COMPETITIVE ABILITY OF MIXED CROPPING SYSTEMS AGAINST WEEDS

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Master's thesis

Master's Programme in Agricultural Science

Plant production science

Department of Agricultural Sciences

University of Helsinki

May 2024

ABSTRACT

HELSINGIN YLIOPISTO — HELSINGFORS UNIVERSITET — UNIVERSITY OF HELSINKI

Tiedekunta/Osasto — Fakultet/Sektion — Faculty	Osasto — Sektion — Department
Faculty of Agriculture and Forestry	Department of Agricultural Sciences

Tekijä — Författare — Author

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Työn nimi — Arbetets titel — Title

Competitive ability of mixed cropping systems against weeds

Oppiaine —Läroämne — Subject

Plant production science, Crop science

Työn laji — Arbetets art — Level	Aika — Datum — Month and year	Sivumäärä — Sidoantal — Number of pages
M.Sc. Thesis	May 2024	46

Tiivistelmä — Referat — Abstract

Weeds have been identified as a threat to arable crop production because crop-weed competition may result in considerable yield losses. Weeds and crops often possess similar characteristics, making weed control challenging. Chemical weed control may lead to environmental and health issues, as well as troubles in crop production. Nowadays the tendency is towards more sustainable agricultural practices to control weeds including mixed cropping systems. In earlier studies, mixed cropping systems were observed to reduce weed biomass, whereas weed diversity was affected by environmental and temporal factors.

The present study was conducted at the Knehtilä organic farm in Hyvinkää to evaluate the competitive ability of mixed cropping systems against weeds. Crop stands were 50:50:50% and 33:33:33% oat, pea, and camelina mixtures, along with 100% oat, 100% pea, and 100% camelina stands. Plant sampling was conducted 24 Days after seeding (DAS), 38 DAS, 52 DAS, 66 DAS, and 97 DAS. Crops and weeds were separated and the number of plants in each species was counted. Weeds at the species level were identified. Dry biomass of crops and weeds was recorded at each sampling time. Weed species richness, Shannon-Weiner diversity index, species evenness, and species dominance were calculated.

The most common weed species was *Chenopodium album* L., while the least common species was *Cerastium fontanum* Baumg. Crop stands accumulated in weed biomass until 52 DAS, followed by a gradual decline over sampling times. Weed biomass was lower in 50% and 33% mixes than sole crop stands in early growth stages. Significant differences in the Shannon-Weiner diversity index, species richness, evenness, and species dominance were found in crop stands at 24 DAS and 66 DAS. There was a positive correlation between weed evenness and crop biomass.

The study proved that mixed crop stands (50% and 33% mixes) have effective weed control ability, indicating low weed biomasses compared to sole cropping systems. Weed diversity indices fluctuated at 24 DAS and 66 DAS, indicating that sampling time influences weed diversity. The positive correlation between weed evenness and crop biomass indicates the impact on species dominance and intraspecific competition. The study suggests that mixed cropping systems are effective at controlling weeds and highlights the importance of understanding temporal dynamics and weed-crop interactions in cropping systems to enhance crop yield. Future research should focus on understanding the fundamental mechanisms behind weed-crop interactions across cropping systems.

Avainsanat — Nyckelord — Keywords

Mixed cropping, Weeds, Species Diversity, Organic agriculture

Säilytyspaikka — Förvaringsställe — Where deposited

Master's Programme in Agricultural Sciences, Department of Agricultural Sciences

Muita tietoja — Övriga uppgifter — Further information

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Table of Contents

Abbreviations

cv	Cultivar
DAS	Days After Seeding
DM	Dry matter
FMI	Finnish Meteorological Institute
LI	Light interception
LUE	Light use efficiency
mm	millimeters
RY	Relative yield
SEM	Standard Error of the Mean

1 Introduction

Weeds are primarily invasive species that tend to grow aggressively resulting in an annual loss of 10-15 % of attainable crop yield (Chauhan 2020). They are independent plants that grow undesirably in cultivated areas (Baker 1974). Weeds have been identified as a risk to arable crop production, while their intensity and duration of crop-weed competition reveal the amount of agricultural yield losses (Swanton et al. 2015). Weed control is critical because, although weeds comprise only 0.1% of the total flora, some weed species can significantly affect agricultural productivity (Andreasen and Stryhn 2008). Weeds and crops have a long history, with 12 crop species in five different families accounting for 75% of the global food production, however, the same five families constitute the most troublesome weeds that cause considerable damage (Liebman et al. 2016). Weeds and crops commonly have similar characteristics and originate in the same places, making weed suppression important to crop production (Scavo and Mauromicale 2021).

Pesticides used in agricultural areas have the potential to contaminate water, soil, and sediments, causing environmental and health risks (Alengebawy et al. 2021). Water contamination may harm aquatic life and cause a variety of health issues, making it an important ecological issue (Lemaire et al. 2014). Repeated application of herbicides with a similar mode of action may lead to weed resistance over time which reduces the efficiency of herbicides, resulting in poor crop production while increasing costs and troubles related to weed management (Green and Owen 2011). Thus, nowadays the tendency is towards more sustainable agricultural practices designed to improve cultural, biological, physical, and ecological weed control methods by minimizing dependency on chemical herbicides (Gomiero et al. 2011).

Crop diversification has the potential to minimize weed impact by restricting the resources available to the weeds (Weisberger et al. 2019). Mixed cropping systems have the potential to improve agricultural biodiversity, climate resilience, production, and sustainability while also reducing the risk of weeds affecting crop yield (Altieri et al. 2015). Mixed cropping systems include the cultivation of multiple crops within the same field or several cultivars of the same crop with distinct life cycles within the same field (Gaba et al. 2015). Dense plant stands in mixed cropping systems allow the leaf and root to cover a larger area increasing water (Morris and Garrity 1993) and nutrition accessibility (Midmore 1993) while lowering the risk of crop failures. Different densities and arrangements in mixed cropping systems may improve crop competitiveness and resource utilization, resulting in lower weed abundance (Lowry and Smith 2018).

In this study, oat (*Avena sativa* L. cv. 'Ivory'), pea (*Lathyrus oleraceus* Lam. cv. 'Astronaute'), and camelina (*Camelina sativa* L. Crantz. 'Landrace') were examined in different mixed and sole crop stands to evaluate their competitive ability to suppress weeds along with weed diversity and weed behavior.

2 Literature review

2.1 Weeds in Cropping Systems

Weeds are plants that are considered undesirable in a certain situation because they can grow in areas that interfere with human preferences, requirements, or goals. They are capable of easily and quickly adjusting to their expanding surroundings (Clements and Ditommaso 2011). Weeds might have an impact on the environment, including natural habitats and cropping systems. Weeds can spread via animals, human activities, and infested seeds (Petit et al. 2011). Regular disruptions, such as those observed in agriculture, attract invasive species, altering the diversity and quantity of weeds, and soil disruption methods encourage the establishment of new germination sites (Murphy and Lemerle 2006). Weed expansion in agricultural areas may vary depending on the relationship between agronomic practices and environmental conditions such as temperature, precipitation, and soil moisture (Peters et al. 2014).

Some plants are known as weeds due to their ability to colonize and become dominant over other plants (Bajwa et al. 2016). Duffus (1971) defined weeds as any plant growing in an undesirable location or out of its proper area. Weeds are defined as herbaceous plants that are not recognized for their purpose or beauty and are growing wild, obstructing the growth of superior vegetation (Harlan and deWet 1965). Crop plants may be termed weeds if they grow in an inappropriate location (Baker 1974). One of the most recent definitions of weeds provided by the Weed Science Society of America (WSSA) indicates that weeds are plants that are undesirably grown in their natural habitat, and threaten human or animal health, while harming the economy or ecology (https://wssa.net/, Accessed on 19 February 2024).

2.2 Benefits and drawbacks of weeds in cropping systems

Weed competition for essential resources such as nutrients, light, and water has been identified as a key disturbance in cropping systems. According to Maun and Barrett (1986), the most frequent weed in rice (*Oryza sativa* L.), *Echinochlou crus-galli* L. Beauv., reduced the rice crop yield by 57%. Weeds can have detrimental effects on crop quality which reduces the economic value of the final harvest (Ekwealor et al. 2019). In some cases, crop and weed seeds are closely identical and they are difficult to distinguish (Barrett 1983). If weed seeds are not efficiently removed through screening techniques, the quality of the production process might decline, causing a reduction in overall value (Decker et al. 2014).

Some weeds serve as alternate hosts for crop pests such as insects, diseases, nematodes, and rodents (Sahrawat et al. 2020). Weeds can harm crop plants by attracting and colonizing insects and pests (Capinera 2005). Weeds are an effective food source for insects, with several insects feeding completely or mostly on them. For example, the sesiid moth (*Carmenta haematica* (Ureta)) entirely targets snakeweeds, *Guterrezia* sp., and *Grindelia* sp. of the Asteraceae family (Cordo et al. 1995). These insects may spread from weeds to crops, causing damage. Furthermore, most of these insects surviving in the weeds are known to transmit diseases. Wild oats (*Avena fatua* L.), barbery (*Berberis thunbergii* DC.), and quick grass (*Agropyron repens* (L.) P. Beauv.) are potential hosts for fungus *Puccinia graminis* f. sp. tritici, which infects cereals with black stem rust (Zhao et al. 2016).

Controlling weeds throughout the growing season is a cultural practice associated with crop cultivation. Weeds can be controlled by methods such as plowing, tillage, mowing, and thermal methods (Sanbagavalli et al. 2020). However, any weed control activity, from hand hoeing to herbicide application, is expensive (Swinton and Van Deynze 2017). Additionally, it is important to consider the expenses associated with machinery wear and tear which lead to an increase in the cost of production (Hobbs 2007). Although, these costs might be recovered in the future by preventing crop failures.

Weeds have certain benefits for agricultural systems apart from their drawbacks. Some weed species serve as natural pest repellents or attract beneficial insects, decreasing the need for synthetic pesticides (Hillocks 1998). Attracting insects like ladybugs (*Coccinella septempunctata* L.) and lacewings (*Leucochrysa insularis* (Walker)), which prey on pests like aphids (*Acyrthosiphon* sp.), potentially reducing the requirement for synthetic pesticides by naturally controlling pest populations

(Shaw 1982). Weeds can help to reduce soil erosion when their roots have established in the soil (Lenka et al. 2017). The presence of roots can alter topsoil resistance to erosion during concentrated flow, while specific weed species have a higher erosion-reducing capability due to increased root density and fine root proportion as in species such as *Plantago albicans* L., *Retama monosperma* (L.) Boiss., *Anthyllis vulneraria* L., *Tamarix* sp., and *Salsola* sp. (De Baets et al. 2007). Plants facilitate minimizing soil erosion by intercepting direct rain splash, promoting infiltration, increasing water retention, and reducing surface runoff (Lewis et al. 2013).

Weeds can be used as indicators of soil conditions and soil management approaches since they respond quickly to changes in the environment where they grow (Swanton and Murphy 1996). Some weeds grow in compacted soils, while others prefer loose, well-tilled soil. Farmers can learn about the pH, salinity, moisture, and nutrient content of the soil while making better cultivation decisions by investigating the growth habits of weeds in their croplands. This helps farmers to improve their agricultural systems while increasing profitability and environmental sustainability (Chauhan et al. 2012).

2.3 Factors influencing weed growth and development in organic farming fields

Weeds typically adapt to their surroundings once they locate a suitable spot to grow with appropriate growing conditions. Sunlight is essential for weed growth since it promotes photosynthesis and nutrient absorption, while light signals detected by specific photoreceptors such as phytochromes, cryptochromes, and phototropin can have diverse effects on weed growth and development (Ballaré and Casal 2000). Macro and micronutrients in the soil are also essential elements that influence the growth rate, biomass allocation, and reproductive ability of weeds (Patterson 1995).

Weeds do not have specific water requirements for their growth, and it depends on the area where they are grown. Garden weeds require adequate moisture by irrigation, but not as much as wetland weeds, while dryland weeds have been developed to withstand drought conditions and prefer less water availability (Mallikarjunarao et al. 2015). Weeds thrive in places with less crop competition and plenty of space to grow, especially in areas with less or no herbicide usage (Manalil et al. 2017). Moreover, certain crop varieties have been identified to compete with weeds more effectively than others. Therefore, cultivar selection also affects weed growth by selecting crops that can better compete with weeds, resulting in less weed growth (Nichols et al. 2015).

Weed infestations in Finnish organic farms cause several agricultural issues, including crop yield losses due to resource competition, and slower decomposition rate of weed biomass leading to weakened soil structure with less organic matter content (Salonen et al. 2011). Deep-rooted and fast-growing weeds remain in Finnish cereal fields, making it difficult to completely remove, while also the development of resistant weed biotypes becoming a serious challenge in organic farms (Lundkvist and Verwijst 2011). Furthermore, the spread of weed seeds to organic fields via various methods increases the spread of new weed species while expanding the seed bank (Salonen et al. 2005).

Finnish organic farmers use diverse weed control strategies to control weeds. Crop rotation and intercropping are common cultural weed control methods used in Finnish organic farms (Lundkvist and Verwijst 2011). Highly competitive cultivar selection and enhanced crop density reduce weed growth due to the ability to outcompete weeds (Salonen et al. 2005). Mechanical control methods such as flame weeding, mowing, and shallow tillage operations like harrowing and rotary hoeing are also common in Finnish organic farming fields (Lundkvist and Verwijst 2011). Proper soil management techniques, such as the usage of crop residue mulches, help to preserve the soil, whilst appropriate seedbed preparation removes weed seeds before planting (Salonen et al. 2005).

Table 1. Most common and competitive weed species in Finnish organic fields (Andreasen and Stryhn 2008, Lundkvist and Verwijst 2011, Salonen et al. 2011)

Most common weeds	Common name	Monocotyledon/ Dicotyledon	Annual, Biennial, Perennial	Most competitive weeds	Common name	Monocotyledon/ Dicotyledon	Annual, Biennial, Perennial
Chenopodium album L.	Lambsquarters	Dicotyledon	Annual (s)	*Cirsium arvense* (L.) Scop.	Canada thistle	Dicotyledon	Perennial
Elymus repens (L.) Gould.	Couch grass	Monocotyledon	Perennial	*Elymus repens* (L.) Gould.	Couch grass	Monocotyledon	Perennial
Erysimum cheiranthoides L.	Wormseed wallflower	Dicotyledon	Annual (w)	*Sonchus arvensis* L.	Field milk thistle	Dicotyledon	Annual (s)
Fallopia convolvulus (L.) Á.Löve	Wild buckwheat	Dicotyledon	Annual (s)				
Galeopsis sp.	Hemp-nettle	Dicotyledon	Annual (s)				
Myosotis arvensis (L.) Hill.	Field forget-me-not	Dicotyledon	Annual (w)				
Polygonum aviculare L.	Common knotgrass	Dicotyledon	Annual (s)				
Spergula arvensis L.	Corn spurry	Dicotyledon	Perennial				

w = winter annual; s = summer annual

2.4 A general overview of mixed cropping systems

Recently, there has been considerable criticism of utilizing intensive agricultural techniques for optimizing crop yield in monoculture systems that reduce crop diversity, since using uniform spacing and high external inputs such as chemical fertilizers, herbicides, and pesticides (Malézieux et al. 2009). There might also be various environmental costs from this modern intense monoculture system, such as soil erosion, increasing atmospheric carbon content, contaminating water supplies, and destroying biodiversity (Demirdogen et al. 2023). These issues encouraged scientists to explore the importance of multiple cropping systems over sole cropping in improving agricultural crop yield while preserving sustainable land use patterns and ecological diversity. Mixed cropping systems, including intercropping, have been identified as the world's oldest form of organized cultivation systems in agriculture (Lizarazo et al. 2020). Mixed cropping is defined as the simultaneous cultivation of two or more species or cultivars of the same species in the same field with no distinct row arrangement (Andrews and Kassam 1976, Lithourgidis et al. 2011). Mixed cropping system patterns exist in many parts of the world and the systems can vary according to region by adding different crop components (Lemaire et al. 2014).

2.5 Crop-weed competition and resource use efficiency in mixed cropping systems

Mixed cropping systems improve resource utilization efficiency by maximizing land, water, and nutrient consumption (Ghosh et al. 2007). This diversification reduces reliance on a single crop while increasing resistance to environmental changes. Furthermore, mixed cropping systems allow for complimentary interactions between plant species, which improves nutrient uptake and reduces the requirement for external inputs (Ehrmann and Ritz 2014). Plant species generally compete for similar essential resources (Craine and Dybzinski 2013). When two plants grow close together and compete for the same resources, their growth, survival, and reproduction can be affected. Weeds are more adapted to the agroecosystem than crop plants (Dekker 1997), allowing them to easily outcompete plants.

Light is one of the most important environmental resources for plant growth, however unlike water and nutrients, light cannot be saved for later use, and it must be used straight away (Poorter et al. 2012). Light influences numerous aspects of plant growth and development, including photosynthesis, stomatal opening, plant height, chlorophyll biosynthesis, branching, and reproduction, and the amount varies with duration, intensity, and quality (Paradiso and Proietti 2022).

Neighboring plants can restrict light supply through direct interception shade (Ballaré et al. 1995). Weeds and crops similarly respond to shading due to their similar morphological adaptations (Harrison and Peterson 1991). Light interception (LI) and light use efficiency (LUE) are two distinctive features of resource capture in mixed cropping systems. According to Liu et al. (2018), the LUE of intercropped soybean (*Glycine max* (L.) Merr.) and maize (*Zea mays* L.) was higher than that of sole cropping systems by 1.51 and 1.18 times, respectively. According to Gou et al. (2017), intercropping altered both light interception and light use efficiency by changing the degree of competitiveness and compensating interactions within and between crop species. Weeds have a greater potential for rapid and effective nutrient absorption than crops, including nitrogen, phosphorus, and potassium, whereas maize began competitive interactions earlier in its growth cycle in fields with lower weed populations (Lehoczky et al. 2003, Rajendran et al. 2004). According to Malicki and Berbeciowa (1986), common weeds particularly *C. album*, *C. arvense*, *Convolvulus arvensis* L., *Polygonum convolvulus* L., *S. arvensis*, and *S. media*, consumed more nutrients than crop species in the experimental field, indicating their significant competition for nutrient absorption. Plant roots compete for moisture below ground, and absorption capacity is determined by rooting volume (Schenk and Jackson 2002). Weeds transpire more water than crops to produce the same quantity of dry matter (Farooq et al. 2019). Dalley et al. (2006) found that Silverleaf nightshade (*Solanum elaeagnifolium* Cav.) decreased soil moisture in dryland cotton (*Gossypium hirsutum* L.) at depths less than 82 cm when compared to weed-free cotton. Variations in water extraction patterns between *Setaria Faberi* Herrm and *C. album* may have contributed to reducing the soil moisture content in the maize field (Dalley et al. 2006).

Crop-weed competition, resource utilization efficiency, and relative yields in intercropping and mixed cropping systems are correlated (Liebman and Dyck 1993). Relative yield measures how effectively one species performs in a mixture under specified conditions and competition from other species (D'Andrea et al. 2024). The two primary concepts that impact relative yield in a mixed cropping system are competitive balance between crops and weeds and dynamic interactions between crops and weeds for essential resources. According to Yu et al (2016), mixed cropping systems have a greater relative yield, indicating higher productive potential, due to efficient resource consumption and less competition from weeds than sole cropping systems.

2.6 Factors to enhance crop competitiveness in mixed cropping systems

According to Ehrmann and Ritz (2014), crop size, abundance, and proximity of growth influence weed growth where cultural practices play a significant role in crop competitiveness in mixed cropping systems. Crop competitiveness in mixed cropping systems can be greatly improved by planting well-adapted crop varieties (Baudoin et al. 1997). These varieties have been developed for their ability to grow in a range of agroecological conditions, allowing them to successfully share resources with other crops in a mixed cropping system thereby enhancing crop competition. Selecting crop varieties with complimentary root structures and phenological traits is critical for optimizing resource use efficiency and for improving overall system resilience (Zhang et al. 2020).

Optimal seeding dates promote crop competitiveness in mixed cropping systems by synchronizing growth stages and resource consumption (Duchene et al. 2017). Planting time is one of the important aspects of determining crop growth and resource gain (Lynch 1995). According to Singh et al. (2018), planting dates that align with the optimal climate improve uniform emergence and early vigor, allowing crops to develop robust root systems and canopy cover. This controls weed growth through shade and nutrient competition (Kumar et al. 2024). Furthermore, optimal timing reduces the danger of inter-crop competition, resulting in increased overall productivity and resilience in mixed cropping systems (Malézieux et al. 2009).

Fertile soil promotes crop competitiveness in mixed cropping systems by providing an optimal environment for plant growth and development (Malézieux et al. 2009), while also increasing plant vigor and competitiveness against weeds (Lowry and Smith 2018). The availability of key nutrients such as nitrogen, phosphorous, and potassium in soil affects crop biomass production, root development, and general physiological processes (Sinha and Tandon 2020). According to Ehrmann and Ritz (2014), soil fertility management in mixed cropping systems is important for crop productivity to reduce yield losses caused by interspecific competition.

Smother crops are a variety of species planted as cover crops that limit weed growth, development, and reproduction (Nosratti et al. 2023). They contribute significantly to crop competitiveness in mixed cropping systems by effectively suppressing weed growth (Mohanty et al. 2024). These cover crops restrict weed interference with primary crops by forming a physical barrier that inhibits weed establishment and growth due to their dense leaves, extended root system, and rapid growth (Nath et al. 2024). The allelopathic effect occurs when one plant produces chemicals that either restrict or encourage other plants' growth, survival, and reproduction, affecting their physiology and behavior (Kong et al. 2024). Smother crops can inhibit the germination and growth of weeds by releasing allelochemical substances such as phytotoxins and volatile organic compounds (Valiño et al. 2023). This combined process of physical and chemical interference reduces weed pressure and increases resource availability for crop growth (Rashid et al. 2023).

2.7 Indicators of weed diversity

Weed diversity indices are used to quantify the variety and abundance of weed species in a particular location, most commonly in agricultural environments (Fried et al. 2008). These indicators are important tools for understanding the ecological composition and dynamics of weed communities, as well as their behavior in agricultural production systems. The Shannon-Weiner diversity index, a widely used metric for assessing species diversity or evenness within a community, considers both species richness and proportional abundance, with higher index values indicating a greater diversity (Sawicka et al. 2020). The Shannon-Weiner diversity index can be calculated using the number of individuals present in a specific area and the total number of individuals present.

Species evenness is defined as the relative abundance of individuals in the community (Roy and Bhattacharya 2023), and the Shannon-Weiner index can be used to measure it by dividing the index by the natural logarithm of the total number of species. Evenness values can range between 0 and 1. A value of 0 corresponds to a community of one species with total dominance or no diversity, whereas a value of 1 to a community represents all species equally abundance (Stirling and Wilsey 2001). Species dominance indicates the prevalence of a particular species within the population which is the inverse of the Shannon-Wiener diversity index (Avolio et al. 2019). Researchers and farmers can estimate the complexity and resilience of weed populations in mixed cropping systems by considering these diversity indices (MacLaren et al. 2019).

Measuring weed diversity is critical in mixed cropping systems to understand the structure and dynamic patterns of weed communities and to support the development of successful weed management approaches that are customized to specific agroecological conditions (Colbach et al. 2021). Different weed species have different competitive capacities, biological niches, and sensitivities to control strategies. Weed diversity analysis enables farmers to identify potential crop production challenges and modify management strategies accordingly (Chauhan et al. 2017).

Furthermore, monitoring weed diversity over time allows for an evaluation of the long-term effects of agricultural activities on ecosystem resilience and environmental health (MacLaren et al. 2020).

3 Research objectives

Mixed cropping systems can have a positive effect on weed control and can reduce the requirement of chemical weed management have already been shown in previous studies (Mortensen et al. 2000, Rudinskienė et al. 2024, Sharma et al. 2021). This study aimed to assess the competitive ability of mixed cropping systems against weeds and weed diversity. The growth of different crop species mixtures was assessed in different seeding densities including 50:50:50% and 33:33:33% of pea:oat:camelina and 100% oat, 100% pea, and 100% camelina respectively in organic soil. The research hypothesis was that various crop stands and sampling times affect weed composition, weed biomass, and weed species diversity indices.

Specific research questions were as follows:

1. How do different crop stands influence weed density, weed composition, and biomass over time?
2. How do different crop stands and sampling times affect weed diversity indices?
3. How do weed evenness and different crop stands affect crop-weed interactions?

4 Materials and Methods

4.1 Experimental site

The field experiment was conducted at the Knehtilä organic farm in Hyvinkää (N 60°59' E 24° 92', 84 meters above sea level) in 2023. The soil type of the experimental site was silty clay loam with a pH of 6.3. The initial soil carbon (C) content of the field topsoil (0-25 cm) was 31.5 g kg^{-1} and the soil nitrogen (N) content was 2.3 g kg^{-1}. In field topsoil (0-25 cm), the phosphorus (P) content was 12 mg L^{-1}, and the potassium (K) content was 208 mg L^{-1}. The pre-crop harvested in autumn 2022 was winter rye (*Secale cereale* L.) with white clover (*Trifolium repens* L.) as a cover crop.

4.2 Plant material and experimental design

The field was harrowed twice in the spring of 2023. Oat (*Avena sativa* L. cv. 'Ivory'), pea (*Lathyrus oleraceus* Lam. cv. 'Astronaute'), and camelina (*Camelina sativa* L. Crantz. 'Landrace') were sown on 19 May 2023 using a plot seeder (Wintersteiger TC2700, Wintersteiger AG, Ried, Austria). The field experiment was arranged in a randomized complete block design (RCBD) with four replicates. The plot size was 1.5 m x 15 m. Sole stand seeding densities were 8 kg ha^{-1} camelina, 500 viable seeds m^{-2} oat, and 120 viable seeds m^{-2} pea. The seeding depth for pea and oat was 5 cm and for camelina was 1 cm. The row spacing was 12.5 cm. Oats and peas were seeded together once before the camelina was seeded. Species mixture seeding densities were 50:50:50% and 33:33:33% of pea:oat:camelina based on sole stand seeding densities. Fertilizers and pesticides were not used.

4.3 Plant sampling

Plant samples were collected five times during the growing season, 24 days after seeding (DAS), 38 DAS, 52 DAS, 66 DAS, and 97 DAS. Plant sampling was conducted from an area of 0.25 m^2 (50 cm × 50 cm) and all plants in the area were uprooted. Plants were shaken gently to remove the soil from the roots. Plants were separated into crop species and weed species. The weed species were identified and the number of plants in each species was counted. Samples were oven-dried at 70° C for four days and weighed. The number of crops per species was counted. The number of tillers and main stems in each species were counted separately. The number of flowers, panicles, and siliquee per plant was counted. Samples were oven-dried at 70° C for four days and weighed after which the samples were ground into fine powder (sieve 0.5 mm and 2 mm; Retsch ZM 200, Retsch GmbH, Haan, Germany). An untouched area of 10 m^2 was harvested from each plot with a plot combine harvester (Wintersteiger Classic Plus, Wintersteiger ag, 4910 Ried, Austria) at full maturity on September 06, 2023. The seeds were dried, sorted (Westrup A/S seed sorter, Westrup A/S, Denmark), and weighed. After that, seed moisture content, thousand seed weight, and test weight were measured.

4.4 Calculations and Indices

Relative yield (RY) describing the yield advantage of crops grown together in mixed cropping stands was calculated according to Bulson et al. (1997).

$$RY = \frac{Y\ mixture}{Y\ monoculture}, \qquad (1)$$

where $Y_{mixture}$ is the average yield of crop mixture and $Y_{monoculture}$ is the average yield in a monoculture system.

The Shannon-Wiener diversity index (H) equation (Weaver 1963) describing the weed diversity in sole cropping and mixed cropping systems was calculated as follows.

$$H = -\Sigma \mathrm{P}i \times \ln(\mathrm{P}i)\ , \tag{2}$$

where p_i is the proportion of the entire community of species *i*. The values of this index range between 1.5 and 3.5 (MacDonald and Kirkpatrick 2003).

Species dominance which is the inverse of the Shannon-Wiener diversity index (1/H) (DeJong 1975) was calculated as.

$$\mathrm{D} = \frac{1}{H}\ , \tag{3}$$

where D is species dominance and H is the Shannon-Weiner Diversity Index.

Weed species evenness measures how evenly distributed the populations of various weed species compared to each other is calculated according to Travlos et al. (2018).

$$Species\ evenness = \frac{H}{\ln\,(\mathrm{S})}\ , \tag{4}$$

where S is the total number of species count, and H is the Shannon-Weiner Diversity Index.

4.5 Weather

The growing season was warm compared with the long-term average temperature (1991 – 2001) (FMI 2023), particularly in May, June, August, and September (Table 2). Furthermore, the precipitation for May, June, and September was lower while in July and August, the precipitation was higher in comparison to the long-term average precipitation (FMI 2023).

Table 2. Monthly mean temperatures and precipitation during the growing period in May – September 2023 and the long-term means from 1991 to 2001 in Hyvinkää Hyvinkäänkylä (N 60°59' E 24° 92'), Finland (FMI 2023).

	Temperature (°C)		Precipitation (mm)	
	2023	1991-2001	2023	1991-2001
May	10.3	9.4	29	35
June	15.8	14.1	38	59
July	16.2	16.6	80	74
August	16.5	14.9	138	76
September	14.1	9.5	47	49

4.6 Statistical analysis

The quantitative analysis was done using a two-way analysis of variance (ANOVA) at a $p = 0.05$ level of significance. Various parameters including plant density, weed biomass, and total yield were taken as dependent factors. Data in different mixed cropping stands were compared within each sole cropping stand, and weeds were analyzed and compared separately. Duncan HSD post hoc test was used to identify pairwise differences between parameters and the crop stands. Descriptive statistics were estimated, and the Homogeneity of variances was estimated by Levene's test. The statistical analyses for data were conducted using SPSS (Version 29.4, SPSS Inc., Chicago, IL, USA).

5 Results

5.1 Weed density, species composition, and weed biomass

Weed density was not affected by crop stands ($p = 0.22$) and sampling time ($p = 0.16$) (Figure 2). There was also no interaction in weed density between crop stands and sampling time ($p = 0.99$). However, crop stand communities differed in terms of community composition (Figure 1). The most common weed in the 50% mix was *C. album* (24% of total weed density) followed by *Lamium* sp. (13% of total weed density). There was 23% of *C. album* in the 33% mix (Figure 2). *C. album* was the primary weed in the 100% oat mix (20% of total weed density) (Figure 2). The most common weed species in 100% camelina and 100% pea was *C. album* (33% and 28% of total weed density respectively). *Galium spurium* L. was the second most common weed in 100% pea stand (11% of total weed density) (Figure 2).

Weed biomass was affected by crop stands ($p < 0.001$) and sampling time ($p < 0.001$) (Figure 3). There was also an interaction in weed biomass between crop stands and sampling time ($p < 0.001$) (Figure 3). There was lower weed biomass in 50% and 33% mix compared to sole cropping systems, where all crop stands initially had lower weed biomasses with gradual increases observed until 66 DAS, except for 100% pea (Figure 3). There was a significant increase in biomass of 100% pea at 52 DAS, followed by a gradual decline towards the subsequent sampling times similar to other crop stands (Figure 3). The weed biomasses were significantly differed at the 66 DAS and 97 DAS (Figure 3).

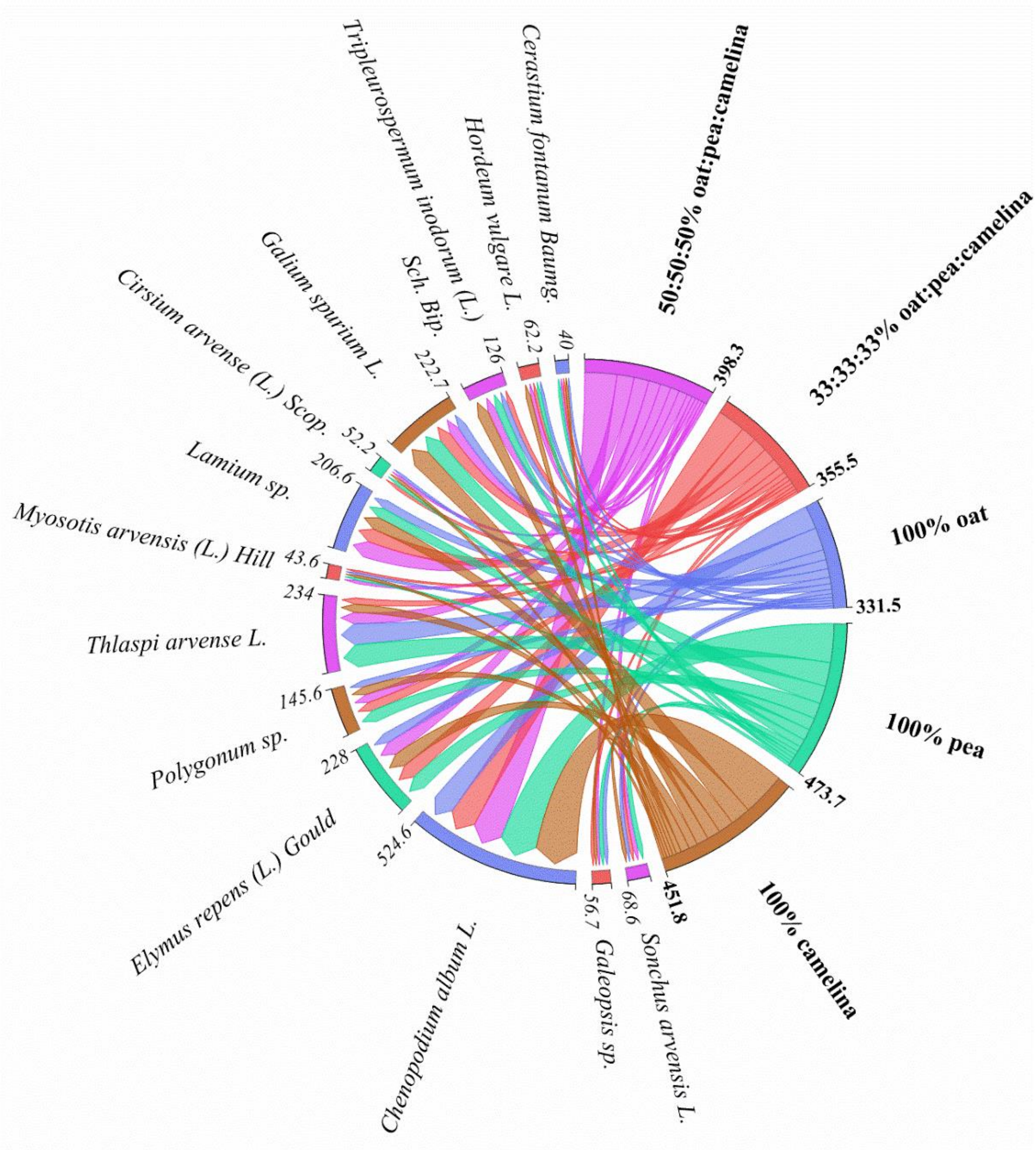

Figure 1. Weed species distribution at the Knehtilä organic farm in Hyvinkää in 2023. The direction of the lines illustrates the weed species associated with each crop stand.

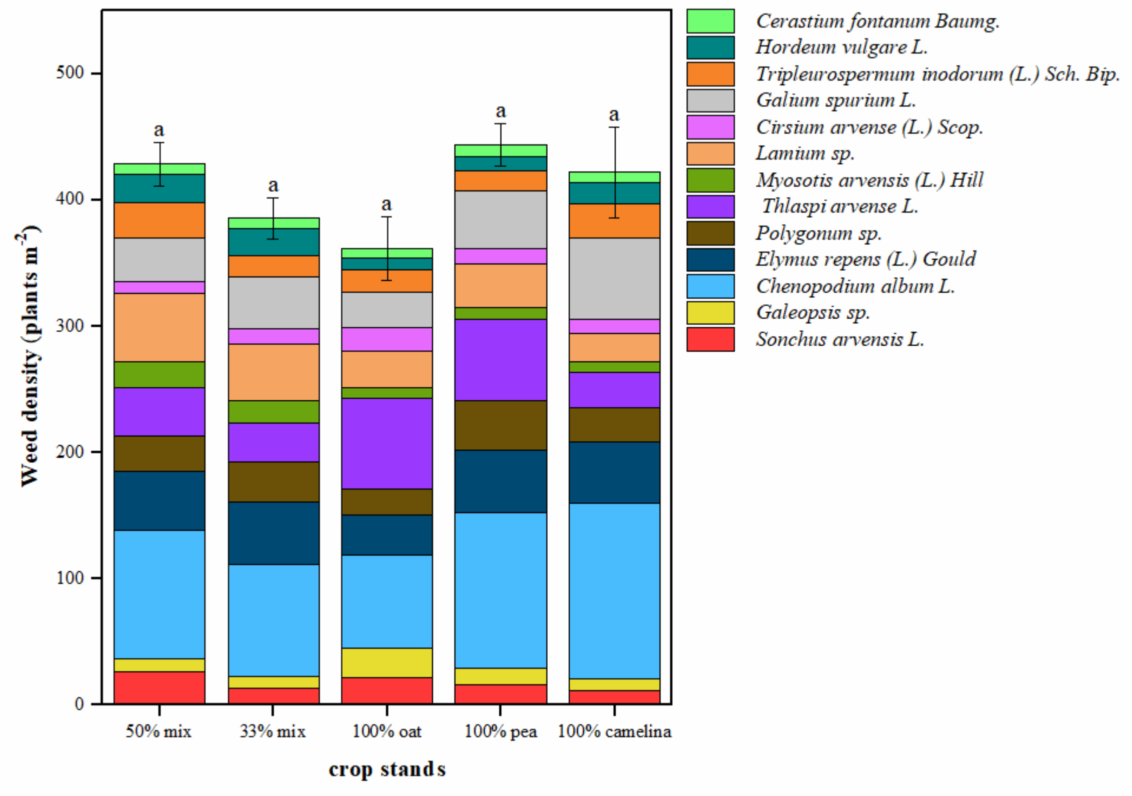

Figure 2. Weed density (number of plants m^{-2}) as affected by different sole and mixed crop stands at the Knehtilä organic farm in Hyvinkää in 2023. Error bars represent the Standard Errors of Mean. The same letters are not significantly different (Duncan's $p < 0.05$).

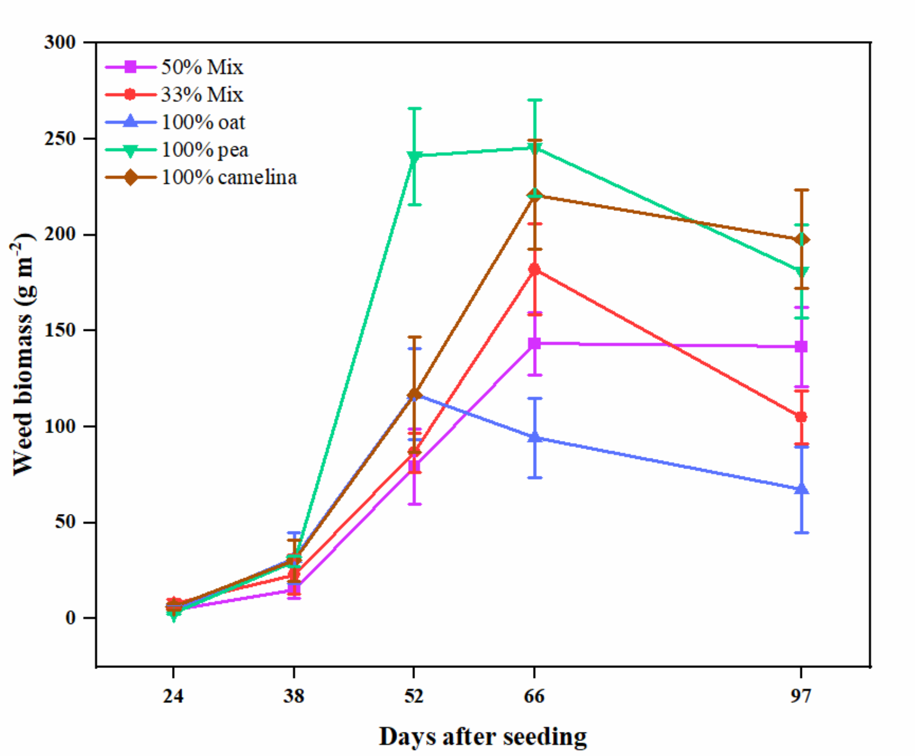

Figure 3. Weed biomass in five different sampling times as affected by different sole and mixed crop stands at the Knehtilä organic farm in Hyvinkää in 2023. Error bars represent the Standard Errors of Mean.

5.2 Weed species diversity indices

There were no differences in species richness in sole stands nor mixed stands ($p = 0.64$) (Figure 4). However, species richness was affected by sampling time ($p <0.001$) (Figure 4). There was no interaction between crop stands and sampling time ($p = 0.66$). The significant differences in sampling time were at 24 DAS and 66 DAS. The highest species richness at 24 DAS was in 100% pea (4.25) whereas the lowest was in 100% camelina (3.25). The highest species richness at 66 DAS was in 100% oat (6.75), 100% pea (6.75), and 100% camelina (6.75), whereas the lowest was in the 33% mix (4.00).

Shannon-Weiner diversity index was not affected by crop stands ($p = 0.89$). There was also no interaction in the Shannon-Weiner diversity index between crop stands and sampling time ($p = 0.42$). However, the Shannon-Weiner index was affected by sampling time ($p < 0.001$) (Figure 4). The significant difference in sampling time was at 66 DAS. The highest Shannon-Weiner diversity index value at 66 DAS was in 100% oat (1.75), followed by 50% mix (1.62), 100% camelina (1.61), and 33% mix (1.61), while the lowest was in 100% pea (1.41) (Figure 4).

Species evenness was not affected by the crop stands ($p = 0.53$). However, the sampling time influenced the species' evenness over time ($p = 0.03$). There was no interaction in species evenness between crop stands and sampling time ($p = 0.79$). The significant difference in sampling time was at 66 DAS. The highest species evenness at 66 DAS was in the 100% oat (0.87), followed by 50% mix (0.81), 33% mix (0.79), and 100% camelina (0.71), whereas the minimum was in the 100% pea (0.67) (Figure 4).

Weed species dominance was not affected by crop stands ($p = 0.98$). However, weed species dominance was affected by sampling time ($p < 0.001$). There was no interaction in weed species dominance between crop stands and sampling time ($p = 0.77$). Weed species dominance patterns were not similar throughout the growing period (Figure 4). The significant difference in sampling time was at 66 DAS. The highest weed species dominance at 66 DAS was in 100% pea (0.30), followed by 100% camelina (0.25), 33% mix (0.23), 50% mix (0.23), while the lowest weed species dominance was in the 100% oat (0.20) (Figure 4).

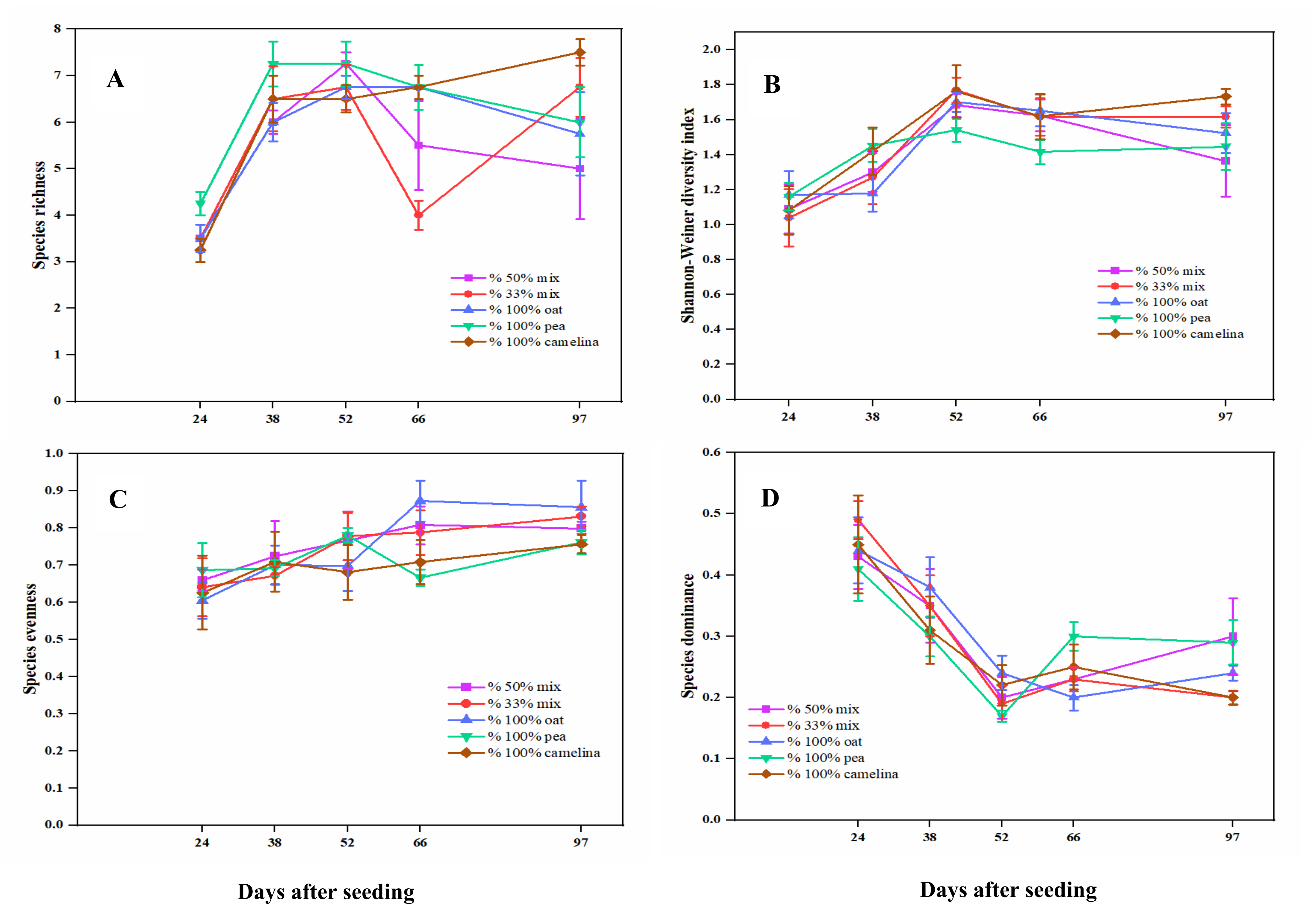
A
Species richness
B
Shannon-Weiner diversity index
C
Species evenness
D
Species dominance
% 50% mix
% 33% mix
% 100% oat
% 100% pea
% 100% camelina
24
38
52
66
97
Days after seeding
Days after seeding

Figure 4. The effect of different sole cropping and mixed cropping stands and sampling time on weed species diversity indices (A) species richness, (B) Shannon-Weiner diversity index (C) species evenness, (D) species dominance. Error bars represent the Standard Errors of Mean. Data shown are means, n=4.

5.3 Weed-crop interactions

Weed biomass until 52 DAS accumulated in all crop stands and then declined gradually over the sampling times of the experiment (Figure 5). There was lower weed biomass in 50% mix and 33% mix compared to sole cropping systems (Figure 5). During the first three sample times, 100% camelina and 100% pea had a similar relationship, with higher weed biomasses compared to other crop stands (Figure 5). However, during the last two sampling times, both had a declining trend where 100% pea showed higher weed biomass than 100% camelina. There was an increasing trend of weed biomasses in 50% mix, 33% mix, and 100% oat until 52 DAS. During the last two sampling times, 100% oat had the lowest weed biomass while all crop stands indicated a declining trend (Figure 5).

As the weed species' evenness increased from 0 to 0.9, crop biomass had a positive correlation except for the noticeable decreasing trend in crop biomass over weed evenness at 24 DAS (Figure 5). At 38 DAS, 52 DAS, 66 DAS, and 97 DAS, crop biomass trendline slopes were (+124), (+770), (+1048), and (+2048) particularly (Figure 5). The minimum slope of the trend line was at 24 DAS (-218) with a negative correlation (Figure 5). There was a negative relationship between weed evenness and weed biomass throughout the growing period (Figure 5). As the evenness of weed biomass increased from 0 to 0.9, the maximum decrement of the trend line was in 97 DAS with a slope of -1233 followed by 66 DAS (-725), 52 DAS (-125), and 38 DAS (-114) while minimum slope was at 24 DAS (-26) (Figure 5). The negative slopes at different sampling times indicate a reduction in weed biomass as weed evenness increases.

There was a lower relative yield compared to sole crop stands in the 50% mix, with relative yields of 0.949 and 0.984 for pea and oat, respectively, while camelina had a higher relative yield of 1.189. The relative yield for pea and oat in the 33% mix was lower compared to the sole cropping systems (0.859 and 0.890 respectively), however, 100% camelina had a higher relative yield of 1.076. Camelina tends to perform relatively better in mixed cropping systems, particularly in both 50% mix and 33% mix. 50% mix stand had higher productivity compared to the relative yield of 33% mix stand.

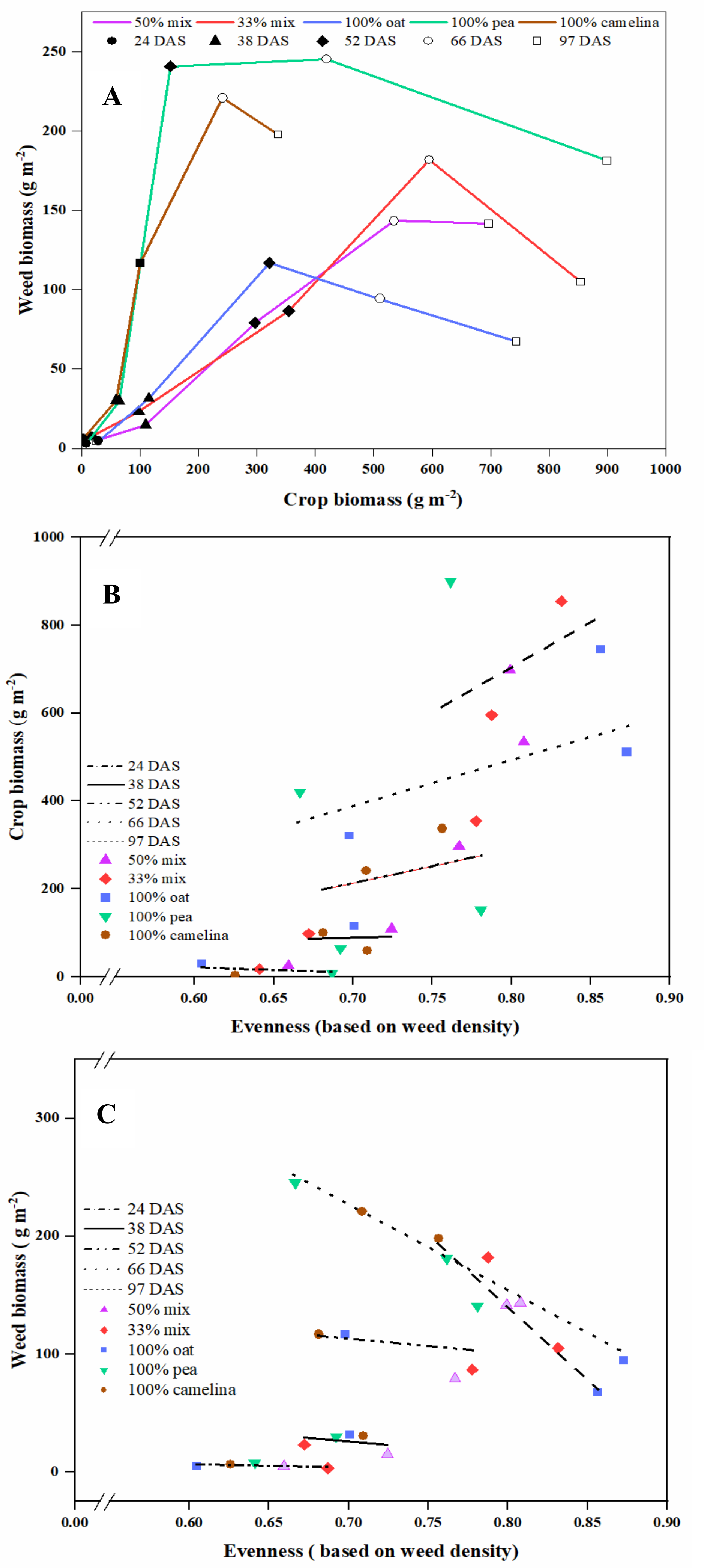
A
50% mix
33% mix
100% oat
100% pea
100% camelina
24 DAS
38 DAS
52 DAS
66 DAS
97 DAS
Weed biomass (g m-2)
Crop biomass (g m-2)
B
Crop biomass (g m-2)
Evenness (based on weed density)
C
Weed biomass (g m-2)
Evenness (based on weed density)

Figure 5. (A) Relationships between crop biomass and weed biomass, (B) weed evenness and crop biomass, and (C) weed evenness and weed biomass at different sampling times. Lines in the relationships between evenness with crop and weed biomass represent linear fit for each sampling time.

6 Discussion

6.1 Weed density, species richness, and composition in sole and mixed crop stands

In this experiment, sole cropping and mixed cropping stands and sampling times did not affect weed density. However, communities differed in terms of community composition in each crop stand. *C. album* was the most common species found in all crop stands followed by *Thlaspi arvense* L. and *E. repens*. A total of 13 weed species belonging to nine families were at the experimental location. Each crop stand creates a unique environment that favors certain weed species due to their preferences for specific conditions. According to Legere et al. (2005) and Barosso et al. (2015), mixed cropping systems have an impact on weed community composition due to the presence of multiple crop species and their management practices. Different crop species have diverse growth characteristics, and different weed management strategies function as ecological filters, influencing the composition and abundance of weed species in the ecosystem. According to Legere et al. (2005), the mixed cropping system had the most diverse weed composition, whereas monoculture barley (*Hordeum vulgare* L.) and red clover (*Trifolium pratense* L.) had fewer weed species each year. This might be due to sole cropping systems having limited resources and growth requirements, leading to a reduction in weed species diversity. Mixed crop stands provide various habitats and niches for weed species because of the resource compatibility and distinct growth requirements of multiple crops planted together. This variety of habitats may result in a wider range of weed species in mixed cropping systems (Malézieux et al. 2009, Picasso et al. 2008). The prevalence of *C. album* across all plant stands in the present experiment highlights the significance of understanding weed community dynamics. This is due to different weed species having varied reproduction and dispersal capacities, and their adaptability to various environmental conditions (Barosso et al. 2015). According to Murphy and Lemerle (2006), the diverse composition of weed species in a cropping system can influence competitive dynamics and cropping system resilience.

In this experiment, species richness was not affected by different crop stands. However, species richness was affected by sampling time. The species richness at 24 DAS was highest in 100% pea and lowest in 100% camelina. There were variations in the species richness at 66 DAS where, 100% camelina, 100% oat, and 100% pea had the highest species richness, while 33% mix had the lowest. This finding aligns with Fried et al. (2008), who postulated that cropping system diversity does not have a direct impact on species richness, factors such as sampling time and environmental conditions might impact weed species diversity within the community. According to Fried et al. (2008), weed species richness peaked in spring and summer and was lowest in autumn and the diversity of species in the community was most likely impacted by environmental factors such as soil pH, landscape, nutrient level, seeding date, temperature, and precipitation. The effect of weed species diversity might also be due to temporal fluctuations in weed emergence and growth (Seifert et al. 2015). The weed species community in this experiment might vary depending on the time of year the samples were taken, as well as environmental factors such as soil type, temperature, and rainfall may all contribute to the diversity of weed species in a specific location.

In this experiment, weed biomass was affected by crop stands and sampling time. There were fluctuations in the biomass at 66 DAS and 97 DAS while the 50% and 33% mixes had lower weed biomass compared to sole cropping systems. Initially, all crop stands had lower weed biomass, followed by an increasing trend until 66 DAS. Previous studies by Ranaldo et al. (2020) and Little et al. (2021) emphasize the importance of crop diversification for reducing weed growth. Crop combinations with increased crop diversification have lower weed biomass than monocultures since the combination of crops with different growth patterns, root structures, and life cycles can improve weed control (Liebman and Dyck 1993). This also might be due to resource competition for nutrients, water, and light where higher crop diversity might result in a stronger environment in which nutrients are more effectively shared across plants, ultimately inhibiting weed growth (Florence et al. 2019). Crop architecture, such as higher and denser crops, can help control weeds by limiting their access to resources (Ehrmann and Ritz 2014). Furthermore, crops in mixed cropping systems may have allelopathic effects, which can have a substantial influence on reducing weeds by releasing toxins or other chemical substances (Scavo and Mauromicale 2021).

6.2 Weed-crop interactions in different crop compositions, and their effect on weed biomass and crop productivity

In this experiment, the relationship between weed biomass and crop biomass varies depending on the crop stand and sampling time. Initially, weed biomass accumulated similarly in all stands until 52 DAS, followed by a gradual decline over subsequent sampling times. This pattern indicates that weeds have an early competitive advantage, followed by a reduction in weed biomass, probably due to crop canopy closure and increased shade, which limit weed development (Bastiaans et al. 2000). According to Rajcan and Swanton (2001), weeds had an early competitive advantage over maize since weeds emerged before the crop. This is also consistent with Colbach et al. (2019) and Holt (1995), according to whom weeds can have an early advantage in competition over crops due to their ability to intercept light. However, crop canopy closure over time significantly reduces sunlight penetration into the soil, resulting in a reduction in available Photosynthetically Active Radiation (PAR) (Korav et al. 2018).

In this experiment, there was a higher weed biomass produced by 100% pea compared to other crop stands. According to Corre-Hellou et al. (2011), pea and barley, intercrops were more effective at suppressing weeds than pea or barley grown as sole crops, with weed biomass in sole pea fields three times greater than in pea-barley intercrop fields due to peas' less competitive ability against weeds at the beginning of the crop cycle. Weeds accumulated 57 kg of soil nitrogen per hectare in aboveground plant parts during the growing season in sole pea crops, whereas pea-barley intercrops had a higher competitive ability against weeds (Hauggaard-Nielsen et al. 2001). This was due to the intercropped pea absorbing inorganic nitrogen from the soil while supplying nitrogen to the barley (Hauggaard-Nielsen et al. 2001).

In this experiment, the relationship between weed biomass and crop biomass further indicated that mixed cropping stands, particularly the 50 % mix and 33% mix had lower weed biomass compared to sole crop stands. Similarly, according to Finn et al. (2013), mixed cropping systems had lower weed biomass in comparison to sole cropping systems. This was mainly due to the phenomena of species complementarity that may promote effective resource usage in mixed cropping systems, therefore diminishing weed abundance. In mixed cropping systems, some species have deep roots that absorb nutrients, whilst others have broad leaves with appropriate leaf angles that allow for better light penetration (Trenbath 1976). On the other hand, sole crops are vulnerable to certain pests, which can lead to pest population explosions, whereas in mixed crops, pest populations are spread among different species, reducing the danger of complete crop destruction (Wenda-Piesik and Piesik 2020). Moreover, the diversified nature of mixed cropping systems might slow down weed establishment because each crop species within the mixture may utilize resources in different ways, creating less favorable conditions for weed growth and spread (Chapagain et al. 2020). Monoculture treatments, on the other hand, often lack functional diversity and may have lesser weed suppression abilities (Dos Santos et al. 2021).

In this experiment, pea and oat had lower relative yields as compared to sole crop stands in both 50% and 33% mixes, however, 100% camelina had a higher relative yield. Camelina tends to perform relatively better in mixed cropping systems. The productivity of 50% mix was higher compared to the relative yield of 33% mix. Planting multiple species of crops together, rather than cultivating them alone, can increase the overall yield within a shared plot of land (Snyder et al. 2020). This is mainly due to the mechanism of selection effect which occurs when different kinds of plants make efficient use of nutrients and water. Planting diverse species together improves the probability of growing a plant that is well-suited to the environment, maximizing productivity. Furthermore, niche complementarity occurs when diverse plant species use resources in different ways, reducing intra-species competition through resource partitioning. Overall productivity increases as resource use becomes more efficient. These facilitative interactions in less favorable times reduce the risk of crop failures leading to higher relative yields compared to monoculture systems (Wu et al. 2023).

6.3 Weed species diversity, weed evenness, crop biomass, and their interactions

In this experiment, the Shannon-Weiner diversity index was not affected by crop stands. However, the Shannon diversity index was influenced by the sampling time. The highest value for the Shannon diversity index at 66 DAS was in 100% oat, whereas the lowest was in 100% pea. According to Pakeman (2011), the dynamic nature of weed species composition varied in response to environmental factors such as temperature, precipitation, soil type, nutrient availability, and different management practices. Calculating the Shannon diversity index at various sampling times had temporal fluctuations in weed community composition during the growing period (Golmohammadi et al. 2018). This might be due to the dynamic changes in weed community composition throughout the growing season, as different species dominate at different points, influencing their presence and abundance throughout the sampling period (Legere et al. 2005). According to Smith and Gross (2007), variations in the Shannon diversity index during the growing season were due to natural fluctuations in population and cyclical weather patterns.

In the present experiment, species evenness was not affected by the crop stands. However, weed evenness was affected by the sampling time. The highest species evenness at 66 DAS was in 100% oat, followed by 50% mix, 33% mix, and 100% camelina, while 100% pea had the lowest species evenness. According to Cordeau et al. (2021), weed evenness changes across sampling times were due to the changes in the soil type, soil nutrient content and temperature, light intensity, soil moisture, and atmospheric CO_2 concentrations. Changing climatic conditions, influence the species composition of arable weed communities in specific locations, possibly leading to functional characteristic shifts and changes in community composition, whereas extreme weather and rapid climatic changes disrupt ecosystem stability and increase disturbance levels (Peters et al. 2014).

In the present experiment, weed species dominance was not affected by crop stands, but it was affected by sampling time. At 66 days after seeding (DAS), the highest species dominance was in 100% pea, followed by 100% camelina, 33% mix, and 50% mix, whereas the lowest species dominance was in 100% oat. According to Raamesh et al. (2017), crop composition has a direct impact on weed species dominance while temporal factors such as climate, sampling time, soil conditions, and management strategies also have important roles in weed species dominance patterns over time in agricultural ecosystems. These parameters can interact with one another as well as with crop composition, influencing total weed species composition and dominance patterns (Fried et al. 2008). According to Petit et al. (2011), these fluctuations also might be due to environmental heterogeneity in modified landscapes and land management strategies such as tillage, fertilization, and pesticide usage.

In the present experiment, there was a positive correlation between weed evenness and crop biomass. As the weed evenness increased from 0 to 0.9, there was a positive correlation in crop biomass except for the noticeable decreasing trend at 24 DAS. The strong relationship between crop biomass and weed evenness shows that when weed biomass is evenly distributed, crops can survive and produce more biomass. According to Gandía et al. (2021), a positive correlation between crop biomass and weed evenness suggests that crops have higher biomass when weeds are equally distributed, possibly due to reduced competition for resources in various cropping systems. According to Lal et al. (2014), a positive correlation between crop biomass and weed evenness indicates that evenly distributed weeds facilitated rice crop growth, resulting in increased biomass production, while also indicating that higher weed evenness may suppress the growth of dominant weed species, reducing their competitiveness for resources such as water and soil nutrients.

In the present experiment, there was a negative relationship between weed evenness and weed biomass throughout the growing period. As the evenness of weed biomass increased from 0 to 0.9, the maximum decrement of the trend line was in 97 DAS while the minimum was in 24 DAS. The negative slopes at different sampling times indicate a reduction in weed biomass as weed evenness increases. According to Adeux et al. (2019), the negative relationship between weed evenness and weed biomass across all sample times was due to decreased intraspecific competition and resource utilization among weed species. Increasing evenness reduces competition across weed species which leads to effective resource utilization among crops while potentially reducing total weed biomass. The negative correlation was also due to the geometric distribution among species in most plant communities, which does not always remain constant (Poggio and Ghersa 2011).

We found limitations during the present experiment due to the fluctuating weather conditions, including temperature and precipitation. Maintaining uniformity in the cropping stands was challenging throughout the experimental period.

7 Conclusions

Weed communities differed in community composition in each crop stand. Mixed crop stands were a promising method to reduce weed biomass and promote weed diversity. Based on the observations, weed species richness in sole and mixed cropping stands was affected by sampling time indicating fluctuations at 24 DAS and 66 DAS. Weed biomass was affected by both crop stands and sampling times, with lower weed biomasses in 50% and 33% mix compared to sole cropping systems. Sole and mixed crop stands had diverse weed-crop interactions. The relationship between weed biomass and crop biomass indicated that all crop stands had accumulated weed biomass until 52 DAS, followed by a gradual decline over subsequent sampling times. The productivity of 50% mix stand was higher compared to the relative yield of 33% mix stand, while camelina performed better in mixed cropping systems. There are significant variations in the Shannon diversity index, species dominance, and species evenness at 66 DAS.

Weed species indices, including species richness, evenness, Shannon-diversity index, and species dominance, were influenced by temporal dynamics whereas mixed-crop stands demonstrated lower weed biomass compared to sole-crop stands. A positive correlation between the evenness of crop biomass suggests that a more even distribution of weeds may enhance resource utilization for crops by reducing weed dominance, resulting in higher crop biomass. The study indicates that mixed cropping systems are more effective at managing weeds while understanding temporal dynamics and weed-crop interactions in organic cropping systems is critical for optimizing crop yield. However, the ultimate crop production of a cropping system can be affected by a variety of environmental and management approaches, suggesting the need for future studies to understand the fundamental mechanisms influencing weed-crop interactions across cropping systems.

Acknowledgment

Prof. Pirjo Mäkelä is acknowledged as my esteemed supervisor of this work. Markku Tykkyläinen is acknowledged for the technical support and assistance in this project. Chao Xiao and Ilja Koli are acknowledged for their support in species identification, plant sampling, and plant handling. My family is acknowledged for their continuous support and encouragement throughout the work.

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