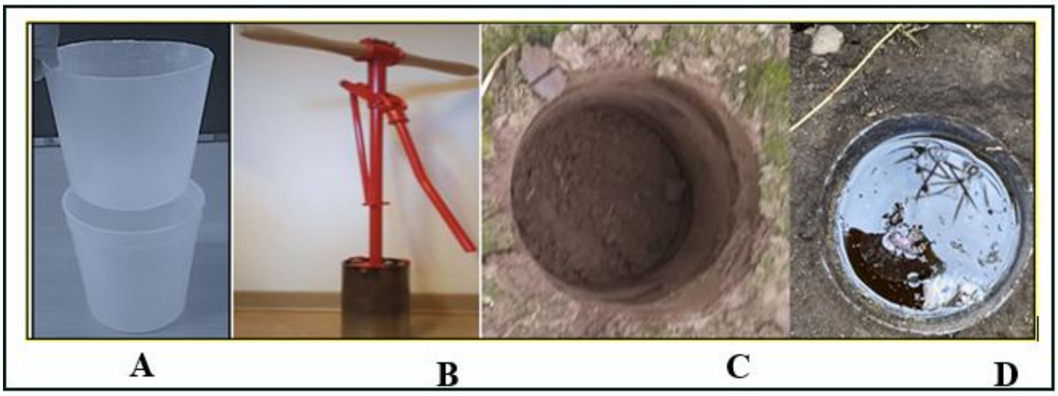

Figure 5. Materials used in Pitfall trap installation

Figure 5(C) illustrates the hole ready, demonstrating a good depth to the cup with the rim even with the soil surface. Section 5(D) illustrates the whole set-up of the pitfall trap in the field, where the cup is positioned and half-filled with water and glycol. Following specimen collection, specimens were stored in 90% ethanol for identification in the laboratory. Sorting was taxonomic with the help of a Nikon SMZ 1000 stereomicroscope (New 1998). The specimens were sorted into Carabidae, Staphylinidae, and spiders. These were chosen to be used in my study based on their roles in biodiversity above ground arthropod abundance and habitat diversity indicators.

Below in (Figure 6), the materials were used in laboratory during the specimen identification were illustrated.

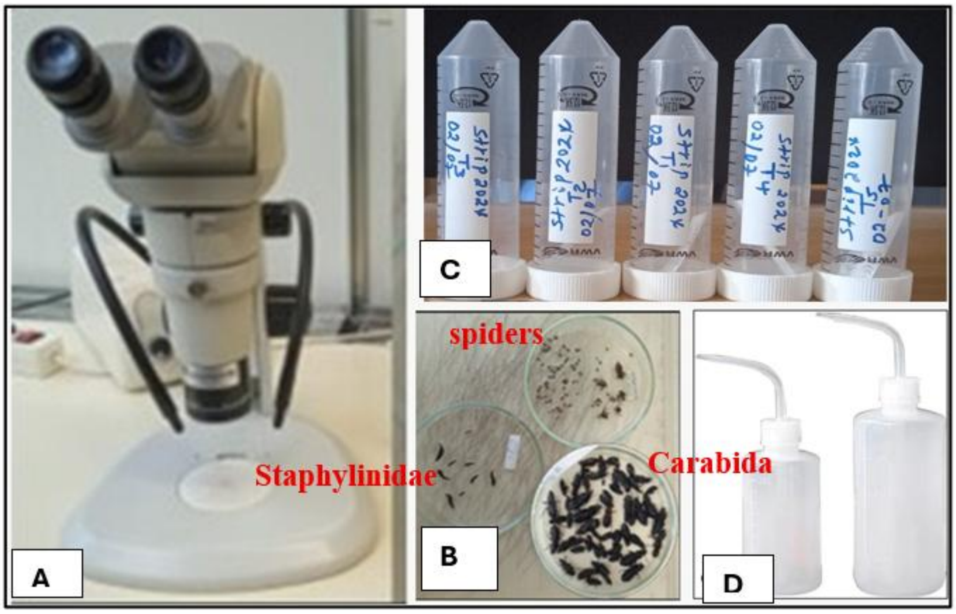

Figure 6. Illustrates the laboratory materials used during identification and sorting of arthropod specimens.

Figure 5(A) shows stereomicroscope used for the detailed observation and identification of arthropod specimens; 5(B) section indicates three Petri dishes displaying sorted arthropod specimens from trap samples. 5(C) indicates the row of labeled centrifuge tubes and bottles containing arthropods preserved in alcohol. 5(D) shows the plastic wash bottles and pipettes, used for handling, cleaning, and processing specimens.

3.4.2. Weed dry matter biomass

To quantify the impact of intercropping (IC) on suppressing weeds, samples of every sole strip cropping (SSC) and IC treatment strips, and reference (Ref) plots were collected, and weed biomass was collected from a 0.5 m² quadrat at every sampling plots. Employing similar 0.5 m² quadrats and the use of uniform harvesting procedures in all the plots raised the credibility and comparability of data (Kolb et al. 2012). The sampling was carried out on four consecutive days, 29th July to 1st August 2024. The sampling was carried out at every 10-meter interval along the 100 m length of the strips, thus providing 10 sample points for each strip. In the reference plots, winter wheat (Ref-W), winter oilseed rape (Ref_ R) and winter pea (Ref_P), five sample points were harvested from each plot: four samples at 2 meters from each corner, and one sample from the center. This sampling strategy was followed to make sure that the data were representative of the whole plot. Out of a total of 215 weed biomass samples 212 were examined. Three of the (R+P), (W+P), and sole strip cropping winter wheat (SSC_W) samples were lost and recorded as "NA" in the data. All weeds in a quadrat were trimmed at the ground level using pruning shears and placed directly into pre-labeled paper bags. Paper bags were utilized as they are permeable, allowing for air passage and avoiding the collection of moisture, thereby eliminating any chances of mold formation or contamination of samples during storage and transportation (Jones & Muehlchen, 1994). A hot air oven at a temperature of 60°C was used to oven-dry for 48 hours, or until constant weight was reached (Cornelissen et al. 2003; Tecco et al. 2013). Then the dried biomass was weighed using the Sartorius 3713, a precision digital balance with ±0.01 grams. The Figure 6 below indicates the dominant weeds found in the research site.

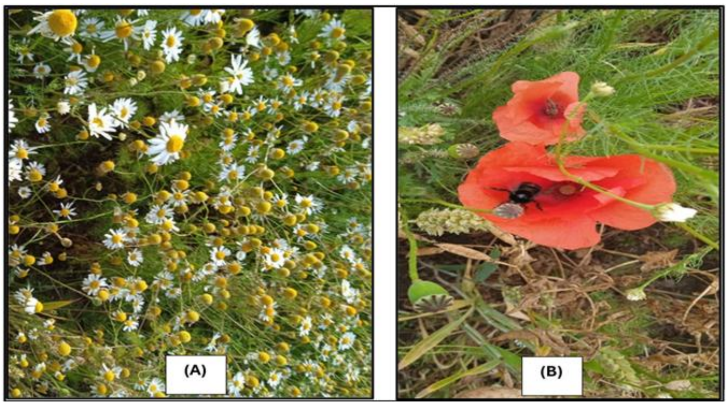

Figure 7. Representative weed species observed and sampled from the research site for biomass analysis.

The dominant weed types observed at the research site were figure 7(A), German chamomile (*Matricaria chamomilla*), which formed a dense ground cover and 7(B), common poppy (*Papaver rhoeas*) as illustrated in Figure 7above.

3.4.3. Crop dry biomass

To measure aboveground dry matter crop biomass, crop samples were collected from the same plots and quadrat size used for weed biomass sampling and following the same procedure. However, the intercropping treatment samples were separated into two distinct by crop types to evaluate the dry biomass and gain yield separately. Because this enabled us to assess and compare the cropping systems of the individual crop growth performance with the treatments on the sole strip cropping (SSC) system. In addition, this approach enables us to determine and quantify the contribution of each crop to the total dry biomass accumulation (Lithourgidis et al. 2011a). Based on this, from a total of 295 samples 293 crop biomass samples were analyzed. Two samples, one from the intercrop of winter wheat-winter pea (W+P) strip and one from the sole strip of winter wheat (SSC- W), were lost and recorded as "NA"). The Figure 8 below shows the material and technique used during the weed and crop biomass sampling.

Figure 8. Crop and weed biomass sampling in a research field plot using the quadrat method.

Figure 8 above illustrates A metal quadrat frame (0.5 m²) was placed on the ground to delineate the sampling area within the crop stand. Pruning shears were used to clip all aboveground plant material within the quadrat.

3.4.4. Grain yield

After the crop biomass was harvested from the 0.5 m² quadrats, oven hot air-drying was dried at 60 C^{O} until a constant weight was achieved. After that crop samples threshing was done to research grain yield (kg ha^{-1}) per treatment. A total of 293 crop yield samples were obtained. Grain yields were obtained from winter wheat (W); after the spikes were manually separated, it trashed using a threshing machine. However, winter pea (P) and winter oilseed rape (R), were threshed manually. For treatment-level yield comparisons, grain weights were standardized to a per-hectare base and recorded immediately after threshing using a Sartorius 3713 precision digital balance (±0.01-gram accuracy).

3.5. Evaluation of land equivalent ratio (LER)

According to Cortés-Mora et al. (2010), the land equivalent ratio (LER) is widely recognized as a key indicator of land-use efficiency in intercropping (IC), as it compares the productivity of crops grown in intercropping systems with that of the same crops cultivated separately under sole cropping. Equation (1) illustrates how LER, assesses the productivity of intercropping in comparison to sole cropping, was determined, as explained by Ofori & Stern (1987):

$$\mathbf{LER} = \sum_{\mathbf{n=1}}^{\mathbf{n}} \frac{\mathbf{Y_i}\,(IC)}{\mathbf{Y_i}(SSC)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (\mathbf{1})$$

Where: n = number of different crops intercropped, Y_i *(SSC),* =The yield for the i^{th} crop under intercropping, Y_i *(SSC)* = The yield for the i^{th} crop under sole strip cropping system on the same area. In order to compute the LER and evaluate land-use efficiency in our study, we deduced Equation (2,3,4, 5 and 6) from Equation (1).

$$\boldsymbol{Partial}\ \mathbf{LER-W} = \frac{\mathbf{YW}(IC)}{\mathbf{YW}\ (\mathrm{SSC})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (\mathbf{2})$$

$$\mathbf{Partial\ LER-P} = \frac{\boldsymbol{YP}\ (IC)}{\boldsymbol{YP}\ (\mathrm{SSC})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots. (\mathbf{3})$$

$$\mathbf{Total\ LER-W+P} = \frac{\mathbf{YW}(IC)}{\mathbf{YP}\ (\mathrm{SSC})} + \frac{\mathbf{Yp}\ (IC)}{\mathbf{Yp}\ (SSC)} \ldots\ldots.\ldots\ldots..\ldots..\ldots\ldots\ldots\ldots\ldots\ldots. (\mathbf{4})$$

$$\boldsymbol{Partial}\ \mathbf{LER-R} = \frac{\mathbf{YR}(IC)}{\mathbf{YR}\ (\mathrm{SSC})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (\mathbf{5})$$

$$\mathbf{Partial\ LER-p} = \frac{\mathbf{YP}\ (IC)}{\mathbf{YP}\ (SSC)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots. (\mathbf{6})$$

$$\mathbf{Total\ LER\_(R+P)} = \frac{\mathbf{YR}(IC)}{\mathbf{YR}\ (\mathrm{SSC})} + \frac{\mathbf{YP}\ (IC)}{\mathbf{YP}\ (SSC)} \ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots\ldots\ldots\ldots. (\mathbf{7})$$

Where: W+P=Winter wheat intercropped with winter pea, R+P=Winter oilseed rape intercropped with winter pea, P+W=Winter Pea intercropped with wheat.

The LER, which was computed using the equation (1-7) above was used to assess the yield advantage of intercropping (IC). Each crop's yield in the IC system was compared to its yield of sole strip crop. In particular, the yield under intercropping (IC) was divided by the yield of each sole strip-cropped species per unit area. This shows how much land of sole strip cropping needs to match the yield from intercropping system. Intercropping is considered as more efficient in land use when the LER value is >1, whereas sole cropping is more effective when the LER value is <1, and if it becomes 1 indicates the two cropping systems are equally efficient as described by Mead & Willey (1980).

3.6. Statistical analysis

All data were processed in Microsoft Excel and analyzed in R (R Core Team, 2021) using RStudio. Abundance estimates of aboveground-dwelling arthropods were examined using Generalized Linear Mixed Models (GLMMs) within the glm TMB package. Since the arthropod abundance was non-normal and over dispersed, negative binomial error structure was selected, and this is the recommended for ecological count data (Zuur et al.2009). The models included cropping system intercropping (IC), sole strip cropping (SSC) and reference plots (Ref), and their treatment-level as fixed effect and (1|Block/as a random effect to account for the randomized complete block design. Above ground dwelling arthropods count data were log-transformed prior to analysis to further improve normality and fit of the model. Model diagnostics (residuals, zero-inflation, and random effects structure) were performed using the DHARMa package. Where the cropping system effect was substantial, post hoc estimation comparisons were conducted with emmeans package and Tukey's adjustment (Lenth 2022),with reference plots treated as the baseline.

Linear Mixed Model (LMM) were also fit for weed dry biomass, crop dry biomass, and grain yield in lme4 package (Bates et al. 2015), crop system or treatment as fixed and block as random factors. These variables were not log-transformed since model diagnostics for normality and homoscedasticity of their residuals had no requirement for transformation. Test for significance of the fixed effects was conducted using Satterthwaite's approximation of degrees of freedom within the lmer Test package (Kuznetsova et al. 2017). When such treatment effect was found to yield significant p-values < 0.05, then emmeans with Tukey's correction for comparisons was derived.

Direct calculation from mean yield was employed to derive the LER using the formula standard by Mead & Willey (1980) and partial LER for each crop and total LER for all combinations of intercropping. Intercepts of LERs greater than one was considered as estimates of land use advantage in intercropping. Correlation analysis was also analyzed to determine the linkage among above ground dwelling arthropod abundance, weed biomass, crop biomass and grain yield across treatments.

All graphical visualizations were produced in R using ggplot2, with bar plots displaying Total mean means count ± standard errors (SE) for above ground dwelling arthropod counts, weed and crop dry matter biomass (kg ha^{-1}), and grain yield (qt ha^{-1}). The bars plots with standard error pairwise were conducted using Tukey's HSD post-hoc tests to identify differences among the cropping systems and the treatments. The significance letters shown in figures correspond to results from these post-hoc comparisons Statistical group letters or asterisks were used to indicate significant differences. Significance levels were denoted as: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, and ns = not significant ($p > 0.05$).

4. Result

4.1. The effects of intercropping (IC) on abundance of aboveground-dwelling arthropods

17,100 aboveground-dwelling arthropods were trapped using pitfall traps. The collected arthropods were classified into three functional groups: Staphylinidae, Carabidae, and spiders. Spiders were dominant (62.5%) of the total capture, followed by Carabidae at 27.9%, and Staphylinidae accounting for 9.6% as indicated in (Appendix5). But for aboveground dwelling arthropod abundance analysis, I use the total of the functional groups.

The results indicated a very significant difference between the three cropping patterns of intercropping (IC), sole strip cropping (SSC) and reference plots (Ref), as indicated in (Figure 9) below. Figure 9 below indicates that the IC system had the most abundant, from SSC and Ref. SSC had significantly abundant values than the Ref plots.

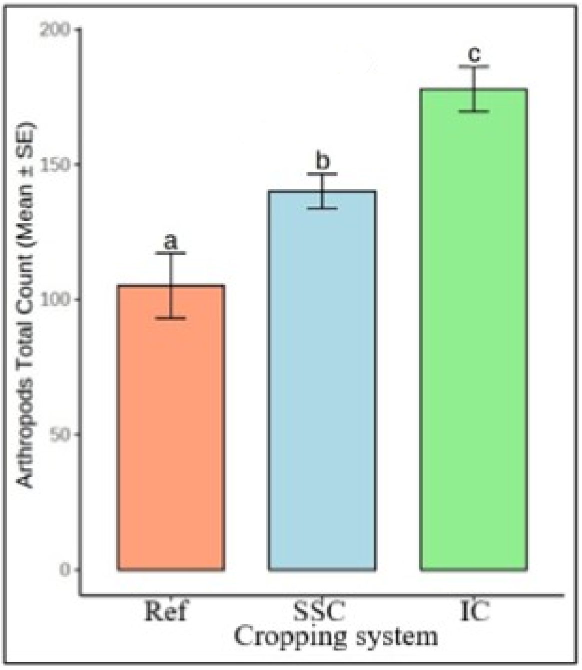

Figure 9. Total mean (±SE) total abundance of above-ground-dwelling arthropods across cropping systems Reference (Ref), sole crop (SSC), and intercrop (IC). Different letters above bars indicate significant differences among systems within each panel and sharing the same letter indicates not significantly different among them (Tukey's HSD test, $p < 0.05$).

Generalized Linear Mixed Model (GLMM) analysis was conducted to identify the significant difference across cropping systems of intercropping (IC), sole strip cropping (SSC) and Reference (Ref) plots. The analysis confirmed that IC cropping systems were indicated statistically significantly abundant compared to the SSC and Ref plots. The statistical grouping indicated by different letters (a, b, and c) above the bars demonstrates significant difference among the cropping systems (p < 0.05 In the analysis Ref were taken as the baseline (table 1 below).

*Table 1. Generalized Linear Mixed Model (GLMM) analysis results of above ground dwelling arthropod abundance (log-transformed). Displayed are the model estimates, standard errors (SE), z values, p values, and significance levels (**p < 0.01, ***p < 0.001)*

Arthropod abundance across Cropping system	Estimate	SE	z value	P-value	Significance
Ref-(Intercept)	4.655	0.094	49.613	<0.001	***
IC	0.526	0.110	4.803	<0.001	***
SSC	0.287	0.105	2.741	0.006	**

Table 1 above describes the IC indicated highly significant of above ground arthropod abundance compared to the Ref plots (p < 0.001). And sole strip cropping (SSC) indicated significant difference from reference (Ref) plots (p = 0.006). The direct comparison between intercropping (IC) and sole strip cropping system (SSC) treatments revealed that IC had a higher arthropod abundance than SSC system.

Based on this analysis meaning across treatments indicated that the cropping system had significant effects on aboveground-dwelling arthropod abundance on treatments winter wheat (W) and winter oilseed rape (R), as in indicated in bar plot Figure 9(A-B) respectively, IC treatments supporting significantly abundant compared to SSC (Figure 10) below. However, treatment winter pea (P) Figure 10 (C), although it shows numerical difference, but doesn't show any significant difference among the treatments.

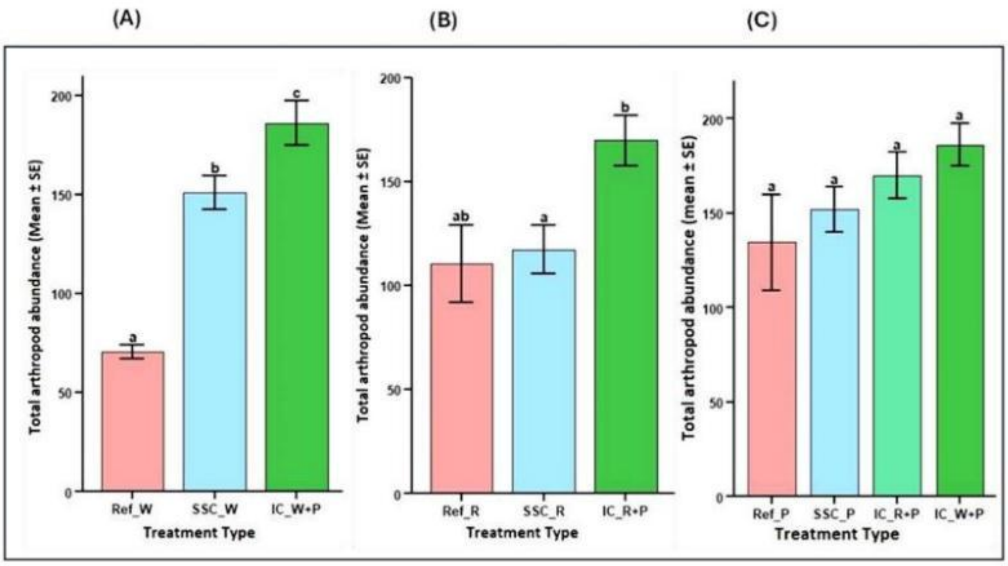

Figure 10. Total Mean (±SE) total abundance of above-ground-dwelling arthropods across different cropping systems and treatments. Different letters above bar plot indicate significant differences among treatments with each panel and sharing the same letter indicates not significantly different among them (Tukey's HSD test, p < 0.05).

Figure 10 (A) above in winter wheat (W) treatments: Intercropping of winter wheat and winter pea (IC_(W+P)) supported the highest abundance, followed by sole strip cropping sole strip winter wheat (SSC_W), while reference winter wheat plot (Ref_W) had the lowest.

In winter oilseed rape (R) treatment Figure 10 (B): Intercropping of winter oilseed rape with winter pea (IC_R+P) also had significantly higher abundance compared to winter oilseed rape (SSC_R), but they do not indicate significant variation with its winter oilseed rape reference (Ref_R).

In winter pea (P) treatments Figure 10 (C): No significant differences were observed among the treatments, the (Ref_P, SSC_P, IC_(R+P), and IC_(W+P).

The GLMM (Appendix1) analysis revealed the results as indicated in the bar plots illustrated in Figure 10 above. Treatments winter pea (P): Neither IC_(R+P) nor SSC_P indicated a significant difference from Ref_P, although, IC_(W+P) showed a marginally significant, with an estimated 38.4% relative to Ref_P ($p = 0.048$).

Winter oilseed rape (R) treatments IC_(R+P) indicated significantly higher arthropod abundance than Ref_R ($p = 0.048$), while SSC_R was not indicted significant difference. In the winter wheat (W) treatments, both IC_(W+P) and SSC_W showed significantly higher arthropod abundance than Ref_W, with increases of about 162% ($p = 0.001$), and 113% ($p = 0.001$), respectively (Appendix 1).

4.2. The effects of intercropping (IC) on suppression of weed

To determine the effect of intercropping (IC), on weed suppression at system-level, analysis was conducted at the three cropping systems: intercropping (IC), sole strip cropping (SSC), and the reference (Ref) as illustrated in figure 11 below.

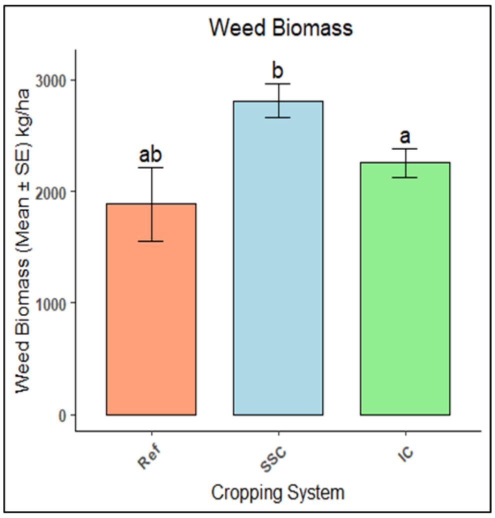

Figure 11. Mean value of weed dry mater biomass (mean ± SE) kg ha -1 across the cropping systems of Sole cropping (Ref), Sole strip cropping (SSC), and intercropping (IC). Different letters above bar plot indicate significant differences among treatments and

sharing the same letter indicates not significantly different among them (Tukey's HSD test, p < 0.05).

The results presented in the bar plot in Figure 11above indicate that weed dry matter biomass varied significantly across the cropping systems. Sole strip cropping (SSC) gained the highest weed biomass, which was significantly greater than intercropping (IC). On the other hand, intercropping recorded the lower than SSC. The Sole cropping or reference plot (Ref) showed intermediate weed biomass, which was not significantly different from either SSC or IC. as indicated by the shared letter "ab." Further analysis, linear mixed model (LMM (Table 2 below), was conducted to investigate the statistically significant difference among the cropping systems. Based on the analysis weed biomass under SSC indicated marginally significant difference from Ref but IC was not significantly varied with the intercept baseline of the reference.

Table 2. Fixed effect estimates from the linear mixed model (LMM) evaluating the effect of cropping system on weed biomass. The baseline biomass (intercept) was highly significant (p < 0.001), SSC significantly increased weed biomass (p < 0.05), while IC showed no significant effect.

Weed biomass by cropping system	Estimate	Std. Error	t value	P value	Significance
(Intercept)	1887.2	428.07	4.40	<0.001	***
IC	368.33	455.35	0.80	0.422	Ns
SSC	926.93	461.22	2.00	0.049	*

From the above LMM analysis (table 2), the interception baseline weed biomass under the reference cropping system, was highly significant (Estimate = 1887.2, p < 0.001). Intercropping (IC) did not affect weed biomass significantly compared to the reference system (estimate = 368.33, p = 0.422). The SSC cropping system significantly increased weed biomass relative to the baseline (estimate = 926.93, p = 0.049). These results indicate that while IC had no significant impact-meaning relatively reduced weed suppression-SSC promoted significantly higher weed biomass relative to the baseline.

Since there was variation among the cropping systems, further analysis was done for individual treatments; even in the intercropping treatments, the intercropped treatments were analyzed separately and not as a combined treatment to show their specific effects. The variation in crop dry biomass among the different treatments statistical significance is indicated by different letters (a, b, ab) above the bar's plots.

Results showed that at the treatment level, numerical variation among the crop treatments occurred consistently except for winter peas (P), which showed a statistical difference. These were shown in detail below, Figure 12A -C. Different letters above the bars indicate significant differences among the treatments within each cropping system (p < 0.05).

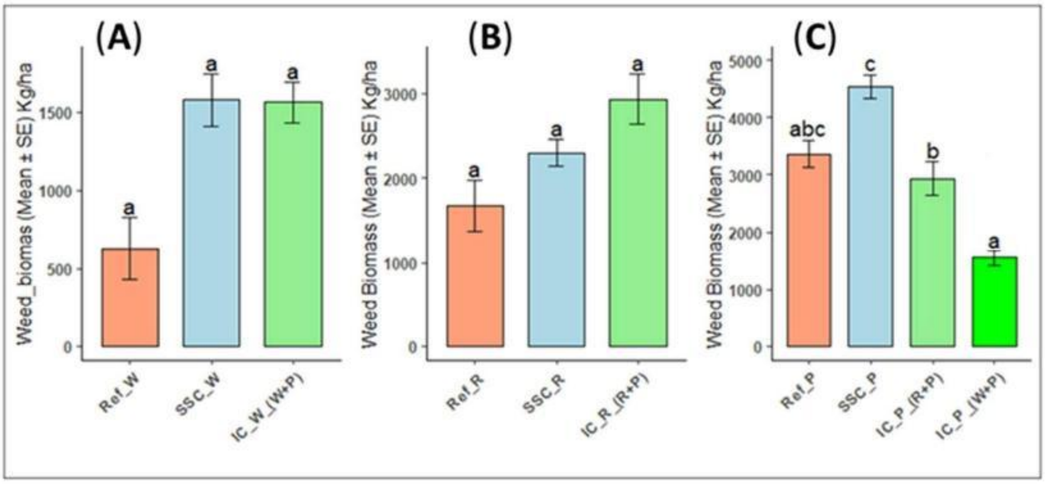

Figure 12. Mean value of weed dry mater biomass (mean ± SE) kg ha -1 across the treatments of winter wheat (W), winter oilseed rape (R) and winter pea (P) treatments indicated by the bar plots (A, B and C). The different letters above bar plot indicate significant differences among treatments and shared the same letter indicates not significantly different among them (Tukey's HSD test, p < 0.05).

Figure 12 (A-B) bar plot indicated weed biomass responses across the treatments. Based on this, winter wheat treatments in Figure 12(A): Indicated that there were no significant differences among the treatments. But, numerically weed biomass was lowest in the reference winter wheat (Ref_W) treatment.

In winter oilseed rape (R) treatments (12B): Similarly to treatments of winter wheat (Figure 12A) significant difference were not observed. But, weed biomass was lowest in the reference winter oilseed rape (Ref_R), intermediate under the sole strip cropping of winter wheat (SSC-R), numerically higher in winter wheat under the intercropped with winter pea (IC_R-(R+P) treatment. In contrast, for winter pea treatments (12C), there were distinct treatment effects: Sole strip winter pea (SSC_P) supported the most weed biomass, whereas with winter oilseed rape (IC_R_(R+P)) and winter wheat (IC_P_(W+P)) resulted in the least biomass. Mainly winter pea intercropped with winter wheat (IC_P_(P+W) indicated the highest weed-suppressed treatment.

Further analysis was therefore done using a linear mixed model (LMM) in order to investigate the variable response of weed biomass to the various cropping treatments. LMM analysis prediction indicated that weed biomass responses differ with the individual treatments are described in (Appendix 2) below. The linear mixed model analysis showed that variable responses of weed biomass to various cropping treatments. In the winter wheat (W) treatments, weed biomass tended to increase under winter wheat (IC_W_(W+P)) and sole strip cropped winter wheat (SSC_W), compared with the baseline, although these effects were not significant ($p = 0.097$ and $p = 0.094$, respectively). In the treatments sole strip cropping of winter oilseed rape (R), the intercept was significant ($p = 0.017$), indicating a positive baseline effect on weed biomass, while winter oilseed rape was intercropped with winter pea (IC_R_(R+P)) showed a marginal, but non-significant, increase ($p = 0.085$). In the treatment winter pea (P) treatments, the intercept was highly significant ($p < 0.001$), reflecting high baseline weed biomass. Notably, the treatment of winter pea under inter-cropped with winter wheat (IC_P_ (W+P)) indicated a significantly reduced weed biomass as compared with the baseline (estimate = -1802.18, $p = 0.022$). While the winter pea under inter-cropped with winter oilseed rape (IC_P_ (R+P)) and sole strip winter pea (SSC_P) showed no significant effects. Overall, only one treatment, winter pea (IC_P_(W+P)), had a significant reduction in weed biomass, while the other treatments did not differ significantly from their respective reference systems.

4.3. Effects of intercropping (IC) on crop dry biomass accumulation

To assess the effect of intercropping (IC) on crop dry biomass accumulation, mean values (±SE) were analyzed as presented in bar plots (Figure 13). The analysis was made for each individual treatment even though the intercropped (IC) treatments were also analyzed separately to highlight their specific effects. These findings indicated that sole strip cropping (SSC) increased biomass in winter wheat (W) and winter oilseed rape (R) treatments, whereas intercropping (IC) treatments, particularly winter pea under intercropping with winter wheat (IC_P _(W+P)), resulted in higher biomass in the winter pea (P) treatments. Even their seed density was 50% less than their sole strip cropping (SSC) and reference (Ref) plots. The variation in crop dry biomass among the different treatments statistical significance is indicated by different letters (a, b, ab) above the bars.

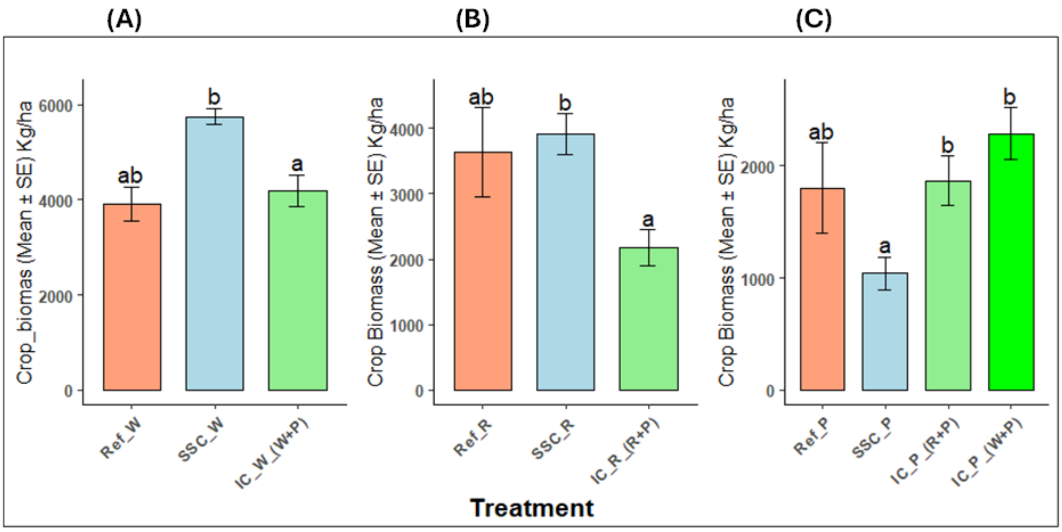

Figure 13. Mean crop dry biomass (± SE) kg ha -1) under different treatments across the bar plots of (A, B and C). Different letters above bars indicate the individual treatments of statistically significant differences based on post hoc mean separation ($p < 0.05$).

Figure 13(A–C) shows that crop biomass responses varied among the treatments depending on the cropping system. For winter wheat (Figure 13A), sole strip cropping (SSC_W) produced the highest wheat biomass, which was significantly greater than that of winter wheat grown in intercrop with pea (IC_W_(W+P)). The reference wheat treatment (Ref_W) showed intermediate values and did not differ significantly from either SSC_W or IC_W_(W+P). It should be noted that IC_W_(W+P) was sow at 50% seeding density, whereas SSC_W and Ref_W were established at full seeding density. For winter oilseed rape (Figure 13B), sole strip cropping (SSC_R) produced the highest oilseed rape biomass, significantly greater than oilseed rape in intercrop with pea (IC_R_(R+P)), while Ref_R was intermediate and not significantly different from either treatment. Both SSC_R and Ref_R were sow at full seeding density. In contrast, for winter pea (Figure 13C), intercropping with winter wheat (IC_P_(W+P)) produced the highest pea biomass, significantly greater than sole strip pea (SSC_P). Both Ref_P and pea intercropped with oilseed rape (IC_P_(R+P)) showed intermediate values and were not significantly different from either SSC_P or IC_P_(W+P). Importantly, IC_P_(W+P) was sow at 50% seeding density, whereas SSC_P, Ref_P, and IC_P_(R+P) were all at full seeding density.

To identify the statistically significant of the intra-individual differences among crop biomass individual treatments were analyzed using LMM. Treatments of intercropping were handled as individual treatments following sole strip and reference systems rather than being combined categories. The intercepts were present in all control treatment references, denoting baseline crop dry biomass of winter wheat (Ref_W: Estimate = 3906.8, $p = 0.046$), winter oilseed rape (Ref_R: Estimate = 3628, $p = 0.037$), and winter pea (Ref_P: Estimate = 1802, $p = 0.012$). In winter wheat application, inter-cropped winter wheat (IC_W_(W+P)) and sole strip wheat (SSC_W) did not significantly differ from Ref_W ($p = 0.857$ and $p = 0.285$, respectively). Similarly, during winter oilseed rape uses, IC_R_(R+P) and SSC_R were also not different from Ref_R significantly ($p = 0.358$ and $p = 0.851$, respectively).

In winter pea treatments, neither IC_P_(R+P), IC_P_(W+P), nor SSC_P significantly differed from Ref_P (all $p > 0.05$). Overall, while the baseline reference treatments were associated with significant crop biomass, none of the intercropped or sole strip treatments produced significant deviations from their respective references (Appendix 3)

4.4. Effect of intercropping (IC) on grain yield compared to sole strip cropping (SSC)

The mean values (±SE) were analyzed to assess the effect of intercropping (IC) on crop dry biomass accumulation, and presented in bar plots, Figure 14. Winter wheat and winter pea (W+P) intercropping were each sow at 50% of their sole crop seeding density. Based on this, the grain yield indicated variation across treatments. The sole strip cropping (SSC) favored grain yield under winter wheat (W) and winter oilseed rape (R) treatments. In contrast to this result, under pea treatment, the IC result indicated better benefit.

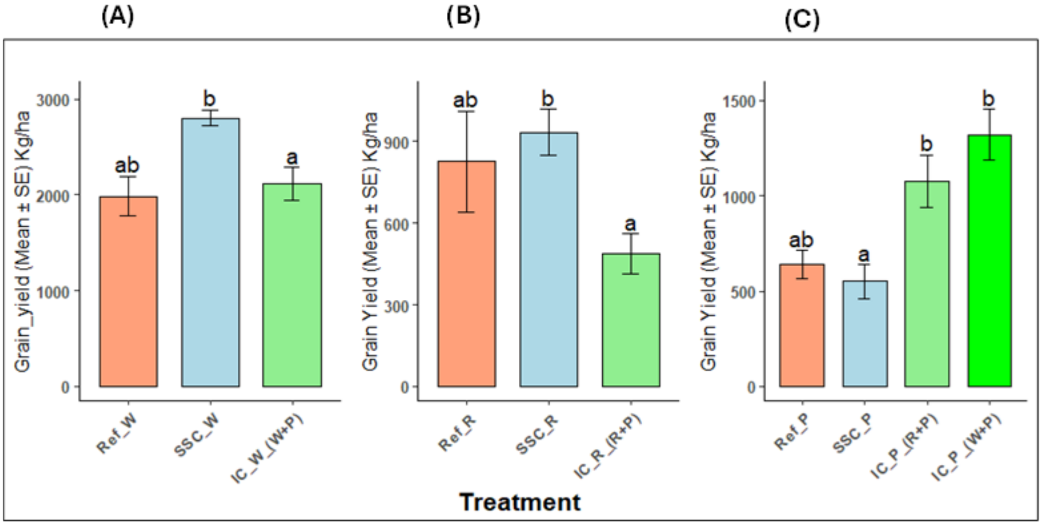

Figure 14. Grain yield (mean ± SE, kg ha⁻¹) of winter wheat (A), winter oilseed rape (B), and winter pea (C) under reference (Ref), sole strip cropping (SSC), and intercropping (IC) systems. The small letters a, b, ab above the bars indicates statistically significant differences among treatments ($p < 0.05$)

The bar plots illustrated in Figure 14 (A-C) above show that the effects of intercropping (IC) on grain yield differ depending on the treatments. For winter wheat (W) treatments Figure (14A), the sole strip cropping treatment of winter wheat (SSC_W) achieved significantly higher grain yield than intercropped winter wheat (IC_W_(W+P)), while the reference treatment (Ref_W) indicated intermediate yields.

Similarly, for winter oilseed rape (R) treatments Figure 14 (B), The sole strip cropping treatment of winter (SSC_R) indicated more than the intercropped of winter oilseed rape (IC_R_(R+P)), with Ref_R again being intermediate.

Similarly, for winter oilseed rape (R) treatments Figure 14 (B), The sole strip cropping treatment of winter (SSC_R) indicated more than the intercropped of winter oilseed rape (IC_R_(R+P)), with Ref_R again being intermediate.

The linear mixed model (LMM) analysis indicated that grain yield responses varied across treatments, but most effects were not statistically significant (Appendix A4). In the winter wheat (W) treatments, The analysis indicated the intercept was marginally significant (estimate = 1986.8, $p = 0.054$), while neither the result of winter wheat intercropped with winter pea (IC_W_(W+P)) nor sole strip winter wheat (SSC_W) showed significant effects on grain yield ($p = 0.884$ and $p = 0.362$, respectively).

In the winter oil rape seed (R) treatments, the intercept was significant (estimate = 826, $p = 0.035$), indicating a positive baseline effect, but both the result of winter oilseed rape intercropped with winter pea (IC_R_(R+P) and sole strip winter oilseed rape (SSC_R) were non-significant ($p = 0.356$ and $p = 0.763$, respectively). In the winter pea (P) treatments, the intercept was not significant (estimate = 638, $p = 0.141$), and none of the treatments winter pea in the intercrop with winter oilseed rape (IC_P_(R+P), intercrop with winter wheat IC_P_(W+P), and sole strip (SSC_P) showed significant differences from the reference (all $p > 0.05$). See in detailed results in (Appendix A4).

4.5. Land equivalent ratio (LER)

Land Equivalent Ratio (LER) was used to analyze the efficiency of land use of strip intercropping systems by comparing the grain yields of sole crops and intercrops. Table 5 below is describes the partial and total Land Equivalent Ratio (LER) values for winter wheat (W) + winter pea (P) and winter oilseed rape (R) + winter pea (P) intercrop systems. Partial LER represents the relative yield advantage of the individual crop component in intercropping compared to its sole strip cropping system, while total LER is the sum of partial values. A result LER > 1 indicates a high land use efficiency, LER = 1 indicates no advantage or the same, and LER < 1 indicates a disadvantage of the intercropping system.

Table 5. Partial and total Land Equivalent Ratio (LER) values.

Intercrop	Crop Component	Partial LER	Total LER
Winter wheat + Winter Pea (W+P)	Winter wheat (W)	0.75	3.15
	Winter Pea (P)	2.40	
Winter Oilseed Rape + Winter Pea (R+P)	Winter Oilseed Rape (R)	0.52	2.47
	Winter Pea (P)	1.95	

The LER analysis showed the land use advantage of intercropping systems as indicated in (Table 5). For winter wheat (W) + winter pea (P), the partial LER values were 0.75 for winter wheat and 2.40 for winter pea, which amounts to an overall LER of 3.15. Similarly, under winter oilseed rape (R) + winter pea (P) system, partial LER values for winter oilseed rape and winter pea were 0.52 and 1.95, respectively, and hence total LER = 2.47. Both the inter-crop mixtures were greater than unity (LER > 1).

4.6. Correlation of the Arthropods, Weeds and crop performance

To examine the relationship of crop performance, competition with weeds, and arthropod abundance, a correlation analysis was conducted. The analysis measured the strength and direction of association between the biomass of crops, grain yield, weed biomass, and arthropod density Figure 14 below shows their exact correlation.

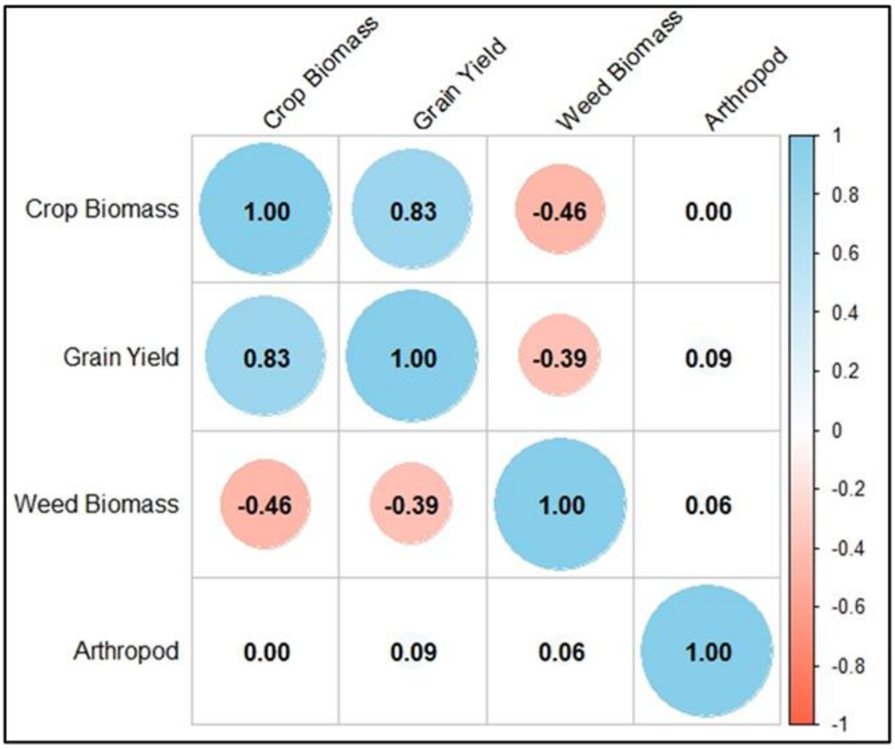

Figure 15. Correlation matrix shows a strong and positive correlation of crop biomass with grain yield, negative correlations of weed biomass, and weak relationships with arthropod abundance.

Strong and positive relationship between grain yield and crop biomass (r = 0.83) was shown by the correlation study, indicating that higher crop biomass was strongly related to higher grain yield. On the other hand, weed biomass had moderate negative correlations with crop biomass (r = -0.46) and grain yield (r = -0.39), meaning that more weed biomass reduced crop growth and yield. Arthropod density had only weak and non-significant correlations with crop biomass (r = 0.00), grain yield (r = 0.09), and weed biomass (r = 0.06) in the sense that little relationship with the variables seemed to exist.

5. Discussion

5.1. The effects of intercropping (IC) on abundance of aboveground-dwelling arthropods

The findings of this study strongly confirmed that the hypothesis of intercropping (IC) production systems enhances higher aboveground-dwelling arthropod abundance across the cropping systems than sole strip intercropping (SSC) and the reference (Ref) plots. A total of 17,100 individuals were taken into account and were dominated by spiders, carabid beetles, and staphylinids respectively. Such predominance is expected, as such spiders are among the most functionally important natural enemies within temperate agroecosystems as per Symondson et al. (2002) documented. Among the tested cropping systems, IC supported more arthropods abundance than both SSC and Refs. The Generalized leaner mixed model (GLMM) confirmed that IC had about 27% and 69.2% more abundance than SSC and Ref Respectively. Plus, SSC system showed 33.3% more abundance than Ref plots. These results indicated that more diversifying crops have, more above ground dwelling arthropod abundance. Because crop diversification enhances living habitats for aboveground arthropods. This aligns with previous research documented by Letourneau et al. (2011) and Rakotomalala et al. (2023) as polycultures hosting higher arthropod abundance than sole cropping systems. In support to this, as per Gurr et al. (2017) described, the positive response to IC is most likely due to increased structural heterogeneity, diversified canopy framework and greater ground covers. Thus, it might create microhabitats, reducing temperature extremes, desiccation stresses. And, intercrops tend to increase food resource availability in terms of space and time (Birkhofer et al. 2008)**.**

GLMM analysis further confirmed this effect at treatment level that arthropod abundance was observed significantly high in IC treatments (Figure 10 A&B). Mainly the IC of winter wheat with winter pea yielding statistically significant positive estimates ($p < 0.001$), highlighting the strong promoting arthropod abundance were 43% and 162% higher than winter wheat shown in SSC, and is sole cropping plot (Ref_W) respectively.

This result is also aligned with Previous research that has shown that cereal-legume IC enhances predator activity and supports natural pest control as compared to sole cropping. For instance, more abundant generalist predators (Carabidae, Staphylinidae, and spiders) were reported in IC than in sole-cropped wheat production (Puliga et al., 2021). The observation implies that the growth morphology of individual crops, meaning canopy structure govern the effect of intercropping on arthropod abundance (Birkhofer et al. 2008)**.** Similarly, winter oilseed rape-winter pea IC supported higher arthropod abundance than winter oilseed rape in sole strip and Ref plots with significant treatment-level effects ($p = 0.048$). But the abundance of dwelling above ground arthropods comparisons among winter pea treatments did not reveal significant differences. Nonetheless, numerical increases were observed in winter oilseed rape and winter pea intercrops.

The absence of statistical significance may be attributed to the relatively small sample size, as per previous studies described by Järvinen et al. (2023) like statistical significance is frequently lacking due to high variability, small sample numbers.

As described by Letourneau et al. (2011), IC of cereal-legume enhances abundance of beneficial insects, which helps with natural pest control. And reduces the use of chemical pesticides. The results of this study are in line with these findings, suggesting that IC can enhance biological pest control and enhance crop performance while limiting external input usage. Likewise, Altieri (1999) observed that such cropping systems of the ecological type enhance soil fertility and biodiversity conservation, as the same time as Wezel et al. (2014) asserted that it supports cost savings in production and long-term sustainability. Combined, these research findings point towards the possibility of IC in terms of soil health sustenance and resilient agroecosystem development.

5.2. The effects of intercropping (IC) on weed suppression

Weed suppression differs considerably among treatment. Based on the cropping system, sole strip cropping (SSC) tends to indicate more dry weed biomass than IC Figure 11. Linear mixed model (LMM) analysis showed that SSC increased weed biomass over the intercept of reference ($p = 0.049$), but IC was not significantly different from the reference ($p = 0.422$). This means IC decreased weed biomass compared to SSC. But the effect was not strong enough to indicate statistically significant. These trends in line with previous research showing as IC suppresses weeds more than sole cropping through advancing canopy closure, enhancing soil resource capture, and shading the ground surface, which influences the soil unfavorably to germination of weeds (Liebman & Dyck 1993).

In winter wheat treatments Figure 11A both SSC and IC had more weed dry biomass than the reference plot (Ref) treatment, although these differences were not statistically significant ($p = 0.094$ and 0.097, respectively). This may be due to the high inherent competitiveness, resulting from a fast and dense tiller structure of winter wheat's which provided enough weed suppression (Hauggaard-Nielsen et al.2001). In this case, IC of winter peas to winter wheat did not significantly improve weed control. This might be due to the 50% Seeding density both winter wheat and winter pea than their sole strip cropping (SSC) and reference (Ref) plots. Additionally, lower growth performance of winter pea compared to its companion crops in the IC system could be offered niches for weed establishment and competition, thus could be lowering the overall potential for weed suppression in the intercrop.

In the winter pea treatment-level analysis Figure 11C, weed biomass of winter pea was measured about 1,560 kg ha^{-1} when intercropped with winter wheat, were as it reached about 4,535 kg ha^{-1} in the SSC. The result indicated about 66% weed biomass reduction under intercropping. This significant difference highlights the strong suppressive effect of IC and supports the view functional complementarity and crop heterogeneity play an important role in reducing weed pressure. Similar results have been reported in earlier studies, where cereal-legume intercrops were found to reduce weed biomass more effectively than sole crops by improving resource use efficiency and canopy closure (Liebman & Dyck, 1993).

On the other hand, the low competitive ability of sole strip-cropped winter pea, characterized by weak canopy cover and slower early growth, may create niches that favor weed establishment (Corre-Hellou et al. 2011). When combined with cereals such as winter wheat, the strong canopy development and rapid nutrient uptake of the companion crop compensated for winter pea's weaknesses, leading to effective suppression of weeds. Plus, weed-suppression through the winter pea-winter wheat IC may be likely to be the result of crop morphological processes through canopy dynamics and resource partitioning. This means vigorous early-season vertical growth of winter wheat creates a dense canopy suppressing light penetration to the soil surface, hence affects the weed germination and emergence (Worthington & Reberg-Horton 2013).

On the contrary, SSC of winter pea indicated the highest weed dry biomass (4,435 kg ha^{-1}) among all treatments Figure 12 (C). Highlighting the weak competitive ability of legumes when planted in sole. Legumes take longer to develop and form open canopies thus may make it prone to more early season weed pressure as described by Liebman et al. (2001)**.** In the case of winter oilseed rape-case Figure 12 (B), intercropping of winter oilseed rape and winter pea, indicted that an implication of low potential weed biomass as compared to its sole strip cropping but not significantly different was observed. As Shah et al. (2016) described, the natural allelopathic effect of crops may suppress weeds. Oilseed rape is one of the crops that can emit allelopathic chemicals. This chemical is considered as eco-friendly natural product used for weed management. However, it might have a negative impact on companion crops and associated weeds similarly as described by (Shah et al. 2016).

From all treatments, winter wheat intercropped with winter pea indicated strong weed suppression. This treatment was also associated with higher arthropod density (Section 4.1). This intersection suggests that intercrops can attain a combination of ecosystem services at the same time, including suppression of weeds, enhance to natural enemies' abundance, and reasonable grain yields. Synergies of this kind are consistent with outcomes of diversified cropping systems such as explained by Gurr et al. (2017).

5.3. The effects of intercropping (IC) on crop biomass accumulation

The results of this study showed that crop biomass responses varied depending on crop type and cropping system. The treatment responses on crop biomass illustrated in Figure 13 (A-C) indicate that sole strip cropping (SSC) of winter wheat and winter oilseed rape produced significantly higher biomass than their respective intercrops with winter pea. In contrast, the intercrops of winter pea with winter wheat and winter oilseed rape produced significantly higher biomass than the sole strip cropping of winter pea. But, in all Figure 13 (A-C) there has been no indicated significant difference with their reference. Statistical comparisons were conducted to indicate significant difference across treatments, however, the linear mixed model (LMM) analysis confirmed that none of the intercropped treatments deviated significantly from their corresponding references P>0.05 (Appendix 3). The efficiency of IC, and their SSC systems were evaluated relative to their corresponding Ref plots.

The result of winter wheat treatments (Figure 13A) indicates sole strip of winter wheat produced the highest biomass (5749.2 kg ha^{-1}), than Winter wheat (4196.6 kg ha^{-1}) under intercrop (IC) with winter peas, whereas reference winter wheat (3906.8 kg ha^{-1}), indicated lowest values. Despite a 50% seeding density, winter wheat under IC with winter peas achieved 73%, and 107% of its fully seeded corresponding sole strip cropped and reference respectively. This suggests that winter wheat could sustain competitive crop biomass efficiency in IC based on compensatory mechanisms and perhaps favorable interactions with winter pea. Similar previous findings support this. As per Hauggaard-Nielsen et al. (2001) demarcated corresponding compensatory growth of cereals in intercrops, with legumes maintain their biomass due to enhanced nitrogen availability and decreased intraspecific competition.

For winter oilseed rape (Figure 13B), sole strip crop of winter oilseed rape produced the highest crop biomass (3910.8 kg ha^{-1}), significantly greater than Winter oilseed rape (2173 kg ha^{-1}) under IC with winter peas, while its reference (3628 kg ha^{-1} was intermediate. Winter oilseed rape under IC with winter peas, had the same seeding density with its corresponded to about 55% of SSC_R and 60% of Ref_R, indicating that oilseed rape was suppressed under intercropping. The reduction may be related to allelopathic effect of winter oilseed rape as described by Singh et al. (2006) with the potential to inhibit companion crops. In the same way, Génard et al. (2017) as highlighted that although legumes can enhance crop supply, nevertheless this might not necessarily translate to biomass or gain for winter rapeseed, with yields depending on timing and density.

On the other hand, winter pea showed an advantage under IC (Figure 13C). Winter pea under IC with winter wheat produced the highest crop biomass (2,284 kg ha^{-1}) at 50% seeding density, achieving about 219% of from its corresponding Sole strip winter pea (1,040.4 kg ha^{-1}), and equivalent to about 128% of Ref_P (1,802 kg ha^{-1}). Similarly, Winter pea under IC with winter oilseed rape (IC-P-(P+R) produced 1,865.7 kg ha^{-1} but it was at fully seeded. Which indicated about 179% of its sole strip cropping (SSC_P, 1,040.4 kg ha^{-1}) and about 104% of its reference plot (Ref_P,1082 kg ha^{-1}). These results suggest that winter peas benefited significantly from IC, particularly with winter wheat, through niche complementarity and nitrogen fixation.

These are in line with broader literature: Rodríguez et al. (2020) employed meta-analysis to verify that legume-cereal intercrops systematically show nitrogen use complementarity, that builds up legume biomass without decreasing cereal yields. In general, the legume's growth greatly, cereals' filling at low density, and brassicas' suppression are strongly assisted by inter-crop research performed (Bedoussac et al., 2018). These findings indicate that while inter-cropping enhances the efficiency of resource utilization and biomass production in certain species, there are extremely variable responses with crop association, density, and competitiveness. The most beneficial effects of inter-cropping were experienced by winter pea in this study, winter wheat productivity was not affected even when planted at lower density, and winter oilseed rape was competitively inhibited by inter-cropping with winter pea.

5.4. Effects of intercropping (IC) on grain yield

The present study revealed that the effect of intercropping (IC) on grain yield was crop-specific, with differing responses among winter wheat, winter oilseed rape, and winter pea. Although the Linear Mixed Model (LMM) analysis did not identify statistically significant treatment effects across most comparisons (Appendix A4), consistent patterns were observed in the mean yields that provide important insights into the relative advantages and trade-offs of intercropping systems. To determine the advantages of IC on grain yield, relative yield production is evaluated with its correspondent SSC and Ref cropping systems. Based on this, treatment-level comparisons were conducted. For example, winter wheat, under IC with winter pea (Figure 14 A) yielded 2112.1 (kg ha^{-1}) at 50% seeding density which is equivalent to about 75% of its sole strip cropped (2802.7 kg ha^{-1}), and 106% of reference plots (1986.8 kg ha^{-1}). Both the sole strip and reference treatments were grown at full seeding density. This indicates that winter wheat was competitive in grain yield in intercrops despite reduced seeding density due to complementary growth and facilitation provided by winter pea. These types of results have also been seen with other cereal-legume agroecosystems, where wheat intercrops either sustained or augmented yields through improved nitrogen use efficiency and light capture (Bedoussac & Justes, 2010). Additionally, as per Brooker et al. (2015) also emphasized that cereals often compensate in intercrops by exploiting complementary resource niches provided by legumes, thereby stabilizing yields under low-input conditions.

Winter pea showed better performance under IC with winter wheat (Figure 14 C) yielded 1321 kg ha^{-1}, corresponding to about 240% of its sole strip cropped (551.1 kg ha^{-1}), and about 207% of Reference plot (638 kg ha^{-1}). Similarly, under winter oilseed rape-winter pea intercrop, winter pea yielded (1077 kg ha^{-1}), or about 195% of its correspondent sole strip cropping (551.4 kg ha^{-1}) and 169% of reference (638 kg ha^{-1}). These results highlight the efficiency of winter pea in intercrops, mainly with winter wheat, where structural and resource complementarity supported legume productivity. This finding that winter pea performed strongly in intercrops, particularly with cereals, is in line with previous studies showing similar advantages. As per Bedoussac & Justes (2010) reported that wheat-pea intercrops improved grain yield and nitrogen uses under low-input conditions, while (Launay et al. 2009) observed better resource use in pea-barley intercrops. Comparable benefits have also been documented in pea-cereal systems under organic management. And across irrigated and rainfed environments by Justes et al. (2021), all pointing to the cropping system and resource complementarity that drives the effect of including legume crops to the system.

On the other hand, winter oilseed rape under IC with winter pea (Figure 14B) indicated yield reduction. Which produced only 486 (kg ha^{-1}), equivalent to 52% of its sole strip cropped (933 kg ha $^{-1}$) and 59% of reference (826 (kg ha^{-1}), suggesting interspecific competition with weed and reduced niche complementarity. The yield reduced may be related to allelopathic effect of winter oilseed rape, which has been shown to affect companion crops through this effect as documented by Singh et al. (2006) it's potential to effect on its companion crops. In addition to this other previous research highlighting its sensitivity to competition and species interactions. Studies have shown that companion crops with rapid establishment can dominate and suppress brassica growth (Hauggaard-Nielsen et al. 2009). Species composition remains critical, as certain mixtures have been shown to reduce rape biomass (Bousselin et al., 2024). Beyond the soil nutrient, sunlight competition, and allelopathic effects, this study did not quantify the relatively poor performance of winter oilseed rape, and the other treatments may also be linked to pressure from the major yield-reducing factors in Skåne like biotic and abiotic factors. The main biotic factors well studied in this area are pollen beetles, aphids, slugs, and vertebrate herbivory like geese and deer (Emery et al. 2023 ; Montràs-Janer et al. 2020; Montràs-Janer 2021). Furthermore, abiotic factors such as spring early-summer drought, wet weather during harvest, waterlogging, compaction, and winter frost events have also been studied (Grusson et al. 2021; Sjulgård et al. 2023). These stresses may reduce crop performance and lead to a decrease in yield, so future experiments need to include monitoring of these factors. Having established the relative yield of the IC strips to their sole strip and reference plots counterparts within the experimental design, it is also important to position these findings in the broader context of productivity within traditional agriculture. Though comparison of in the field experiment across IC, SSC and Ref system highlights ICs' relative advantage under uniform management and low resource. National average production provides a benchmark to how such systems perform relative to high-input conventional farm system. The Swedish national average grain yield in 2024 production year was about 6,540 kg ha^{-1} for winter wheat, 3,190 kg ha^{-1} for winter oilseed rape, and 2,890 kg ha^{-1} for peas, according to (Jordbruksverket, 2025). Conversely, the zero-external agrochemical input intercropping systems employed in this study produced lower yields than the national average yield achieved. For example, winter wheat-winter pea inter-crop winter wheat produced around 32%, pea 46%, and in the winter oilseed rape-winter pea inter-crop yield, winter oilseed rape 34% and winter pea 17% of the average national yield. These contrasts identify the input dependency and management intensity in traditional systems, while relative effectiveness of inter-crops under zero-input conditions still depicts biological complementarity and increased efficiency in resource utilization (Raseduzzaman & Jensen 2017). This broader comparison therefore identifies not only the productivity trade-offs but also the ecological and sustainability potential of diversified low-input systems when contrasted with the conventional monoculture baseline.

Generally, the grain yield results of this study indicated that IC substantially enhanced winter pea productivity while maintaining winter wheat yield stability relative to its reference but reduced oilseed rape performance. These results highlight that the outcomes grain yield in IC systems is highly crop-specific and context-dependent. Importantly, the absence of yield advantage does not negate the ecological services provided, such as intercropping improved biodiversity, weed suppression, and arthropod abundance key attributes of agroecological intensification and sustainable farming as described by Gurr et al. (2017).

5.5. The land equivalent ratio (LER)

The analysis of land-use efficiency reveals a clear advantage intercropping. Both winter wheat and winter pea intercrop with 50 % seeding density indicated 215% more efficient than its sole crops. And winter oilseed rape and winter pea system, with 147% more efficient. This demonstrates a strong resource complementarity. The significant efficiency of these systems stands from the contribution of winter peas. Because in the winter wheat-winter pea intercropping combination, winter peas had a partial LER of 2.40 (140% yield increase over sole its sole cropping), while winter wheat had an LER of 0.75 meaning 25% of yield decrease. Similarly, in the winter oilseed rape-winter pea combination, winter peas provided 1.95 (95% yield increase) and winter oilseed rape 0.52 (48% yield drop). In spite of these declines, winter pea performed well, showing how legumes are advantaged by intercropping production system. This study is consistent with earlier research Likewise, earlier research in Iran indicated that the LER values for grain were > 1, indicating towards the advantage of IC compared to sole cropping. For instance, winter oilseed rape-pea intercrops registered a total LER of 2.85 in 2022, equating to +185% land-use benefit. Under such cropping system, rapeseed introduced LER of 0.86 (−14% compared to sole cropping) and pea introduced an LER of 1.99 (+99% compared to sole cropping), with high complementarity between species and considerable overall productivity gains (Blanc et al. 2024b).

In this research, winter oilseed rape-winter pea intercropping, while less productive compared to winter wheat-winter pea, still provides about a 147% land-use efficiency advantage over sole cropping, as in other brassica-legume intercrops where competition may reduce by legume nitrogen fixation (Raseduzzaman & Jensen, 2017). Besides conserving nutrients, the higher canopy diversity enhances biodiversity, beneficial arthropods that enhance natural pest control (Hauggaard-Nielsen et al. 2009). This cropping diversification increases resistance to both abiotic and biotic stress with sustainability in production. In essence, the observed strong land use efficiency provides strong evidence for the advantage of agroecological diversification. That can demonstrate resource conservation, biodiversity protection, and gain reasonable yield can be achieved simultaneously. However, despite these clear agronomic and ecological benefits, intercropping remains limited adopted in Sweden and Europe. For example, Cereal-legume mixtures represent about 1.7% of Swedish arable land (Manevska-Tasevska et al. 2024). Research indicates that the main challenges for adoption, in addition to the existing research gap, limited farmers knowledge, and advisory support, as adoption needs strongly with awareness creations and technical understanding (Ha et al. 2023). The technical challenges are notably the lack of specialized machinery for sowing, harvesting, and post-harvest grain separation along with economic constraints, such as poor market access, absent value chains, and low-price premiums for mixed grains (Manevska-Tasevska et al. 2024). Because agricultural mechanizations are designed based on sole cropping system. Over this, these barriers are reinforced by market incentives favoring sole cropping, driven by high cereal prices and low fertilizer costs (Manevska-Tasevska et al. 2024).

5.5. Correlations among arthropod abundance, weed biomass, crop biomass and grain yields

Correlation analysis showed significant trends among the response indicators of this research biomass, grain yield, weed biomass, and arthropod density. High positive correlation between crop biomass and grain yield (r = 0.83) indicates that higher crop growth is significantly associated with improved grain yield performance. This implies the presence of canopy closure and active crop growth enhance resource capture, which would have significant value on crop grain yield increasement. This aligns with previous studies showing that vigorous vegetative growth enhances photosynthetic capacity and assimilate availability for grain filling. For example, Fischer & Kohn (1966) demonstrated that higher wheat biomass was closely linked to yield potential under favorable conditions. Whereas biomass had a negative relationship with crop biomass (r = -0.46) and grain yield (r = -0.39). Therefore, it implies that increased weed pressure reduces crop growth and grain yield, presumably because of competition for light, nutrients, and water. These findings are consistent with studies highlighting suppressive impacts of weeds on grain yields, especially in cereal-legume intercrops where competition is intense (Horvath et al. 2023). The negative correlation highlights the necessity for effective weed control to ensure high yields. Arthropod abundance was weak and non-significant correlated with crop biomass, yield, and weed biomass (r = 0.00-0.09). The result indicates that arthropod abundance within this cropping system isn't primarily dictated by crop or weed performance, but rather by crop diversification. Factors like the overall habitat composition, the diversity of plants present, or the seasonal cycle appear to be the dominant regulatory elements. This aligns with findings from diverse cropping systems, where arthropod communities typically respond more strongly to habitat complexity (heterogeneity) than to variables directly related to yield (Cuperus et al. 2023). Furthermore, the influence these insects have on specific parameters, such as yield or weed biomass, is often distributed and non-linear, meaning it's experienced and not a simple, scalable relationship (Hussain et al. 2025). Instead of directly generating yield increases, immediately, arthropods' main contribution is to ecosystem stability by acting as a natural pest control (Litovska et al. 2025). Consequently, their population dynamics are shaped more by habitat features (e.g. refuges, plant diversity) than by the density of a single crop or weed species.

Over all the findings of this study provide strong evidence for the role of intercropping as an agroecological practice that enhances ecosystem services while maintaining reasonable crop performance. By increasing arthropod abundance, suppressing weeds, and improving land-use efficiency (LER > 1), intercropping demonstrates the principles of ecological intensification, where biodiversity supports productivity and reduces dependence on external inputs. Agroecology emphasizes the use of natural processes, such as resource complementarity and habitat diversification, to strengthen resilience in farming systems (Altieri, 1999; Wezel et al., 2014). In this study, the winter wheat-winter pea intercrop exemplified how combining functional traits of cereals and legumes can deliver both ecological and agronomic benefits, supporting biodiversity conservation while maintaining yields. This aligns with agroecological goals of building sustainable, low-input, and resilient production systems that contribute to long-term food security and environmental stewardship.

6. Conclusion and recommendations

6.3. Conclusion

This study showed that intercropping (IC) provides clear ecological and agronomic benefits, even if it differs from crop-to-crop combination performance. Winter wheat-winter pea IC indicated significant abundance of above ground arthropod compared with their sole strip cropping of winter wheat (SSC_W) and the winter wheat reference plot (Ref_W), arthropod abundance in the winter wheat winter pea intercrop was about 43% and 162% higher, respectively. In addition to this, weed biomass was reduced by 66% compared with sole winter pea. Yield responses were mixed: winter pea performance improved substantially, winter wheat yields were maintained at 50% seeding density, while winter oilseed rape was suppressed. All intercrops achieved LER > 1, with gains of up to 215% in winter wheat-winter pea and 147% in winter oilseed rape-winter pea systems. Overall, the finding reveals that intercropping gives significant ecological benefits by the conservation of beneficial insects as well as utilization of resources even though short-term benefits in terms of yield are not considerable. The finding underscores the advantage of intercropping as a strategy of ecological intensification that can contribute towards sustainable production and reducing reliance on external farm inputs.

6.2. Recommendations

Based on the climatic and edaphic conditions of Skåne, southern Sweden, intercropping of winter wheat and winter pea indicates a promising cropping system of enhancing biodiversity, weed suppression, and improving land-use efficiency. This cropping system can be used as an ecological intensification model in crop production areas where the reduction of dependence on external inputs is a critical consideration. This cropping system can be used as an ecological intensification model in crop production areas where the reduction of dependence on external inputs is a critical consideration. To promote broader adoption, a coordinated approach is needed that connects agronomic practice innovation with market development, farmer education, and supportive policy frameworks. The collaboration of researchers, advisors, and policymakers could have a vital role on develop incentive programs, giving extension services, and knowledge-sharing platforms for crop producer farmers. Future studies should include long-term trials that assess economic returns, soil health, and ecosystem services such as natural pest regulation, to strengthen the evidence base and ensure the resilience and sustainability of intercropping systems in Sweden and northern Europe.

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Popular science summary

Intercropping growth of two or more crops grown together on the same field at the same time, in a planned arrangement is an option and promising. In Skåne southern, Sweden, researcher tried strip intercropping with peas intercropped with winter wheat or oilseed rape and compared these systems to the standard sole cropping. The outcomes were promising: Intercropped crops fields drew about twice as many helpful insects as sole strip crops and suppressed weeds naturally, especially when winter peas were intercropped with winter wheat.

The crops themselves responded differently. Wheat held yields even at half seeding density, but winter peas produced two to three times more when cropped with winter wheat than when sowing alone. Winter Oilseed rape performed poorly in intercropping. Overall, intercropping growth of two or more crops together on the same field at the same time, in a planned arrangement produced more food per unit of land, with definite advantages for land efficiency.

On the side of grain yields, such systems also had important ecological benefits like biodiversity maintenance, natural weed control with minimal, reduce cost of chemicals, and better utilization of natural resources. While short-term grain yields were not always increased, the net gains recognize intercropping as a viable path to sustainable agriculture aligned with the EU Green Deal and the UN Sustainable Development Goals 2015.

Appendix 1

GLMM results in the effects of cropping system treatments on the log-transformed abundance of aboveground-dwelling arthropods. Estimates (± SE), z values, p values, and significance levels are shown for each treatment comparison. For each treatment type (P, R, W), the reference (Ref_P, Ref_R, Ref_W) is used as the model intercept respectively. Significant positive effects (p < 0.05).

Treatments	Estimate	SE	z value	P-adjusted	Significance
(Intercept)-Ref_P	4.901	0.147	33.260	<0.001	***
R+P	0.234	0.165	1.421	0.155	ns
W+P	0.325	0.164	1.979	0.048	*
P	0.122	0.165	0.744	0.457	ns
(Intercept)-Ref_R	4.708	0.194	24.273	<0.001	***
R+P	0.427	0.216	1.975	0.048	*
R	0.046	0.218	0.212	0.832	Ns
(Intercept)-Ref_W	4.256	0.147	28.980	<0.001	***
W+P	0.962	0.163	5.909	0.001	***
W	0.758	0.163	4.648	0.001	***

Appendix 2

Fixed effect estimates from the linear mixed model (LMM) assessing the effects of different cropping treatments on weed biomass. The intercepts represent baseline weed biomass for each treatment block, while estimates for IC and SSC are expressed relative to their respective reference systems. Among treatments, only IC_P_(W+P) showed a significant reduction in weed biomass ($p < 0.05$).

Weed biomass by treatments	Estimate	Std. Error	t value	P value	Significant
(Intercept)	627.2	477.21	1.31	0.213	ns
IC_W_(W+P)	939.09	515.48	1.82	0.097	ns
SSC_W	945.83	515.48	1.83	0.094	ns
(Intercept)	1670.8	665.71	2.50	0.017	*
IC_R_(R+P)	1262.45	707.29	1.78	0.085	ns
SSC_R	629.5	707.29	0.89	0.381	ns
(Intercept)	3363.6	680.92	4.93	<0.001	***
IC_P_(R+P)	-430.35	730.27	-0.58	0.561	ns
IC_P_(W+P)	-1802.18	731.10	-2.46	0.022	*
SSC_P	1171	730.27	1.60	0.123	ns

Appendix 3

LMM results in the effect of crop treatment on crop dry biomass. Intercepts correspond to the reference plots for each crop. Estimates are differences relative to the reference. SE = standard error. Significant value: *$p < 0.05$; ns = not significant.

Crop_biomas by treatments	Estimate	Std. Error	t value	P value	Significance
(Intercept)	3906.8	1357.803	2.87	0.046	*
IC_W_(W+P)	289.82	1505.51	0.192	0.857	ns
SSC_W	1872.791	1505.85	1.24	0.285	ns
(Intercept)	3628	1301.75	2.78	0.037	*
IC_R_(R+P)	-1455	1432.33	-1.01	0.358	ns
SSC_R	282.75	1432.33	0.19	0.851	ns
(Intercept)	1802	648.45	2.77	0.012	*
IC_P_(R+P)	63.65	698.27	0.09	0.928	ns
IC_P_(W+P)	471.33	698.98	0.67	0.510	ns
SSC_P	-761.65	698.27	-1.09	0.292	ns

Appendix 4

LMM analysis for the effect of crop treatment on grain yield. Intercepts correspond to the reference plots for each crop. Estimates represent differences relative to the reference. SE = standard error; Significance: *p < 0.05; ns = not significant.

Grain yield by treatments	Estimate	Std. Error	t value	P value	Significance
(Intercept)	1986.8	722.45	2.75	0.054	*
IC_W_(W+P)	125.25	801.63	0.15	0.884	ns
SSC_W	832.38	801.80	1.03	0.362	ns
(Intercept)	826	310.58	2.65	0.035	**
IC_R_(R+P)	-339.85	339.76	-1.00	0.356	ns
SSC_R	106.95	339.76	0.31	0.763	ns
(Intercept)	638	407.06	1.56	0.141	ns
IC_P_(R+P)	438.7	440.47	0.99	0.339	ns
IC_P_(W+P)	674.42	440.86	1.52	0.153	ns
SSC_P	-86.6	440.47	-0.19	0.847	ns

Appendix 5

Arthropod abundance (Carabids, Staphylinids, and Spiders) recorded in winter wheat, winter oilseed rape, and winter pea plots across two sampling dates (25 June 2024 and 2 July 2024), categorized by block, strip, and plot identification codes. These data were used for statistical analyses evaluating the effects of cropping system treatments on aboveground arthropod communities.

				25-06-2024			**2/7/2024**		
Crops	**Block_ID**	**Strip_ID**	**Plot_ID**	**Carabids**	**Staphylinids**	**Spiders**	**Carabids**	**Staphylinids**	**Spiders**
Winter oilseed rape	1	A	A1	44	11	73	21	11	29
Winter oilseed rape	1	A	A2	10	15	44	23	5	41
Winter oilseed rape	1	A	A3	45	13	97	16	6	22
Winter oilseed rape	1	A	A4	24	8	45	5	4	13
Winter oilseed rape	1	A	A5	25	16	37	30	13	30
Winter Pea	1	B	B1	72	8	45	33	7	30
Winter Pea	1	B	B2	21	1	51	18	17	33
Winter Pea	1	B	B3	20	11	60	13	7	46
Winter Pea	1	B	B4	18	5	34	19	8	20
Winter Pea	1	B	B5	15	0	30	1	1	9
Winter Wheat	1	C	C1	12	13	66	21	9	59
Winter Wheat	1	C	C2	8	25	85	6	6	56
Winter Wheat	1	C	C3	19	15	63	17	13	40
Winter Wheat	1	C	C4	17	13	89	28	14	64
Winter Wheat	1	C	C5	22	15	61	16	12	48
Winter Wheat+Winter Pea	1	D	D1	12	3	68	20	4	55
Winter Wheat+Winter Pea	1	D	D2	15	7	95	9	3	48
Winter Wheat+Winter Pea	1	D	D3	34	0	94	14	4	24

Winter Wheat+Winter Pea	1	D	D4	14	16	83	13	1	32
Winter Wheat+Winter Pea	1	D	D5	8	21	18	13	17	54
Winter oilseed rape+ Winter Pea	1	E	E1	25	18	70	13	17	54
Winter oilseed rape+ Winter Pea	1	E	E2	26	7	41	19	10	35
Winter oilseed rape+ Winter Pea	1	E	E3	22	8	73	5	5	35
Winter oilseed rape+ Winter Pea	1	E	E4	20	13	103	24	8	30
Winter oilseed rape+ Winter Pea	1	E	E5	24	14	49	6	8	78
Winter Wheat	2	F	F1	22	2	92	6	8	78
Winter Wheat	2	F	F2	20	2	85	20	4	35
Winter Wheat	2	F	F3	17	2	56	17	4	61
Winter Wheat	2	F	F4	2	2	43	2	1	64
Winter Wheat	2	F	F5	24	3	74	11	3	24
Winter Pea	2	G	G1	27	7	25	11	7	43
Winter Pea	2	G	G2	31	7	44	18	3	35
Winter Pea	2	G	G3	28	3	11	9	5	30
Winter Pea	2	G	G4	26	4	11	7	9	21
Winter Pea	2	G	G5	15	12	31	25	22	23
Winter oilseed rape	2	H	H1	23	14	99	14	5	52
Winter oilseed rape	2	H	H2	31	15	26	24	6	28
Winter oilseed rape	2	H	H3	29	15	105	11	4	18
Winter oilseed rape	2	H	H4	47	8	34	5	1	3
Winter oilseed rape	2	H	H5	51	15	6	28	10	11
Winter oilseed rape+ Winter Pea	2	I	I1	29	19	73	34	7	43
Winter oilseed rape+ Winter Pea	2	I	I2	30	18	61	3	9	19
Winter oilseed rape+ Winter Pea	2	I	I3	26	22	64	16	5	33
Winter oilseed rape+ Winter Pea	2	I	I4	30	26	122	18	8	54
Winter oilseed rape+ Winter Pea	2	I	I5	37	12	28	1	1	2

Winter Wheat+Winter Pea	2	J	J1	20	10	74	14	9	94
Winter Wheat+Winter Pea	2	J	J2	8	9	125	25	19	96
Winter Wheat+Winter Pea	2	J	J3	23	25	136	16	13	54
Winter Wheat+Winter Pea	2	J	J4	25	22	145	9	18	48
Winter Wheat+Winter Pea	2	J	J5	45	10	75	27	17	54
Winter Pea	3	K	K1	39	21	97	13	7	40
Winter Pea	3	K	K2	29	26	70	22	5	19
Winter Pea	3	K	K3	4	11	55	2	3	23
Winter Pea	3	K	K4	36	12	57	8	6	34
Winter Pea	3	K	K5	23	9	59	30	7	18
Winter Wheat	3	L	L1	24	6	50	31	4	30
Winter Wheat	3	L	L2	31	5	46	8	3	47
Winter Wheat	3	L	L3	9	1	20	37	7	22
Winter Wheat	3	L	L4	22	4	24	16	0	22
Winter Wheat	3	L	L5	32	4	23	18	5	32
Winter oilseed rape	3	M	M1	13	1	6	7	2	4
Winter oilseed rape	3	M	M2	17	13	45	21	4	19
Winter oilseed rape	3	M	M3	11	5	34	24	2	9
Winter oilseed rape	3	M	M4	12	11	53	19	0	10
Winter oilseed rape	3	M	M5	23	9	8	9	0	20
Winter oilseed rape+ Winter Pea	3	N	N1	18	0	51	38	6	27
Winter oilseed rape+ Winter Pea	3	N	N2	80	7	87	40	2	22
Winter oilseed rape+ Winter Pea	3	N	N3	20	4	72	29	4	41
Winter oilseed rape+ Winter Pea	3	N	N4	30	1	130	25	7	41
Winter oilseed rape+ Winter Pea	3	N	N5	47	5	59	28	6	40
Winter Wheat+Winter Pea	3	O	O1	20	3	55	18	27	122
Winter Wheat+Winter Pea	3	O	O2	33	6	67	30	13	58

Winter Wheat+Winter Pea	3	O	O3	5	0	42	17	7	52
Winter Wheat+Winter Pea	3	O	O4	12	3	49	30	9	32
Winter Wheat+Winter Pea	3	O	O5	51	7	43	10	4	51
Winter Pea	4	P	P1	53	15	69	26	5	61
Winter Pea	4	P	P2	29	8	46	51	3	18
Winter Pea	4	P	P3	43	10	88	32	15	37
Winter Pea	4	P	P4	43	9	92	29	6	46
Winter Pea	4	P	P5	22	11	70	35	3	75
Winter oilseed rape	4	Q	Q1	16	3	23	17	2	51
Winter oilseed rape	4	Q	Q2	20	3	17	15	2	7
Winter oilseed rape	4	Q	Q3	11	1	11	1	2	12
Winter oilseed rape	4	Q	Q4	5	0	26	35	3	75
Winter oilseed rape	4	Q	Q5	7	2	29	10	0	15
Winter Wheat	4	R	R1	22	16	48	12	5	51
Winter Wheat	4	R	R2	27	16	64	8	3	15
Winter Wheat	4	R	R3	14	0	13	21	5	42
Winter Wheat	4	R	R4	19	2	57	14	2	50
Winter Wheat	4	R	R5	29	4	72	37	2	52
Winter oilseed rape+ Winter Pea	4	S	S1	30	9	16	12	1	3
Winter oilseed rape+ Winter Pea	4	S	S2	45	12	106	26	3	47
Winter oilseed rape+ Winter Pea	4	S	S3	21	14	38	17	5	40
Winter oilseed rape+ Winter Pea	4	S	S4	23	9	87	24	6	51
Winter oilseed rape+ Winter Pea	4	S	S5	22	7	35	2	1	7
Winter Wheat+Winter Pea	4	T	T1	11	8	35	13	3	51
Winter Wheat+Winter Pea	4	T	T2	20	7	71	18	5	46
Winter Wheat+Winter Pea	4	T	T3	18	5	31	20	4	70
Winter Wheat+Winter Pea	4	T	T4	21	8	81	22	8	57

Winter Wheat+Winter Pea	4	T	T5	20	7	72	7	4	39
Reference Winter Pea	Reference	REFP	REFP1	42	4	121	18	1	21
Reference Winter Pea	Reference	REFP	REFP2	18	1	26	12	1	17
Reference Winter Pea	Reference	REFP	REFP3	16	1	46	0	3	26
Reference Winter Pea	Reference	REFP	REFP4	14	0	34	44	2	25
Reference Winter Pea	Reference	REFP	REFP5	47	10	75	25	1	21
Reference Winter oilseed rape	Reference	REFR	REFR1	21	2	38	25	3	26
Reference Winter oilseed rape	Reference	REFR	REFR2	2	4	31	17	6	7
Reference Winter oilseed rape	Reference	REFR	REFR3	9	2	35	14	0	18
Reference Winter oilseed rape	Reference	REFR	REFR4	20	0	86	28	7	31
Reference Winter oilseed rape	Reference	REFR	REFR5	21	2	38	22	6	32
Reference Winter Wheat	Reference	REFW	REFW1	14	2	29	4	1	27
Reference Winter Wheat	Reference	REFW	REFW2	6	0	34	0	3	26
Reference Winter Wheat	Reference	REFW	REFW3	14	0	30	9	0	22
Reference Winter Wheat	Reference	REFW	REFW4	4	1	17	13	2	20
Reference Winter Wheat	Reference	REFW	REFW5	5	0	28	10	2	29

Appendix 6

Experimental dataset showing block, strip, and plot identification, crop type (winter wheat, winter oilseed rape, and winter pea), cropping system, and measured crop dry biomass, grain yield, and weed dry biomass (all in kg/ha). These data were used as input variables for statistical analyses assessing the effects of cropping system treatments on crop performance and weed suppression.

Block_ ID	Strip ID	Plot_ ID	Crop with Strip ID	Crop type	Croping_System	Weed_biomas(kg/ha)	Crop_biomas (kg/ha)	Grain yield(kg/ha)
1	A	A1	RA	R	SSC	692	6564	1700
1	A	A2	RA	R	SSC	2328	5632	1324
1	A	A3	RA	R	SSC	996	5362	1484
1	A	A4	RA	R	SSC	2032	3646	846
1	A	A5	RA	R	SSC	470	5590	1702
1	A	A6	RA	R	SSC	2258	2694	696
1	A	A7	RA	R	SSC	1838	5150	1286
1	A	A8	RA	R	SSC	2824	2088	434
1	A	A9	RA	R	SSC	4200	5076	1428
1	A	A10	RA	R	SSC	2422	4462	1158
1	B	B1	PB	P	SSC	4416	3812	2164
1	B	B2	PB	P	SSC	3824	2844	1754
1	B	B3	PB	P	SSC	4108	2264	1362
1	B	B4	PB	P	SSC	7796	2630	1590
1	B	B5	PB	P	SSC	4824	1124	736
1	B	B6	PB	P	SSC	5184	1578	906
1	B	B7	PB	P	SSC	5592	1944	1076
1	B	B8	PB	P	SSC	5958	464	350

1	B	B9	PB	P	SSC	7734	3144	1828
1	B	B10	PB	P	SSC	4048	56	124
1	C	C1	WC	W	SSC	6542	6926	3406
1	C	C2	WC	W	SSC	1860	6228	3116
1	C	C3	WC	W	SSC	2138	6156	3166
1	C	C4	WC	W	SSC	2752	6788	3458
1	C	C5	WC	W	SSC	756	6892	3666
1	C	C6	WC	W	SSC	1392	5814	3040
1	C	C7	WC	W	SSC	1512	6316	3096
1	C	C8	WC	W	SSC	880	5796	3010
1	C	C9	WC	W	SSC	1058	4328	2212
1	C	C10	WC	W	SSC	1702	5400	2802
1	D	D1	WD	W_(W+P)	IC	190	5004	2654
1	D	D2	WD	W_(W+P)	IC	1986	2210	1146
1	D	D3	WD	W_(W+P)	IC	1444	4654	2406
1	D	D4	WD	W_(W+P)	IC	1934	3832	1912
1	D	D5	WD	W_(W+P)	IC	1270	4870	2568
1	D	D6	WD	W_(W+P)	IC	886	3090	1592
1	D	D7	WD	W_(W+P)	IC	1540	6130	3244
1	D	D8	WD	W_(W+P)	IC	1982	7450	4034
1	D	D9	WD	W_(W+P)	IC	808	5650	2934
1	D	D10	WD	W_(W+P)	IC	2288	6408	3420
1	D	D1	PD	P_(W+P)	IC	190	4496	2910
1	D	D2	PD	P_(W+P)	IC	1986	2590	1734
1	D	D3	PD	P_(W+P)	IC	1444	778	576
1	D	D4	PD	P_(W+P)	IC	1934	3488	2204

1	D	D5	PD	P_(W+P)	IC	1270	1526	1058
1	D	D6	PD	P_(W+P)	IC	886	3096	2032
1	D	D7	PD	P_(W+P)	IC	1540	578	342
1	D	D8	PD	P_(W+P)	IC	1982	368	220
1	D	D9	PD	P_(W+P)	IC	808	660	392
1	D	D10	PD	P_(W+P)	IC	2288	3974	2542
1	E	E1	RE	R_(R+P)	IC	3542	842	330
1	E	E2	RE	R_(R+P)	IC	1142	2366	564
1	E	E3	RE	R_(R+P)	IC	1480	1744	276
1	E	E4	RE	R_(R+P)	IC	3746	332	54
1	E	E5	RE	R_(R+P)	IC	4796	1524	338
1	E	E6	RE	R_(R+P)	IC	638	3708	1030
1	E	E7	RE	R_(R+P)	IC	4232	2380	684
1	E	E8	RE	R_(R+P)	IC	0	2350	740
1	E	E9	RE	R_(R+P)	IC	5530	116	28
1	E	E10	RE	R_(R+P)	IC	7404	568	154
1	E	E1	PE	P_(R+P)	IC	3542	384	222
1	E	E2	PE	P_(R+P)	IC	1142	794	446
1	E	E3	PE	P_(R+P)	IC	1480	2798	1262
1	E	E4	PE	P_(R+P)	IC	3746	556	294
1	E	E5	PE	P_(R+P)	IC	4796	990	590
1	E	E6	PE	P_(R+P)	IC	638	3678	1186
1	E	E7	PE	P_(R+P)	IC	4232	1788	610
1	E	E8	PE	P_(R+P)	IC	0	1408	922
1	E	E9	PE	P_(R+P)	IC	5530	386	234
1	E	E10	PE	P_(R+P)	IC	7404	1030	604

2	F	F1	WF	W	SSC	508	5482	2614
2	F	F2	WF	W	SSC	1262	7328	3414
2	F	F3	WF	W	SSC	NA	NA	NA
2	F	F4	WF	W	SSC	1152	6496	3118
2	F	F5	WF	W	SSC	1656	6762	3260
2	F	F6	WF	W	SSC	1262	6474	3180
2	F	F7	WF	W	SSC	666	6702	3262
2	F	F8	WF	W	SSC	1540	6198	3066
2	F	F9	WF	W	SSC	1662	6274	3040
2	F	F10	WF	W	SSC	1100	6768	3350
2	G	G1	PG	P	SSC	4818	516	212
2	G	G2	PG	P	SSC	4548	98	24
2	G	G3	PG	P	SSC	4344	1242	576
2	G	G4	PG	P	SSC	5140	2554	1378
2	G	G5	PG	P	SSC	3614	954	446
2	G	G6	PG	P	SSC	4532	594	260
2	G	G7	PG	P	SSC	3638	358	72
2	G	G8	PG	P	SSC	4570	30	0
2	G	G9	PG	P	SSC	3042	992	448
2	G	G10	PG	P	SSC	6584	40	0
2	H	H1	RH	R	SSC	2732	3582	744
2	H	H2	RH	R	SSC	1900	5182	1192
2	H	H3	RH	R	SSC	2344	8106	1816
2	H	H4	RH	R	SSC	1184	2552	506
2	H	H5	RH	R	SSC	4390	1952	444
2	H	H6	RH	R	SSC	2480	6298	1514

2	H	H7	RH	R	SSC	2524	4100	1016
2	H	H8	RH	R	SSC	2398	7066	1690
2	H	H9	RH	R	SSC	2788	4278	878
2	H	H10	RH	R	SSC	2128	4404	1094
2	I	I1	RI	R_(R+P)	IC	2152	8250	2264
2	I	I2	RI	R_(R+P)	IC	2212	928	202
2	I	I3	RI	R_(R+P)	IC	3922	1252	330
2	I	I4	RI	R_(R+P)	IC	3610	756	170
2	I	I5	RI	R_(R+P)	IC	2574	572	124
2	I	I6	RI	R_(R+P)	IC	5214	958	152
2	I	I7	RI	R_(R+P)	IC	5624	848	230
2	I	I8	RI	R_(R+P)	IC	490	2038	566
2	I	I9	RI	R_(R+P)	IC	1256	4006	1202
2	I	I10	RI	R_(R+P)	IC	6768	1370	428
2	I	I1	PI	P_(R+P)	IC	2152	1200	636
2	I	I2	PI	P_(R+P)	IC	2212	2698	1492
2	I	I3	PI	P_(R+P)	IC	3922	368	200
2	I	I4	PI	P_(R+P)	IC	3610	368	196
2	I	I5	PI	P_(R+P)	IC	2574	830	478
2	I	I6	PI	P_(R+P)	IC	5214	560	336
2	I	I7	PI	P_(R+P)	IC	5624	94	42
2	I	I8	PI	P_(R+P)	IC	490	1412	908
2	I	I9	PI	P_(R+P)	IC	1256	402	132
2	I	I10	PI	P_(R+P)	IC	6768	246	144
2	J	J1	WJ	W_(W+P)	IC	1846	6881	3400
2	J	J2	WJ	W_(W+P)	IC	1208	904	2272

2	J	J3	WJ	W_(W+P)	IC	3194	3868	1746
2	J	J4	WJ	W_(W+P)	IC	2490	3226	1474
2	J	J5	WJ	W_(W+P)	IC	1918	6866	2192
2	J	J6	WJ	W_(W+P)	IC	2868	5802	2800
2	J	J7	WJ	W_(W+P)	IC	1380	8074	4144
2	J	J8	WJ	W_(W+P)	IC	584	6696	3990
2	J	J9	WJ	W_(W+P)	IC	1108	7622	3782
2	J	J10	WJ	W_(W+P)	IC	282	9224	5160
2	J	J1	PJ	P_(W+P)	IC	1846	NA	NA
2	J	J2	PJ	P_(W+P)	IC	1208	826	462
2	J	J3	PJ	P_(W+P)	IC	3194	792	414
2	J	J4	PJ	P_(W+P)	IC	2490	1648	992
2	J	J5	PJ	P_(W+P)	IC	1918	1992	1168
2	J	J6	PJ	P_(W+P)	IC	2868	1146	610
2	J	J7	PJ	P_(W+P)	IC	1380	3508	1100
2	J	J8	PJ	P_(W+P)	IC	584	1576	902
2	J	J9	PJ	P_(W+P)	IC	1108	3466	1518
2	J	J10	PJ	P_(W+P)	IC	282	1496	932
3	K	K1	PK	P	SSC	4498	718	324
3	K	K2	PK	P	SSC	5142	1010	508
3	K	K3	PK	P	SSC	4344	1736	530
3	K	K4	PK	P	SSC	6406	630	340
3	K	K5	PK	P	SSC	5516	172	82
3	K	K6	PK	P	SSC	5822	232	108
3	K	K7	PK	P	SSC	5210	1190	506
3	K	K8	PK	P	SSC	3738	688	202

3	K	K9	PK	P	SSC	4318	116	12
3	K	K10	PK	P	SSC	4342	380	138
3	L	L1	WL	W	SSC	2252	4882	2276
3	L	L2	WL	W	SSC	2980	6094	2782
3	L	L3	WL	W	SSC	1316	5822	2610
3	L	L4	WL	W	SSC	2894	5800	2634
3	L	L5	WL	W	SSC	2400	5902	2588
3	L	L6	WL	W	SSC	1612	5694	2706
3	L	L7	WL	W	SSC	1480	7184	3618
3	L	L8	WL	W	SSC	808	7214	3504
3	L	L9	WL	W	SSC	534	5142	2588
3	L	L10	WL	W	SSC	1278	6142	2918
3	M	M1	RM	R	SSC	1142	2172	442
3	M	M2	RM	R	SSC	2778	6764	1418
3	M	M3	RM	R	SSC	1502	5182	956
3	M	M4	RM	R	SSC	1294	2752	554
3	M	M5	RM	R	SSC	882	1386	264
3	M	M6	RM	R	SSC	4116	3698	822
3	M	M7	RM	R	SSC	2914	5614	1272
3	M	M8	RM	R	SSC	2838	6424	2132
3	M	M9	RM	R	SSC	470	6470	1480
3	M	M10	RM	R	SSC	2564	5000	1184
3	N	N1	RN	R_(R+P)	IC	640	4960	1328
3	N	N2	RN	R_(R+P)	IC	696	5668	1404
3	N	N3	RN	R_(R+P)	IC	3820	5012	266
3	N	N4	RN	R_(R+P)	IC	3142	2500	486

3	N	N5	RN	R_(R+P)	IC	4722	5264	1192
3	N	N6	RN	R_(R+P)	IC	1058	2692	256
3	N	N7	RN	R_(R+P)	IC	2732	3574	324
3	N	N8	RN	R_(R+P)	IC	2548	3750	618
3	N	N9	RN	R_(R+P)	IC	1966	2472	706
3	N	N10	RN	R_(R+P)	IC	772	1924	302
3	N	N1	PN	P_(R+P)	IC	640	5624	3948
3	N	N2	PN	P_(R+P)	IC	696	3776	2202
3	N	N3	PN	P_(R+P)	IC	3820	2916	1564
3	N	N4	PN	P_(R+P)	IC	3142	1840	1148
3	N	N5	PN	P_(R+P)	IC	4722	3700	2184
3	N	N6	PN	P_(R+P)	IC	1058	1336	740
3	N	N7	PN	P_(R+P)	IC	2732	1828	1054
3	N	N8	PN	P_(R+P)	IC	2548	328	222
3	N	N9	PN	P_(R+P)	IC	1966	1568	938
3	N	N10	PN	P_(R+P)	IC	772	3736	2246
3	O	O1	WO	W_(W+P)	IC	2134	4730	2140
3	O	O2	WO	W_(W+P)	IC	1216	4154	1962
3	O	O3	WO	W_(W+P)	IC	2998	4024	1822
3	O	O4	WO	W_(W+P)	IC	2228	4864	1022
3	O	O5	WO	W_(W+P)	IC	3038	3578	1658
3	O	O6	WO	W_(W+P)	IC	2792	4044	1980
3	O	O7	WO	W_(W+P)	IC	1718	4098	1734
3	O	O8	WO	W_(W+P)	IC	NA	2766	1402
3	O	O9	WO	W_(W+P)	IC	926	3352	1800
3	O	O10	WO	W_(W+P)	IC	1884	4130	2080

3	O	O1	PO	P_(W+P)	IC	2134	2722	1560
3	O	O2	PO	P_(W+P)	IC	1216	2784	1636
3	O	O3	PO	P_(W+P)	IC	2998	1168	686
3	O	O4	PO	P_(W+P)	IC	2228	2200	1074
3	O	O5	PO	P_(W+P)	IC	3038	3648	2226
3	O	O6	PO	P_(W+P)	IC	2792	4056	2288
3	O	O7	PO	P_(W+P)	IC	1718	888	316
3	O	O8	PO	P_(W+P)	IC	NA	912	550
3	O	O9	PO	P_(W+P)	IC	926	2996	1972
3	O	O10	PO	P_(W+P)	IC	1884	1782	1142
4	P	P1	PP	P	SSC	6070	186	54
4	P	P2	PP	P	SSC	4440	594	266
4	P	P3	PP	P	SSC	2708	508	214
4	P	P4	PP	P	SSC	2966	528	234
4	P	P5	PP	P	SSC	2336	1632	956
4	P	P6	PP	P	SSC	2806	548	272
4	P	P7	PP	P	SSC	2952	528	280
4	P	P8	PP	P	SSC	3272	1312	844
4	P	P9	PP	P	SSC	3416	1224	736
4	P	P10	PP	P	SSC	2768	444	144
4	Q	Q1	RQ	R	SSC	1292	1864	382
4	Q	Q2	RQ	R	SSC	2524	2634	562
4	Q	Q3	RQ	R	SSC	2170	2474	614
4	Q	Q4	RQ	R	SSC	3106	1068	128
4	Q	Q5	RQ	R	SSC	2970	1050	234
4	Q	Q6	RQ	R	SSC	3000	1506	260

4	Q	Q7	RQ	R	SSC	2924	1066	274
4	Q	Q8	RQ	R	SSC	2950	1152	240
4	Q	Q9	RQ	R	SSC	1816	3040	816
4	Q	Q10	RQ	R	SSC	3832	1330	332
4	R	R1	WR	W	SSC	1814	5176	2570
4	R	R2	WR	W	SSC	2094	3578	2002
4	R	R3	WR	W	SSC	1814	5142	2340
4	R	R4	WR	W	SSC	1436	5662	2460
4	R	R5	WR	W	SSC	1014	3068	1526
4	R	R6	WR	W	SSC	1226	4468	2116
4	R	R7	WR	W	SSC	600	4636	2172
4	R	R8	WR	W	SSC	864	3812	1852
4	R	R9	WR	W	SSC	606	4338	2168
4	R	R10	WR	W	SSC	998	5336	2600
4	S	S1	RS	R_(R+P)	IC	3156	2782	704
4	S	S2	RS	R_(R+P)	IC	3290	290	90
4	S	S3	RS	R_(R+P)	IC	6242	1784	450
4	S	S4	RS	R_(R+P)	IC	3622	570	114
4	S	S5	RS	R_(R+P)	IC	3606	1848	398
4	S	S6	RS	R_(R+P)	IC	434	288	58
4	S	S7	RS	R_(R+P)	IC	3654	790	76
4	S	S8	RS	R_(R+P)	IC	1800	1986	556
4	S	S9	RS	R_(R+P)	IC	1580	614	74
4	S	S10	RS	R_(R+P)	IC	1518	1244	178
4	S	S1	PS	P_(R+P)	IC	3156	4882	3118
4	S	S2	PS	P_(R+P)	IC	3290	2792	1684

4	S	S3	PS	P_(R+P)	IC	6242	2376	1412
4	S	S4	PS	P_(R+P)	IC	3622	2520	1504
4	S	S5	PS	P_(R+P)	IC	3606	2698	1550
4	S	S6	PS	P_(R+P)	IC	434	3814	2150
4	S	S7	PS	P_(R+P)	IC	3654	2508	1908
4	S	S8	PS	P_(R+P)	IC	1800	2512	1528
4	S	S9	PS	P_(R+P)	IC	1580	1182	752
4	S	S10	PS	P_(R+P)	IC	1518	700	282
4	T	T1	WT	W_(W+P)	IC	2050	2080	1048
4	T	T2	WT	W_(W+P)	IC	1572	1500	712
4	T	T3	WT	W_(W+P)	IC	508	1336	742
4	T	T4	WT	W_(W+P)	IC	580	2480	1276
4	T	T5	WT	W_(W+P)	IC	1452	2304	1176
4	T	T6	WT	W_(W+P)	IC	1360	1300	652
4	T	T7	WT	W_(W+P)	IC	980	1784	878
4	T	T8	WT	W_(W+P)	IC	746	2490	1282
4	T	T9	WT	W_(W+P)	IC	1280	2394	1274
4	T	T10	WT	W_(W+P)	IC	194	1996	972
4	T	T1	PT	P_(W+P)	IC	2050	778	456
4	T	T2	PT	P_(W+P)	IC	1572	2060	1172
4	T	T3	PT	P_(W+P)	IC	508	6106	2764
4	T	T4	PT	P_(W+P)	IC	580	3806	2244
4	T	T5	PT	P_(W+P)	IC	1452	1972	1146
4	T	T6	PT	P_(W+P)	IC	1360	2644	1702
4	T	T7	PT	P_(W+P)	IC	980	5582	3320
4	T	T8	PT	P_(W+P)	IC	746	0	0

4	T	T9	PT	P_(W+P)	IC	1280	2140	1496
4	T	T10	PT	P_(W+P)	IC	194	2828	1646
Ref_Pea	Ref_P	P_Ref1	P_Ref	Ref_P	Ref	3412	1420	764
Ref_Pea	Ref_P	P_Ref2	P_Ref	Ref_P	Ref	3124	2266	748
Ref_Pea	Ref_P	P_Ref3	P_Ref	Ref_P	Ref	3018	1134	386
Ref_Pea	Ref_P	P_Ref4	P_Ref	Ref_P	Ref	4252	1030	552
Ref_Pea	Ref_P	P_Ref5	P_Ref	Ref_P	Ref	3012	3160	740
Ref_Rape	Ref_R	R_Ref1	R_Ref	Ref_R	Ref	2240	2438	508
Ref_Rape	Ref_R	R_Ref2	R_Ref	Ref_R	Ref	1706	2896	604
Ref_Rape	Ref_R	R_Ref3	R_Ref	Ref_R	Ref	992	3468	728
Ref_Rape	Ref_R	R_Ref4	R_Ref	Ref_R	Ref	2430	3058	742
Ref_Rape	Ref_R	R_Ref5	R_Ref	Ref_R	Ref	986	6280	1548
Ref_Wheat	Ref_W	W_Ref1	W_Ref	Ref_W	Ref	372	3952	1944
Ref_Wheat	Ref_W	W_Ref2	W_Ref	Ref_W	Ref	700	3414	1746
Ref_Wheat	Ref_W	W_Ref3	W_Ref	Ref_W	Ref	392	3428	1734
Ref_Wheat	Ref_W	W_Ref4	W_Ref	Ref_W	Ref	1364	3488	1710
Ref_Wheat	Ref_W	W_Ref5	W_Ref	Ref_W	Ref	308	5252	2800

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Intercropping for Sustainable Crop Production and Cost Reduction

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September 2025

A FACT SHEET AIMED TOWARDS SOLE CROP PRODUCERS.

1. Introduction

- Farming is the foundation of sustained human existence and the global economy by providing the world with vital commodities such as food, raw materials, and energy.
- However, producing sole crop and using too many chemicals has become affecting soils health, biodiversity loss, increase production costs, and harm the environment.
- To keep farming productive and profitable, it needs sustainable crop production system that protect soil health, enhance beneficial insects, and reduce reliance on external chemical inputs. Which is diversified cropping system.

2. Background

- Skåne, Southern Sweden is well known by its agricultural production potential. Due to its fertile soil and longest growing season, it covers nearly 60% of the total country's arable land.
- Despite its potential, crop production, in Skåne has become dominated by Sole cropping system. Mainly winter wheat, barley, oats, sugar beet, and oilseed rape.
- Over this the production system
- Is highly reliance on intensive external agrichemical inputs.
- Due to this biodiversity loss, soil nutrient depletion, and nutrient leaching has become problems.
- This situation highlights the need for more sustainable, resilient, and diversified cropping systems that doe not rely on external agrochemical inputs while maintaining productivity.
- One of the promising practices to reduce the negative impact of sole cropping is intercropping (IC).
- Based on this we tested this cropping system using winter wheat, winter oilseed rape and winter pea crops.

2.1. Why intercropping?

- Intercropping (IC) is the technique of growing two or more crops together at a time in the same farm.
- Intercropping helps farmers by improving soil health, boosting beneficial insects, reducing weeds, enhancing nutrient cycling, increasing land-use efficiency, and raising overall yield while lowering input costs and total grain yield risks.

3. What we tested?

- Intercropping crop production system was tested if it could be:

1. Enhance beneficial insects that helps to control pests.
2. Reduce weeds.
3. Improve crop growth and maintain or increase grain yields than sole strips or sole cropping systems while using fewer input with no chemical spray.

- **Sole Strip Cropping (SSC):** Means growing one crop per strip in the same field. Each strip is managed separately in the same farm at the same time.
- **Sole Cropping (Ref):** Means Growing only one crop at a time in a give farmland.
- The research was conducted at Lönnstorp, Skåne research center on 2023/2024 crop production year.

Figure 1. The three cropping systems tested in this study.

3.1. Practical steps

Table1. Land preparation and sowing dates

Activity	Details
Soil tillage	Up to **20 cm**, then leveled
Sowing dates	Winter Oilseed rape: 26–27 Aug 2023 Winter pea & Wheat: 28 Sep 2023

Abbreviations

- SSC-R=Sole strip winter Oilseed Rape
- SSC-W=Sole strip winter Wheat
- SSC-P=Sole strip winter Pea
- IC-R+P=Winter Pea + winter Oilseed Rape
- IC-W+P=Winter Wheat + winter Pea
- Ref-W=Winter wheat on uniform plot
- Ref-P=Winter Pea uniform plot
- Ref-R=winter Oilseed Rape uniform plot

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How we tested…

Table 2. The planting distance between crops.

Crop	Row Distance
Oilseed rape	50 cm
Wheat & Pea	12.5 cm

Table 3. The intecropped crop combinations and planting metheds

Combination	Planting Method
Pea + Oilseed rape	Between rows
Wheat + Pea	Alternating rows

Table 4. The seed density within the different cropping systems

System	Crop	Seeds/m²
Sole Crops	Oilseed rape	50
	Pea	60
	Wheat	300
Intercrops	Oilseed rape + Pea	50 + 60
	Wheat + Pea	150 + 30

Table 5. The type and amount of input used.

Input	Details
Fertilizer	• Biofer (10:3:1 N:P:K) • 50 kg/ha
Chemicals	• None used

Figure 2. The actual site where we tested the three cropping systems.

4. Key Findings

4.1. Beneficial insects

- Intercropping of winter wheat with winter pea increased about 162% more beneficial insects as compared with sole cropping (Ref) and 43 % from sole strip cropping (SSC).
- This helps for biological pest control and reduces the need for agro chemical use.

Figure 3. The three beneficial insects collected during this study were compared for their abundance across the three cropping systems.

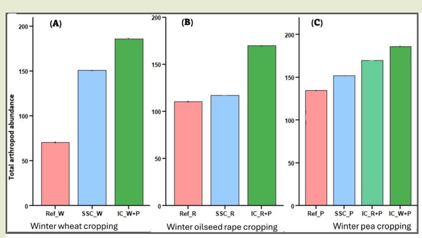

Figure 4. Beneficial insect abundance across the three cropping types. Red bars = Reference (Ref), representing the common farming system with only single crop in the given plot. Blue bars = Sole strip cropping (SSC), where a single crop is planted in wide strips. Green bars = Intercropping (IC).

4. 2. Weed suppression

- Intercropping winter pea with winter wheat reduced weed growth by 66%,
- mainly due to strong canopy cover soil shading that slowed weed growth and nutrient competions.

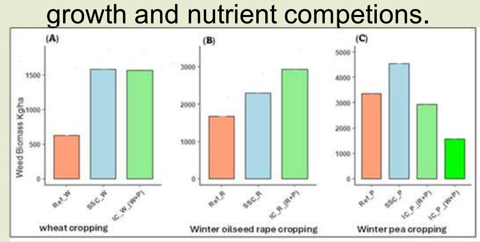

Figure 5. Weed biomass across cropping types. Orange bars = Reference (Ref), representing the common farming system with single crops. Blue bars = Sole strip cropping (SSC), where a single crop is planted in wide strips. Green bars = Intercropping (IC), where two crops are grown together.

4.3. Crop Vegetative growth (biomass)

- Winter pea intercropped with winter wheat indicated more benefited from in intercropping system.

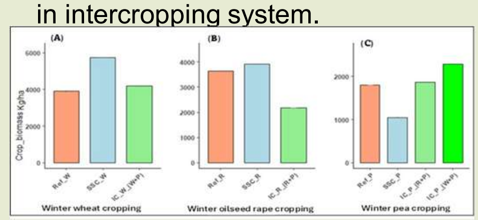

Figure 6. Winter pea gained higher biomass when intercropped with winter wheat, even at 50% lower seeding density. Winter wheat biomass remained stable across treatments, while winter oilseed rape showed reduced competitiveness in intercrops.

Abbreviations

- SSC-R=Sole strip winter Oilseed Rape
- SSC-W=Sole strip winter Wheat
- SSC-P=Sole strip winter Pea
- IC-R+P=Winter Pea + winter Oilseed Rape
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- Ref-W=Winter wheat on uniform plot
- Ref-P=Winter Pea uniform plot
- Ref-R=winter Oilseed Rape uniform plot

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Key findings…

4.4. Grain yields

- Winter Wheat and winter oilseed rape sometimes produced higher yields when grown alone, while winter peas performed much better in intercrops.
- Winter pea increased by up to 240% in intercropped with winter wheat compared to when grown alone. Figure 7 below presents the comparison among the crops individual results across cropping systems.

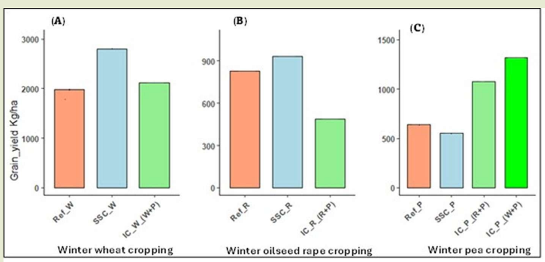

Figure 7. Grain yield under different cropping systems. Winter peas indicated more benefited when intercropped with winter wheat and winter wheat also achieved 75% of its sole strip cropping system. Both winter pea and winter wheat were at 50% seeding density.

5. Conclusion

- This study indicates that intercropping Better for nature and crops:
- Improves both soil health and crop performance.
- More helpful insects: Winter wheat and winter pea grown together had many more beneficial insects than fields with only one crop.
- Fewer weeds: Weed growth was cut by about two-thirds compared with pea grown alone.
- Good yields: Winter Pea yields increased. Wheat yields stayed stable even with 50% seeding density. Oilseed rape didn't perform as well when mixed.

In summary Intercropping supports, protects soil health, conserves biodiversity, reducing reliance on chemical fertilizers, pesticides and builds resilience for long-term farming.

6. Recommendations

- Start with wheat + pea intercropping this combination gave better results for weed control, beneficial insects, and pea grain more yield.
- Reduce fertilizer use when peas are included, since peas fix nitrogen naturally.
- Plant in intercropped rows so crops can complement each other: wheat helps suppress weeds, and peas add nitrogen to the soil.
- Use intercrops to manage weeds naturally; if weed pressure is high, combine with mechanical weed control.
- Expect stable or slightly lower yields in wheat and oilseed rape, but much higher yields in peas.
- Begin small test intercropping on part of your land before expanding to the whole farm.

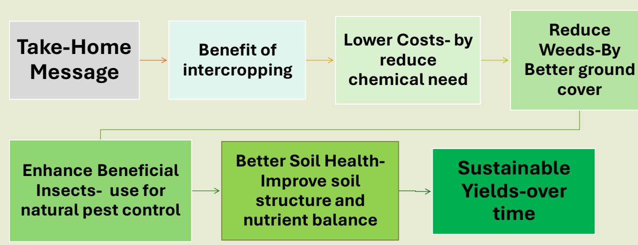

Figure 8. Key Benefits of Intercropping

Abbreviations

- SSC-R=Sole strip winter Oilseed Rape
- SSC-W=Sole strip winter Wheat
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- Ref-W=Winter wheat on uniform plot
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- Ref-R=winter Oilseed Rape uniform plot

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