Companion crops in winter oilseed rape

Effects on nitrogen concentration, biomass, and prevalence of weeds at the end of autumn growth

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Companion crops in winter oilseed rape – effects on nitrogen concentration, biomass, and prevalence of weeds at the end of autumn growth

Kompanjon grödor i höstraps – effekt på kväveinnehåll, biomassa och ogräsförekomst på hösten

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Abstract

Intercropping can be used as a management system to promote higher yield as well as less weeds, diseases, and insect damage. Legumes are a commonly used companion crop (CC) in intercropping due to the benefit of nitrogen (N) fixation. In this thesis, intercropping winter oilseed rape (WOR) with legumes (faba bean, blue lupin, common vetch, and clover mixture) will be tested to explore the possibilities of improved N concentration, biomass and weed suppression in organic oilseed rape at the end of autumn growth. Biomass of WOR, legumes, and weeds as well as N concentration were assessed from two field trial studies from two consecutive years, in Örebro county and in Västra Götaland county in November each year. The N concentrations were higher in WOR intercropped with legumes than in the sole crop in 2021, but not in 2022. The biomass of WOR was higher in 2022 than 2021. The biomass of WOR was significantly higher for the sole crop compared to when intercropped with legumes in 2021, but there was no significant difference between the treatments (CCs and row spacing) in 2022. For the sole crop and WOR intercropped with a clover mixture, there was a significant positive relationship between the wet weight of WOR and weeds in 2021, but not for any other treatment during any of the years. There was no significant difference between the CCs regarding any of the three most common weeds. Intercropping with legumes seems to increase the N concentration in WOR, but not the biomass. In 2021, the biomass, competitiveness, and yield of WOR were probably affected by a late sowing date. More biomass of WOR does not seem to lead to less weeds, instead the opposite, probably due to interspecific competition. Changes in soil type within the field of 2022 is likely to have affected the weed prevalence and wet weight of weeds. More data for several years and field trials would be preferable to evaluate the influence of site-specific factors. Yet, there is indications that intercropping could be a promising agricultural practice to increase the N concentration in WOR and may have the possibility to decrease the need for N fertilizers in organic cultivation.

Keywords: biomass, companion crops, intercropping, legumes, nitrogen concentration, organic cultivation, weeds, winter oilseed rape

Sammanfattning

Samodling av växter kan användas för att främja en högre skörd samt minimera förekomst av ogräs, sjukdomar och insektsskador. Baljväxter används ofta som en kompanjongröda i samodling eftersom de kan fixera kväve. I detta arbete undersöktes möjligheterna för högre kväveinnehåll, större biomassa och bättre ogräskonkurrens i ekologisk höstraps som odlats tillsammans med baljväxter (åkerböna, lupin, vicker och klövermix) på hösten. Biomassa av raps, baljväxter och ogräs samt kväveinnehåll samlades in i november från två fältförsök från två olika år, ett från Örebro län och det andra från Västra Götalands län. Kväveinnehållet var lägre i höstraps utan kompanjongröda än i samodlad höstraps 2021. Det var mer biomassa av höstraps hösten 2022 än 2021. Det fanns en signifikant skillnad i biomassa 2021, där biomassan av höstraps utan kompanjongröda var högre än för höstraps samodlad med baljväxt. Det fanns ingen signifikant skillnad mellan behandlingarna (baljväxter och radavstånd) för hösten 2022. Det fanns ett positivt samband mellan biomassa av höstraps och ogräs för 2021 för två av behandlingarna, höstraps utan kompanjongröda samt höstraps odlad tillsammans med en klöverblandning, men inget signifikant samband för resterande behandlingarna under samma år eller 2022. Det fanns inget signifikant samband mellan kompanjongrödorna när det gäller skillnader mellan de tre mest förekommande ogräsen. Det var mer biomassa av kompanjongrödorna i 2021 än 2022, men det var mer ogräs i 2022 än 2021. Samodling tillsammans med baljväxter verkar öka kväveinnehållet i höstraps, men verkar inte ha någon påverkan på mängden biomassa. Under 2021 verkar den sena sådden ha påverkat både biomassan, konkurrenskraften och skörden av höstraps. Större biomassa av höstraps verkar inte leda till en mindre biomassa av ogräs, snarare tvärtom, troligtvis på grund av interspecifik konkurrens. En jordartsförändring av fältet inom försöket för 2022 påverkade troligen ogräsförekomsten och våtvikten av ogräs. Ytterligare data över flera år och från fler fältförsök vore fördelaktigt för mer tillförlitliga resultat. Trots detta finns det tecken på att samodling kan vara en fördelaktig metod inom jordbruket för att öka kväveinnehållet i höstraps och kanske kunna minska behovet att kvävegödsel i ekologisk odling.

Nyckelord: baljväxter, biomassa, ekologisk odling, kompanjongrödor, kväveinnehåll, höstraps, ogräs, samodling

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Abbreviations

ANOVA	Analysis of Variance
CC	Companion Crop
DW	Dry Weight
NUE	Nitrogen Use Efficiency
RS	Row Spacing
SLU	Swedish University of Agricultural Sciences
SMNC	Soil Mineral Nitrogen Content
SNF	Symbiotic Nitrogen Fixation
WOR	Winter Oilseed Rape

1. Introduction

Agricultural practices have always been important for the provision of grains, meats, and other nutritional products to the inhabitants of the world. With an increasing world population, the current practices must be developed in a sustainable way to prevent environmental harm (Tilman et al. 2001). Historically, the great advantages in crop productivity have been vital and life-saving for millions of people during the 20th century (Borlaug 1983), but the intensive production throughout the years have resulted in high greenhouse gas emissions and biodiversity losses (Tilman et al. 2002). To prevent any further harm, the agricultural systems needs to be optimized to improve efficiency and mitigate losses (Tilman et al. 2002, 2011) in order to provide enough food for a growing population and take care of the environment at the same time.

Over the world, there is a high consumption of fertilizers and other pesticides. It has been estimated that an increased fertilization rate might not lead to further increased yields (Alexandratos & Bruinsma 2012) and an excessive use of pesticides against weeds, as well as other pests and diseases, might lead to an increased herbicide resistance worldwide (Heap 2014). These inputs will over time become less effective, and an increased amount might not lead to better yields. Instead, a change of practices might lead to better results without any excessive use of chemical inputs.

Organic cultivation does not allow any chemical means of control and is generally associated with a higher biodiversity than other practices (Bedoussac et al. 2015). When compared to conventional farming, there is usually a lower and more variable yield for organic cultivation (David et al. 2005; Seufert et al. 2012). However, depending on the management practices, different crop rotations and intercrop systems might result in a smaller yield gap between organic and conventional cultivation (Ponisio et al. 2015). It is important to take care of the arable land that is already in use for cultivation, and with an increased availability of organic fertilizers (Alexandratos & Bruinsma 2012), organic intercrop systems could be a possible solution to mitigate the impact from the agricultural practices.

1.1 Intercropping

The most general definition of intercropping is the simultaneous growth of two or more crops in the same field at the same time (Willey 1979; Vandermeer 1989). Several studies report the beneficial effects of intercropping in both cereal-legume systems (Hauggaard-Nielsen et al. 2001; Naudin et al. 2010; Amossé et al. 2013, 2014) and oilseed-legume systems (Cadoux et al. 2015; Lorin et al. 2015, 2016; Emery et al. 2021; Dayoub et al. 2022). In these cases, cereals or oilseed rape are grown as the main crop with the legumes as an intercrop, called a companion crop (CC).

The effects of intercropping can be variable. While some studies have shown yield loss or no change in yield at all (Bergkvist 2003), other studies have shown positive effects on yield (Hauggaard-Nielsen et al. 2001), weed suppression (Liebman & Dyck 1993; Gu et al. 2021), diseases (Trenbath 1993; Stoltz et al. 2018), and insect damage (Cadoux et al. 2015; Emery et al. 2021).

Different design choices for intercropping may influence the results depending on how the crops are arranged, where some of the most common designs are additive, replacement and relay design. In an additive design, the CC are grown in between the rows of the main crop (Vandermeer 1989; Cadoux et al. 2015; Emery et al. 2021). In a replacement design, the CC is replacing the main crop in every other row (Vandermeer 1989; Dayoub et al. 2022). In a relay design, the intercrop is grown in the same field, but only partially at the same time with some overlap during the growing season (Vandermeer 1989; Amossé et al. 2013, 2014). Sowing dates, crop varieties and densities are other factors that influence intercropping since they affect the interaction between the different species (Bergkvist 2003) as well as nutrient management and sensitivity to diseases (Verret et al. 2017; Dayoub et al. 2022).

1.1.1 Plant interactions

The interactions between species become important for intercropping since the system relies on the beneficial traits from the CC to improve the sole crop. This is partially based on niche theory, where competition only becomes substantial if the species share space and have a niche overlap where the populations may be affected (Vandermeer 1989). This interaction between plants can be intraspecific (within species) or interspecific (between species) (Lee et al. 2016), hence affecting the sole crop itself but also the interaction with the CC. In several studies, the main parts of plant interactions are divided into competition, facilitation, and complementarity.

Competition is when two plants, or populations of plants, interfere with each other in a way that results in a negative effect on at least one of the two (Vandermeer 1989). Facilitation is when two plants, or populations of plants, interact with each other in a way that results in a positive effect on at least one of the two, with a positive effect on both is equal to mutualism (Vandermeer 1989). Complementarity is when two plants, or populations of plants, can grow together in the same proximity by using different resources and even complement each other by making better use of the resources than they would have if grown separately (Willey 1979).

Thus, the intercrop system has a better use of environmental factors when the crops are complementary of resources such as light, water, nitrogen (N), and other nutrients (Willey 1979). The evolution of plants has been altered by competition where these shared and limited resources have forced species to differentiate into having deeper roots for nutrients, be more tolerant to lower water potential, and be taller with bigger canopies to reach more light to perform better than other species (Craine & Dybzinski 2013).

A study from Dayoub et al. (2022) concludes that CCs with contrasting traits from the main crop, where they have a complementarity over the shared resources, will have better competition against weeds since they reduce the amount of light and nutrients left for the weeds. Several studies have shown that intercropping is an effective method to reduce weed biomass compared to the sole crop (Liebman & Dyck 1993; Bedoussac et al. 2015; Lorin et al. 2015). If the CC is sown in between the rows of the main crop, the CC will cover more ground and potentially compete for light against weeds (Cadoux et al. 2015). The dry biomass and density of weeds in early winter are suggestively linked to the biomass of the main crop, as well as the N uptake by weeds (Valantin-Morison & Meynard 2008).

1.2 Oilseed-Legume intercropping system

Winter oilseed rape (WOR) is an important agricultural crop especially in Europe and since the year of 2000, the area used for growing WOR in Sweden have increased from approximately 25 000 ha to 110 000 ha in 2022 (Jordbruksverket 2022b). Common area of use is feed, rapeseed oil and biofuel (Knutsson 2008).

1.2.1 Legumes as companion crops

Nitrogen is one of the most important nutrients for plant development. The amount of N available in the soil and the plants’ ability to take up the N are essential for plant growth (Leghari et al. 2016). Nitrogen use efficiency (NUE) is explained as the uptake and utilization of N and is defined as the grain production per unit of N available in the soil (Moll et al. 1982). By improving traits such as root development, resource allocation before maturing, and N uptake after flowering, the NUE could be improved without any yield losses (Berry et al. 2010).

The main reason for the advantage of legumes as CCs is the competition for N between the legumes and main crop. Since both species compete for N in the soil, the legumes will instead turn to symbiotic nitrogen fixation (SNF) by rhizobium bacteria (Udvardi & Poole 2013; Dowling et al. 2021). Verret et al. (2017) performed numerous experiments with different intercrops, both legumes and non-legumes, in WOR between 2009 and 2015 but abandoned the non-legume CCs over time due to too much competition with WOR.

The possibility for legumes to rely on SNF makes it beneficial to have legume intercrops systems in soils with a low soil mineral nitrogen content (SMNC) (Willey 1990; Naudin et al. 2010; Jamont et al. 2013; Bedoussac et al. 2015), since the legume will rely on N from SNF instead of the soil mineral N. Studies have shown that intercropping with legumes will provide more N to the main crop compared to monoculture (Jamont et al. 2013; Amossé et al. 2014; Lorin et al. 2016), a higher yield under fertilized conditions (Verret et al. 2017), a higher biomass (Génard et al. 2017), and less N fertilizers needed without any significant yield loss (Verret et al. 2017; Emery et al. 2021).

To maintain growth and yield quality, WOR requires high amounts of N and sulphur (Malagoli 2005; Jordbruksverket 2022a), which makes it important to meet these requirements by the nutrient contents in the soil or by application of fertilizer. Due to the high requirement for N, legumes are beneficial CCs in an intercrop system with WOR.

1.3 Aims & objectives

The aim of this thesis was to explore the possibilities to use intercropping of frost-sensitive legumes with WOR to provide N in the spring, improve weed suppression and increase the biomass of WOR in organic cultivation.

This thesis is based on results from a research study called "*Increased nitrogen availability and biodiversity in winter oilseed rape by intercropping annual frost sensitive legume plants*". The study is financed by SLU EkoForsk (2021/2022) and The Swedish Board of Agriculture (2022/2023). Data of biomasses of WOR, legumes, and weeds for this thesis are provided by this field trial study. Assessments for yield and insect damage are also included in the original report but not in this thesis.

1.3.1 Hypotheses

This thesis investigates whether intercropping with legumes will affect the nitrogen concentration, biomass production and competition against weeds in winter oilseed rape before the winter. To answer these questions, I hypothesize that intercropping with legumes:

1. will increase the nitrogen concentration in winter oilseed rape,
2. will increase the biomass of winter oilseed rape,
3. will increase the competitiveness of winter oilseed rape against weeds,
4. will affect the growth of different weeds depending on the companion crop,
5. will have different effects in winter oilseed rape between years and site conditions.

2. Materials & methods

2.1 Field experiment

2.1.1 Site characteristics

Data for this thesis were acquired from field trial studies conducted during 2021/2022 and ongoing during the winter and spring of 2022/2023. In 2021, the field trial was located west of Örebro, Örebro county (N 59.287167 E 15.068383) and in 2022, the field trial is located south of Lidköping, Västra Götalands county (N 58.424685 E 13.159668). In Örebro, the field trial was managed by HS Konsult AB, Säbylund, and in Lidköping by Lanna Field Research Station, SLU. Prerequisite for a low SMNC before establishment is a preceding crop low in N, where the preceding crop was winter rye in Örebro and winter wheat in Lidköping. In 2021, the soil was a silty loam with a pH of 5.9 (Appendix 1) and in 2022, the soil was a clay loam with a pH of 6.6 (Appendix 2). The temperature was similar between the two years and sites. However, there were more precipitation during October, January and March for 2022 (Figure 1).

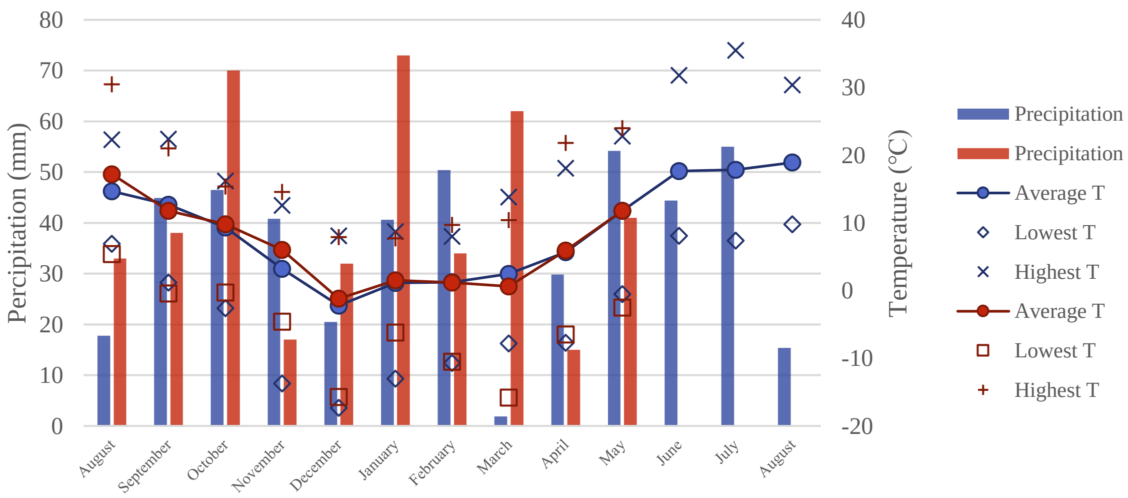


Figure 1. Weather (precipitation and temperature, T) for each month during the period between sowing and harvest for 2021/2022 (blue) and the weather during the period between sowing and until the end of May for 2022/2023 (red). Data compiled from different weather stations: temperature from Örebro and precipitation from Vintrosa (2021), temperature and precipitation from Saleby Grid (2022) (SLU Lantmet 2023).

2.1.2 Experimental design

Winter oilseed rape was seeded with different companion crops: faba bean, blue lupin, common vetch, and a clover mixture (Table 1). The legumes were either spring varieties or crops not adapted for the Swedish winter climate in which to ensure that they will freeze away during the winter.

*Table 1. Species, variety and quantity of main crop (winter oilseed rape) and companion crops (legumes) included in the field trials in an intercropping experiment conducted in Sweden in 2021 and 2022. *50% of normal quantities.*

Species		Variety	Quantity
Winter oilseed rape	*Brassica napus ssp. napus*	Explicit	45 seeds/m^2
Faba bean	*Vicia faba*	Tiffany	139 kg/ha*
Blue lupin	*Lupinus angustifolius*	Boregine	100 kg/ha*
Common vetch	*Vicia sativa*	Tempy	50 kg/ha*
Clover mixture			
Berseem clover	*Trifolium alexandrinum*		2 kg/ha
Squarrosum clover	*Trifolium squarrosum*		2 kg/ha
Persian clover	*Trifolium resupinatum*		2 kg/ha

For the experimental design, a randomized split-plot design was used with three replicates and two different factors: legume species and row spacing (RS) (Table 2, Figure 2). The plots were 24 x 3 m in size where the CCs were sown in between the rows of WOR in an additive design, except for the clover mixture that was seeded with WOR in the same row. In the first experimental year, seeding date was 24th of August 2021 and harvest date 16th of August 2022. In 2022, the seeding date was 14th of August. Organic fertilizers were applied to the experimental area corresponding to 50 kg N per ha. In 2021, *Ekoväx 8-3-5-3* (625 kg/ha) was applied at sowing and *Biofer 10-3-1* (550 kg/ha) was applied the 27th of April. For 2022, *Ekoväx 8-3-5-3* (365 kg/ha) was applied before sowing. Both fields were ploughed before sowing. Inter-row hoeing was done in April of 2022 in Örebro.

Table 2. Treatments in an intercropping experiment in Sweden conducted in 2021 and 2022. Numbers (1-5) represent the sole crop and different companion crops sown between the rows of WOR: faba Bean, blue lupin, common vetch, and clover mixture (berseem clover, squarrosum clover, and persian clover). Letters (A-B) represent different row spacings: 12.5 cm and 50 cm.

Factor		Treatment
Companion crops	1	Winter oilseed rape
	2	Winter oilseed rape + faba bean
	3	Winter oilseed rape + blue lupin
	4	Winter oilseed rape + common vetch
	5	Winter oilseed rape + clover mixture
Row spacing	A	12.5 cm
	B	50 cm

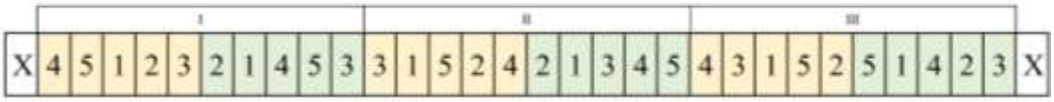


Figure 2. Overview of experimental design in an intercropping experiment in Sweden conducted in 2021 and 2022. Different row spacings in yellow (12.5 cm) and green (50 cm) for each of the three blocks. The numbers (1-5) represent the sole crop (1) and different companion crops sown in between the rows of WOR: faba Bean (2), blue lupin (3), common vetch (4), and clover mixture (berseem clover, squarrosum clover, and persian clover) (5). The same design was used both 2021 and 2022.

2.1.3 Field sampling

Cuttings for biomass of WOR, CCs and weeds were done on the 31st of October and 1st of November 2022. For the 12.5 cm RS, 6 rows of WOR and 6 row gaps were cut in an area of 1 × 1 m, 2 for each plot (Figure 3A-B). For 50 cm RS, 3 rows of WOR and 3 row gaps were cut in an area of approximately 0.7 × 1.4 m, 2 for each plot (Figure 3C-D). The WOR, CCs and weeds were put into separate bags and weighed directly in the field. The bags with WOR and CCs were brought to Lanna Research Station, dried and weighed there before sent to MV Laboratory, Department of Soil and Environment, for analyses of N concentration of WOR and CCs. The bags with weeds were brought to HS Konsult AB, Brunnby, Västerås, where they were sorted, dried, and weighed. Cuttings for biomass of WOR and CCs were done on the 12th of November 2021, and the weeds on the 7th of July 2022 for the same site.

In 2022, the weeds were sorted into the three most common weeds and a separate category for remaining weeds. The sorting was done just for the sake of this thesis and is not included in the original project, where only the total weight of the weeds was recorded. The most common weeds were determined in the field as common chickweed (*Stellaria media*), field pennycress (*Thlaspi arvense*) and treacle mustard (*Erysimum cheiranthoides*). Until sorting, the weeds were stored cold. For three days, the weeds were sorted into their categories and put in separate weed bags. The weed bags where dried on cold air dryer for 2-3 days and then dried at 105 °C for three hours. The dry weight (DW) of the weeds was recorded. The category of *remaining weeds* consisted primarily of deadnettle (*Lamium sp.*), shepherd’s purse (*Capsella bursa-partoris*), scentless mayweed (*Tripleurospermum inodorum*) and cleavers (*Galium aparine*) along with residues of CCs and WOR as well as dirt. Other weeds in smaller proportions were hempnettle (*Galeopsis sp.*), black bindweed (*Fallopia convolvulus*), common fumitory (*Fumaria officinalis*), common knotgrass (*Polygonum aviculare*), lamb’s quarters (*Chenopodium album*), pale persicaria (*Persicaria lapathifolia*), thistles (*Cirsium sp.*), sow thistles (*Sonchus sp.*), speedwell (*Veronica sp.*), sun spurge (*Euphorbia helioscopia*), violet (*Viola sp.*), and a few other unidentified herbs and grasses.

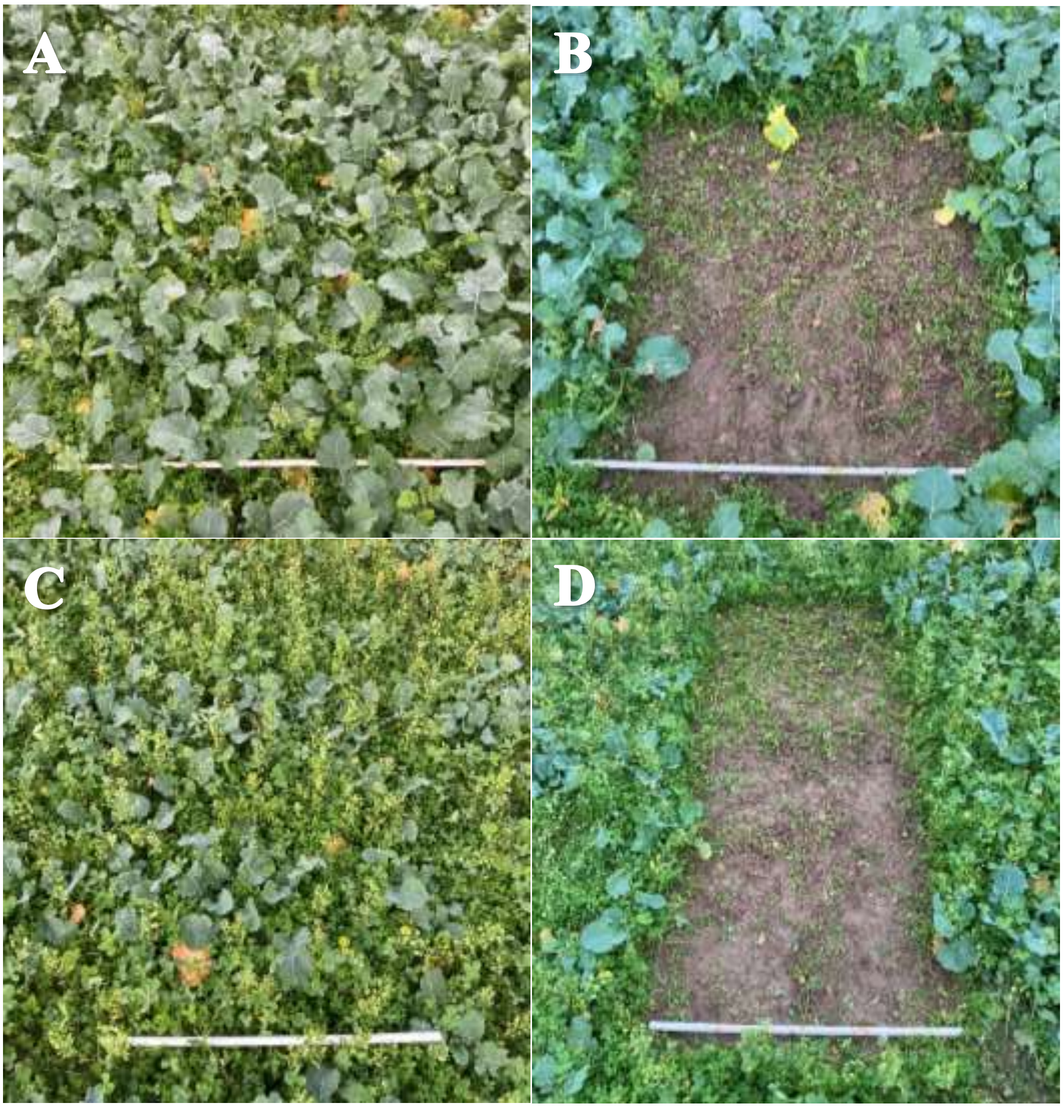


Figure 3. The cut area from two experimental plots in an intercropping experiment in Lidköping, November 2022. A) WOR and common vetch before and B) after cutting of the area for 12.5 cm row spacing with the area of 1 x 1 m (the white stick as measurement, 1 m) including 6 rows of winter oilseed rape. C) WOR and clover mixture before and D) after cutting of the area for 50 cm row spacing with the area of approximately 0,7 x 1,4 m (the white stick as measurement, 0,7 cm) including 3 rows of winter oilseed rape. Photos: by Stina Johansson.

2.2 Statistical analysis

Statistical analyses were done using Minitab Statistical Software (Minitab, LLC 2022). Analysis of variance (ANOVA) and regression analysis were used. All the data were checked to fulfil the assumptions for the model, and if not, transformed with logarithms. Dry weight (DW) of winter oilseed rape (WOR), companion crops (CC) and weeds as well as N concentration for WOR were used as response variables, with block (1-3), RS (12.5 cm and 50 cm) and legumes (faba bean, blue lupin, common vetch, and clover mixture) as factors. Due to low number of replicates, it was not possible to test the interactions. When the years (2021 and 2022) were combined, the data showed a bimodal distribution and did therefore not fulfil the assumptions for the test. Hence, the years were tested separately when comparing the DW of WOR and CC as well as wet weight of weeds between the years. Regression analysis was used for interaction between WOR and weeds. Comparison between the different factors were done with Tukey's pairwise comparison. Data collections and preparations before Minitab as well as figures were made with Microsoft Excel (2023).

3. Results

3.1 Effect of intercropping on nitrogen concentration

The lowest N concentration was found in WOR grown as sole crop in 2021 (Figure 4). Between the CCs, there was significantly higher N concentration in WOR intercropped with faba bean compared to WOR intercropped with blue lupin in 2021 (Figure 4). This equals a N content in WOR of 8.3 kg N per ha for the sole crop and 5.2 kg N per ha for WOR intercropped with faba bean. There was no significant difference depending on RS (Table 3). There was significant difference between the blocks (Table 3), where the WOR in blocks 1 and 2 have a higher N concentration than the WOR in block 3.

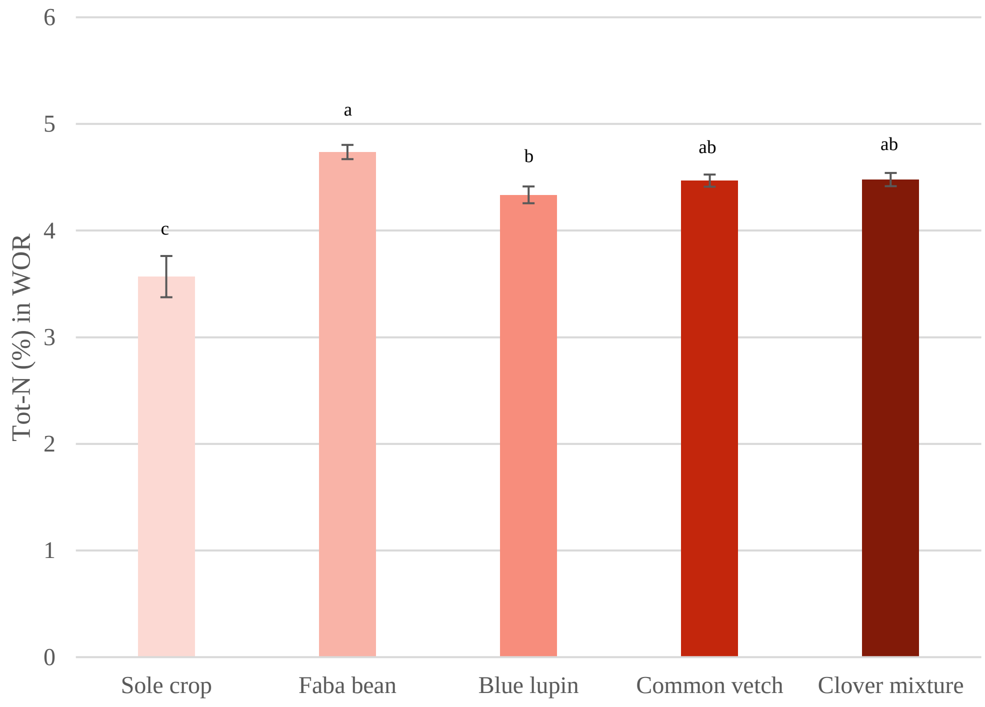


Figure 4. Nitrogen concentration (tot-N %) in winter oilseed rape (mean ± SE) for each treatment (WOR, WOR + faba bean, WOR + blue lupin, WOR + common vetch, and WOR + clover mixture) at the experimental site Örebro, November 2021. Letters represent significant differences from Tukey's pairwise comparison, p-*value < 0.05. In each group there was six replicates.*

Table 3. Results from statistical analysis of nitrogen concentration (tot-N %) in winter oilseed rape in November 2021 (Örebro) for each treatment dependent on block, row spacing (RS) and companion crops (CC): WOR, WOR + faba bean, WOR + blue lupin, WOR + common vetch, and WOR + clover mixture. Results show degrees of freedom, F-value, and p-*value.* p-*value < 0.05 suggests statistical difference indicated by*.*

	DF	*F-value*	p-*value*
Block	2	8.63	0.002 *
RS	1	0.05	0.819
CC	4	28.00	0.000 *

3.2 Effect of intercropping on biomass

There was a significant difference in DW of WOR between the years (different experimental sites each year). The DW of WOR in November was higher in 2022 than in 2021 (Figure 5, Table 6). There was a significant difference between the CCs in 2021, where the DW of WOR in the sole crop was higher compared to the other treatments (Figure 5A, Table 4). There was a significant difference between the RS (Table 4), with higher DW of WOR in 12.5 cm.

There was no significant difference in DW of WOR between the CCs (Figure 5B, Table 4) or the RS in 2022 (Table 4), but there was a significant difference between the blocks where the DW was lower in block 1 (Table 4).

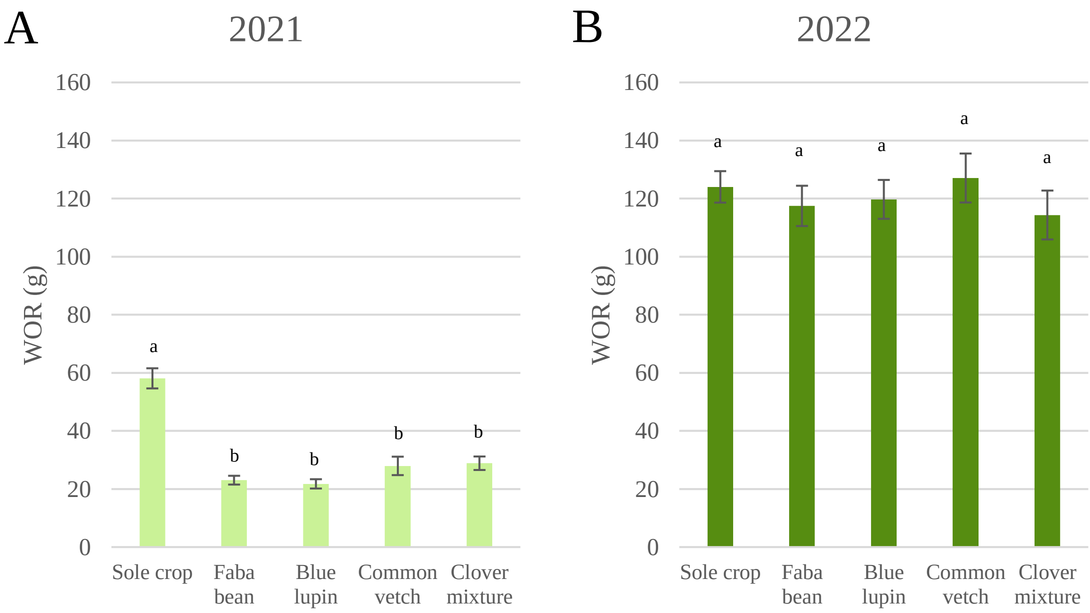


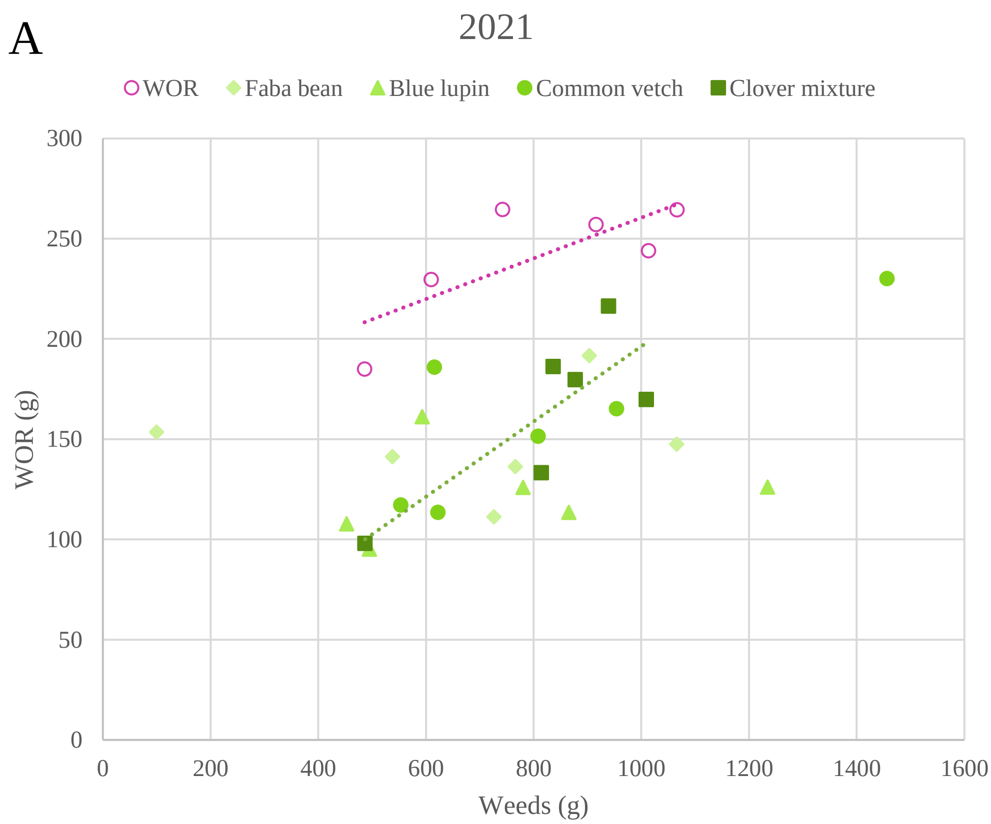
Figure 5. Biomass (mean ± SE) of winter oilseed rape for each treatment (WOR, WOR + faba bean, WOR + blue lupin, WOR + common vetch, and WOR + clover mixture) and year (2021 and 2022). Biomass represented by dry weights of WOR. Data was collected at Örebro in November 2021 and at Lidköping in November 2022. Letters represent significant differences between the treatments from Tukey's pairwise comparison. In each group there was six replicates.

Table 4. Results from statistical analysis of biomass (dry weights) of winter oilseed rape for several factors: block, row spacings (RS: 12.5 cm and 50 cm), companion crops (CC: sole crop, faba bean, blue lupin, common vetch, and clover mixture). Data was collected at Örebro in November 2021 and at Lidköping in November 2022. Results show degrees of freedom (DF), F-value, and p-value*.* p-value *< 0.05 suggests statistical significance indicated by*.*

		2021		*2022*	
	DF	*F-value*	p-*value*	*F-value*	p-*value*
Block	2	2.22	0.132	7.54	0.003 *
RS	1	6.61	0.017 *	0.04	0.850
CC	4	30.71	0.000 *	0.80	0.535

3.3 Effect of intercropping on weed prevalence

Only two of the treatments showed a significant relationship between the biomass of WOR and the biomass of weeds. In 2021, there were positive relationships between the weed biomass and the biomass of WOR as sole crop as well as WOR intercropped with clover mixture (Figure 6A, Appendix 3). In 2022, none of the treatments were significant (Figure 6B, Appendix 3).



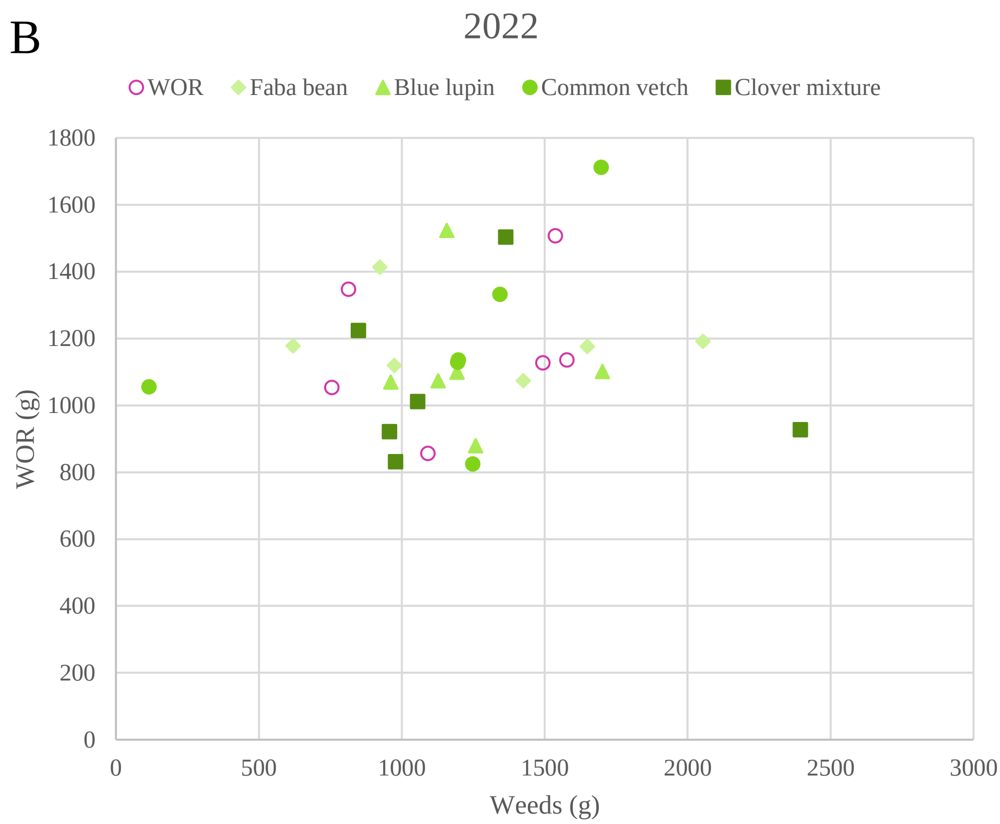


Figure 6. Wet weight (g) of winter oilseed rape and weeds for each treatment (WOR, WOR + faba bean, WOR + blue lupin, WOR + common vetch, and WOR + clover mixture) for WOR in November 2021 and weeds in July 2022, Örebro, (A) as well as November 2022 for both WOR and weeds, Lidköping (B). Each dot represents a repeat from each year. The sole crop (only WOR) is represented by pink rings. The other treatments (WOR + companion crop) are represented by different shapes in greens. Trendlines represent significant positive relationship between biomass of winter oilseed rape and weeds for the sole crop (pink line) and for clover mixture (dark green line) for 2021.

3.4 Similarities in growth patterns of companion crops and weeds

There was no difference in DW for the three most common weeds (common chickweed, field pennycress, and treacle mustard) between the four legumes (faba bean, blue lupin, common vetch, and clover mixture) (Figure 7, Table 5). Common chickweed made up the largest proportion of the three most common weeds (Figure 7).

There was a significant difference in DW between the blocks for field pennycress and treacle mustard as well as for RS for field pennycress (Table 5), but no significant difference for any factor for common chickweed. There was a higher DW of field pennycress and treacle mustard in the RS of 50 cm than 12.5 cm.

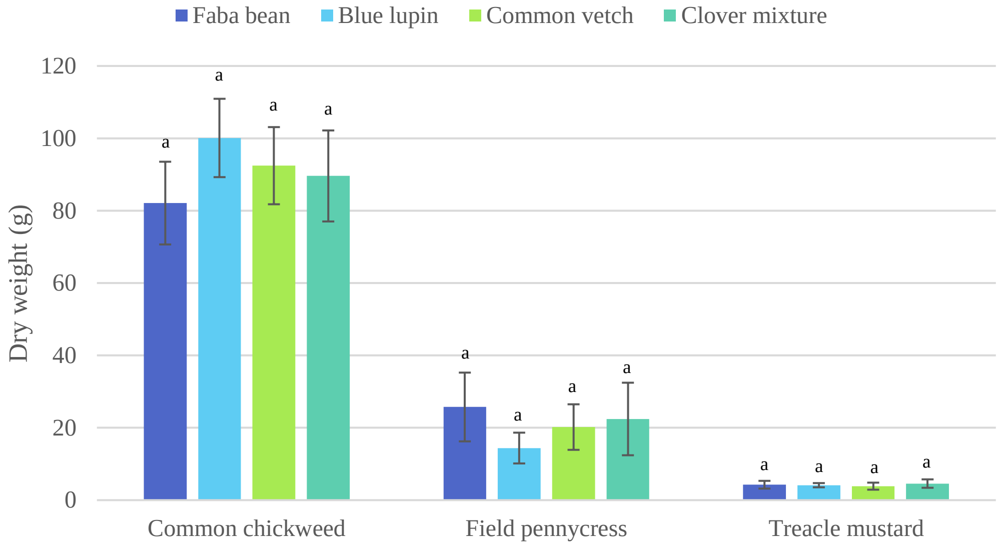


Figure 7. Dry weight (mean ± SE) of common chickweed (Stellaria media), field pennycress (Thlaspi arvense), and treacle mustard (Erysimum cheiranthoides) for each legume treatment (faba bean, blue lupin, common vetch, and clover mixture) for intercropping with winter oilseed rape in November 2022, Lidköping. Letters represent significant differences from Tukey's pairwise comparison between the treatments for each of the weeds. In each group there was six replicates.

Table 5. Results from statistical analysis of the dry weight of common chickweed, field pennycress and treacle mustard for several factors: block, row spacings (RS: 12.5 cm and 50 cm), companion crops (CC: (faba bean, blue lupin, common vetch, and clover mixture). Data was collected at Lidköping in November 2022. Results show degrees of freedom, F-value, and p-value. p-value < *0.05 suggests statistical difference indicated by*.*

		Common chickweed		**Field pennycress**		**Treacle mustard**	
	DF	*F-value*	p-*value*	*F-value*	p-*value*	*F-value*	p-*value*
Block	2	0.14	0.872	25.09	0 *	5.30	0.016 *
RS	1	0.97	0.339	12.55	0.003 *	4.94	0.040 *
CC	3	0.39	0.763	2.05	0.146	0.15	0.929

3.5 Differences in growth conditions and year

There were significant differences between the years for both DW of WOR and CCs (Figure 8, Table 6). The biomass of WOR in November 2022 was almost four times the weight of the WOR in November 2021 (Figure 8A). In contrast, the CCs in 2022 was almost half the weight of the CCs in 2021 (Figure 8B).

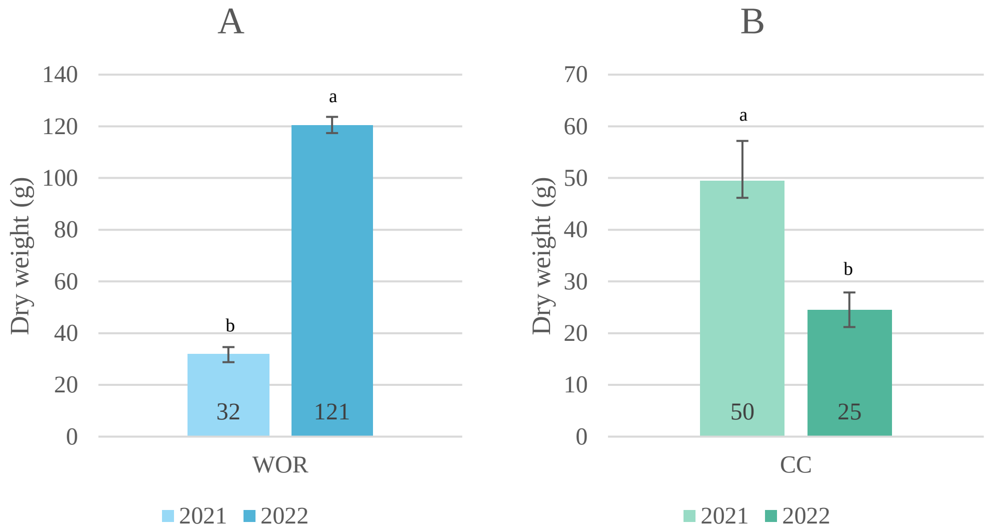


Figure 8. Biomass (mean ± SE) of winter oilseed rape (A) and companion crops (B) for Örebro (November 2021) and Lidköping (November 2022). Different lowercase letters represent significant differences from Tukey's pairwise comparison, p-*value < 0.05. Each group consists of all plots, 30 replicates in total.*

Table 6. Results from statistical analysis for biomass of winter oilseed rape (WOR) and companion crops (CC) for different years. Data was collected at Örebro in November 2021 and at Lidköping in November 2022. Results show F-value and p-*value. Degrees of freedom = 1.* p-*value < 0.05 suggests statistical difference indicated by*.*

	WOR	**CC**
F-value	323.35	7.15
p-*value*	0.000 *	0.010 *

4. Discussion

4.1 Intercropping and nitrogen concentration

The results show that WOR intercropped with legumes have a higher N concentration than without a CC in 2021 (Figure 4), which supports the hypothesis that intercropping with legumes will affect the N concentration in WOR. Intercropping might therefore give a higher N concentration in WOR than monocropping. The results also show that WOR intercropped with faba bean will have a significantly higher N concentration than with lupin, but not significantly more compared to the other CCs (Figure 4). Other studies have shown similar results with good performance of faba bean, for example that faba bean is complementary for N resources when grown with WOR due to interspecific competition for soil N, resulting in a niche separation where faba bean rely on SNF instead (Jamont et al. 2013). Fertilization of the field at sowing might interfere with the SNF of the legumes, which makes it important to regulate the amount of N that is added to the field to promote growth of the WOR whilst not interfering with the N fixation.

The result from the analysis of N concentration in WOR for 2022 could not be included due to delays in the lab. If several years could have been included in the thesis, the results would have been more reliable. Regardless, the results still suggest that there is a possibility to increase the availability for WOR by using intercropping. It is of importance to increase the NUE instead of increasing the amount of fertilizers (Tilman et al. 2002), to find a way to maintain the crop yield with the use of less inputs, and intercropping might be a solution.

4.2 Higher biomass with intercropping?

According to the results of this thesis, intercropping with legumes does not increase the biomass of WOR (Figure 5). There were no significant differences in DW of WOR between the treatments in 2022 (Figure 5B), while the sole crop had the highest DW of WOR in 2021 (Figure 5A). Hence, my hypothesis that intercropping will increase the biomass of WOR at the end of autumn growth was not supported, despite other sources claiming that there is a higher DW of WOR in intercropping than monocropping (Jamont et al. 2013). However, there might be too early to detect differences already in the autumn and a follow-up in the spring would be interesting.

Despite only two weeks difference in cutting of the biomass in the autumn, the biomass of WOR in 2021 is still lower compared to 2022 (Figure 5), which is probably due to a late sowing date in 2021. Sowing date is a recurring factor that could affect biomass and yield of crops (Lutman et al. 2000; Verret et al. 2017), and the fields were sown on the 24th of August in 2021 and the 14th of August in 2022. The recommended sowing date for WOR in Sweden is between 1st-15th of August for the middle of Sweden, and 15th-25th of August for the southern of Sweden (Jordbruksverket 2021). Örebro is a part of the middle of Sweden and therefore is the 24th of August a little late for that area. So, the two weeks delay with the sowing date in August seems to be of more importance for the biomass of WOR than the difference in sampling dates in November.

Suggestively, sowing date seems to be important for the competitiveness of WOR. Since the CCs are sown at the same time as the main crop, the competitiveness of the CC will also be affected by the late sowing date. All the CCs are frost-sensitive, either spring varieties or varieties not suitable for the Swedish winters. This becomes a disadvantage for the WOR after late sowing since spring varieties usually produce biomass more quickly than winter varieties and will likely compete more (Lorin et al. 2015; Verret et al. 2017). Hence, a combination of late sowing and interspecific competition can influence the growth of WOR, which can be visualized by comparing the DW of WOR and CCs between the years. The biomass of the CCs were higher in 2021 while the biomass of WOR was lower in November 2021, and vice versa for 2022 (Figure 8A-B).

In 2022, the DW of WOR was significantly lower in block 1 than the others (Table 4), which is interesting for two reasons. Firstly, there is a change in soil type somewhere between the first and the last plots of the field trial of 2022 (personal observation). This influenced the weed abundance, with more weeds in block 3 (discussed in section 4.5). Secondly, due to the difference in weed abundance, the biomass of WOR might be less in block 3 due to more competition from weeds and more biomass of WOR in block 1 due to less competition from weeds. However, the results are the opposite, with less DW of WOR in block 1. The soil change most likely influenced both WOR and the weeds, resulting in higher abundance of weeds and higher biomass of WOR.

Even though the focus of this thesis was on the N concentration, biomass, and weed prevalence at the end of autumn growth, I think it is interesting to speculate what will happen in the spring and with the seed yield. This due to the usage of the WOR, which in many cases are the seeds (yield) and not the biomass of the plant. Since the field trial of 2022 have not been harvested yet, I am not able to compare the yields between the years and compared the biomass instead. Suggestively, a higher biomass could possibly lead to a higher yield, or at least be linked in one way or another. For 2021, like the low biomass, the yield was also lower than for other field trials within the same project that year (personal communication). Some sources claim that a higher DW in the winter may lead to less yield loss (Lutman et al. 2000).

The field trial of 2021 had a lower DW at the end of autumn and had as a result also a lower yield, but in addition to the low biomass due to late sowing date, application of fertilizer in spring was also later than desired. Preferably, the WOR would have been fertilized in March instead of the 27th of April, so that the crop had access to nutrients when it began to grow in spring (Yara 2023). Due to the late fertilization, the growth rate was probably slow and did not have the ability to produce as much seeds as it would if the plants had been larger before flowering and maturation.

Dayoub et al. (2022) express how the conditions of the site and the agricultural practices such as sowing date, sowing density and design choice will affect the performance of WOR. A lot of different factors will determine the state of the crop after winter and how the managements in spring can be conducted, such as the harshness of the winter and the drying up of the soil in the spring. Regardless, the field trial of 2021 is an example of how these practices affected the result, where an earlier sowing date and fertilization in the spring might have given a higher biomass at the end of autumn and a higher yield, respectively.

4.3 Weed prevalence and the effect on weed competition

There were more weeds in 2022 than in 2021 (Figure 6A-B). The wet weights of weeds in 2021 ranged from approximately 100 and 1500 g per m^2, with most of the plots in between 400-1100 g of weeds (Figure 6A). The wet weights of weeds in 2022 ranged between approximately 100-2400 g, with the most plots in range of 600-1700 g of weeds (Figure 6B). No weed density was calculated, but most of the ground was covered by common chickweed (personal observation), which constituted the largest proportion of the weight in most of the plots (Figure 7, Appendix 4). The humidity was high when the biomass of weeds were collected in November 2022 (SLU Lantmet 2023), and as a result, the plants were very wet, especially the common chickweed (personal observation). It does however become problematic to fully compare the results since there were no assessment of weeds in November 2021, so the weeds that are compared are from July 2022. Since I do not have this assessment of weeds from the same occasion as the WOR and CCs, I have to assume that the wet weight of WOR in July 2022 can to some extent reflect on the weed prevalence in November the previous year.

The interactions between the wet weights of WOR and weeds were not as expected, as I had hypothesized a difference in the weights of WOR grown as a sole crop compared to when grown with CC. Furthermore, I expected a negative relationship between the biomass of WOR and weeds, where more biomass of WOR would lead to less biomass of weeds. Instead, there was two positive interactions between the sole crop and WOR + clover mixture in 2021, where an increase in wet weight of weed will increase the wet weight of WOR. So instead of more biomass of WOR with less weeds, there seem to be another kind of competition between the species. When the WOR is thriving, the weeds need to increase their competitiveness to be able to compete for resources.

It may not be possible to prevent weeds all together, especially not in organic cultivation, but there might be methods to mitigate the effects. Even if the results from this thesis did not show any signs of less weeds with intercropping, other studies have shown promising results of a lower weed abundance with different CCs. The complementarity between WOR and the CC has led to higher competitiveness against weeds, leading to less weeds in intercropping than monocropping after the winter (Dayoub et al. 2022). So even though there was no significant difference before winter, the CC might have an effect after winter. It also seems that spring faba bean showed better results on weed control than winter faba bean when intercropped with WOR (Emery et al. 2021). More N in the autumn may lead to better competitiveness for WOR against weeds, and therefore reduce the problems with weeds (Valantin-Morison & Meynard 2008).

Other types of weed control have been tested, for example mechanical, thermal, and smothering (Velička et al. 2016). The mechanical weed control in the form of inter-row loosening, thermal weed control with water steam, and self-regulation with smothering. The most efficient weed control was mechanical and was recommended for cultivation of WOR with a wide RS, over 48 cm (Velička et al. 2016). For the field trial study in 2021, inter-row hoeing was done in April, but there is no assessment whether the inter-row hoeing was more efficient for the 12.5 cm RS or the 50 cm RS. Other studies have also reported positive effects by less usage of herbicides with mechanical weed control (Emery et al. 2021). Even though it may not be possible to have no weeds at all, it is desired to have a cultivation that uses less herbicides (Lorin et al. 2015).

4.4 Similar growth or contrasting traits for better competition against weeds?

The hypothesis about different competitiveness between legume crops against weeds is based on how they grow, whether legumes and weeds with similar growth patterns will compete more with each other than any other legume crop or weed. Emery et al. (2021) conclude that the legume intercrops used in their study had different advantages and disadvantages, and could be differently suited against pests, weeds, and diseases. Based on this, I hypothesized that clover and common vetch might compete better with common chickweed due to similarities in growth than faba bean and lupin. Similarly, I hypothesized that faba bean and lupin might compete better with field pennycress and treacle mustard than clover and common vetch.

However, this thesis finds that there was no significant difference between any of the legume crops for either weed species (Figure 7, Table 5). This suggests that there is no special competitiveness between any of the specific weeds or CCs and that there are no indications that the choice of CC might affect specific weeds differently. Therefore, the hypothesis for this thesis cannot be supported.

Even though there was no statistical significance between the CCs for common chickweed, by looking at the average weights of the weeds (Figure 7), it seems like faba bean could be more competitive against common chickweed. However, this contradicts my hypothesis that common vetch and clover mixture might compete better than faba bean, but faba bean might just have a better overall competitiveness than the other CCs due to complementary traits to WOR (Dayoub et al. 2022). So even though the growth pattern might not be specific to certain kinds of weeds, the CCs may have other traits that makes them good competitors against weeds.

4.5 Importance of site and year

When comparing the years, the most prominent result was the large difference in biomass, where the biomass of WOR in 2022 was approximately four times greater than in 2021 (Figure 8A). As discussed in sections above, the late sowing date affected the biomass production in the autumn, which could in turn have affected the crops' ability to survive the winter. Therefore, the later sowing date was probably the main reason for the low biomass of WOR at the end of autumn growth.

In contrast, the biomass of the CCs in 2021 was double the weight of the CCs in 2022 (Figure 8B). I believe that the low biomass of WOR, and interspecific competition between the crops was another consequence to the late sowing date. In 2022, the biomass of WOR was larger and the plants could probably compete better for space and nutrients with the CC than in 2021 where the WOR probably had a decreased competitiveness due to lower growth. It suggests that just a few days in

August could be crucial for the ability to compete with other plants or even survive the winter.

The fields are at two different locations in Sweden, and not only from different years. The sites in Örebro and Lidköping were in closer proximity to each other than the other locations, but they still have different site conditions that separate them in addition to different years of establishment. There are a few site-specific conditions that may influence the growth of the main crop and the CC, specifically the SMNC in the soil. Despite both fields having a pre-crop that is low on N, as a prerequisite for low SMNC before sowing, natural variations of soil mineral N will occur between different sites. Other differences in soil composition and pH may affect the growth conditions for the plants between the sites. The field of 2022 have a higher clay content and pH than in 2021 (Appendix 1-2), and the precipitation was slightly higher in October for 2022 (Figure 1). All these factors can be very variable between sites and therefore, I can only speculate which factors may influence the final results. It might also become more complex to actually conclude any effects from the year or site, since they are the same in this case, and the result from each trial becomes dependent on both the site-specific conditions of the field but also the variations that differentiate each year.

Site-specific variation could be the reason to the difference in weed prevalence, where the wet weight of weeds was higher in 2022 than 2021 (Figure 6A-B). It could of course also be a result of the sowing dates and competition such as for WOR and the CCs, but I think that the specific conditions of the fields (soil type and weather conditions) as well as tillage and other agricultural practices (Liebman & Dyck 1993) might affect the weed composition more. For example, the location of the 2022 site showed signs of differences within the field, which seems to have affected the weed abundance (Appendix 4). The most prominent result was the one for field pennycress that showed a significant difference between the first and the last plots (Appendix 4), as well as for treacle mustard. The last plots of the field trial (3B) had a mean DW of 55 g compared to the first plots (1B) which had a mean DW of 10 g of field pennycress. This difference in abundance of field pennycress was also visible by ocularly examining the field, where the change in soil type between the first and last plots likely has caused the uneven distribution of field pennycress. This highlights the importance of many repeats and that the placement of the trial within the field might interfere with the results.

4.6 Evaluation of study design

When comparing the N concentration in WOR, biomass of WOR and CCs, as well as weeds between the treatments, there might be some problems when it comes to lupin in 2022 due to poor establishment. When examined in the field and by looking at the plant per m^2 (Appendix 5), the lupin had problems with the emergence. For faba bean and common vetch, the plant density was 16 and 11 plants per m^2 for 12.5 cm RS, respectively. In contrast, the plant density for lupin was 4 plants per m^2, with equivalent results for the 50 cm RS. I believe that is due to a too deep sowing depth, since when the lupins were dug up, the length from the seed to the point of emergence were approximately 10 cm. The best sowing depth for rapid emergence is 3 cm for small-seeded species, such as *L. angustifolius* (Wilson & Thurling 1996). Therefore, it might be likely that the poor establishment is due to a too deep sowing depth and highlights the importance of good management during sowing for the establishment of the crop.

This might have affected all results from lupin in 2022. Even though the WOR intercropped with faba bean had a significantly higher N concentration than WOR intercropped with lupin (Figure 4), I wonder whether I can trust that result due to the poor establishment and if the N concentration would be higher if plants per m^2 were higher. It might also have affected the competitiveness when it comes to biomass of WOR and weeds as well (Figure 5-7), where most of these results is compared within its own year, and the results from lupin might therefore not be very representative. If additional years were included, the results might have been more reliable with more reliable conclusions for blue lupin and the other CCs.

I think an interesting approach for further studies would be to survey whether a specific CC can be used to compete with a problematic weed. According to Emery et al. (2021), the different CCs had their advantages and disadvantages and thereby could be used for different purposes. Depending on the focus of the cultivation, a specific legume could be chosen to either compete with a problematic weed that causes yield loss to the main crop or chosen as a complementary crop to increase yield. Either way, it would be interesting to further explore the interactions between specific main crops, intercrops, and weeds.

One thing that I might have done differently is the choice of the three weeds. The three weeds were chosen ocularly in the field during the first cutting dependent of the visible abundance. Common chickweed and field pennycress were the most abundant and were easy to choose. However, the third weed could easily have been another than treacle mustard if I would have chosen it during or after the sorting. Apart from the treacle mustard, shepherd's purse and deadnettle could have been chosen as the third most common weed, but I had to choose the weed before sorting. Since the treacle mustard was flowering at the time for the cutting, it was easier to spot throughout the field compared to deadnettle and looked therefore more abundant that it might have been. Shepherd's purse's similarities to field pennycress made it blend it with all the other weed, and like the field pennycress, the abundance of shepherd's purse was higher in the last plots in block 3 (Appendix 4). I do not necessarily think that treacle mustard was the wrong choice, even with just a few individuals, it was present in all the plots. I think that presence is more important than having a larger biomass, as for perhaps shepherd's purse, which I am not sure was present in the first plots. The reason I might consider deadnettle as a better alternative instead, is that treacle mustard and shepherd's purse both have a similar growth as field pennycress, and if the hypothesis focuses on different growth pattern, a different growth pattern apart from common chickweed and field pennycress might have been preferred.

Apart from the importance of sowing date, which have been discussed for 2021, other factors such as sowing density and design choice can also be of importance for the result of the field trial. The field trial studies in the original project have an additive design, similar to many other studies (Cadoux et al. 2015; Lorin et al. 2015, 2016; Emery et al. 2021) and in contrast to others (Amossé et al. 2013, 2014; Dayoub et al. 2022). An additive design is easy to establish but is dependent on the environmental conditions of the field for accurate results, while a replacement design is good to evaluate mechanisms for weed competition but might not be representative of the normal conditions of a field (Swanton 2015). An additive design might have a better weed suppression than a replacement design (Gu et al. 2021, 2022), but that might depend on the crop arrangement (Dayoub et al. 2022). Additionally, both are highly dependent on the plant densities of the sole crop and CC for accurate results (Swanton 2015). The design choice is a factor that will affect the results of the trial in different ways, and depending on the purpose of the trial, the design will be chosen accordingly. I think that the additive design for this field trial study has been suitable since it is more applicable to farm conditions to be able to get as representative results as possible.

Overall, more data over several years would have been preferred to be able to draw more reliable conclusions for all results. For the original project, there were more sites in other places in Sweden that could have been included, two in 2021 and one in 2022. These other sites where however not included in this thesis due to limitations that were decided beforehand. If the original project continues for a few more years, then the hypotheses from this thesis could be tested again but with additional repeats. My focus has been on the effects of intercropping at the end of autumn growth, but it would of course have been interesting to follow up with biomass, N concentration, and weed prevalence in the spring as well to see if effects will be present after the winter.

5. Conclusion

Throughout the years, intercropping has proven to be a useful agricultural practice. In this thesis, the effects of intercropping were not so distinct. The effect of intercropping seems to be dependent on the context in which is it grown, such as site conditions and field managements. However, despite a desire for more data and to have more repeats, the results do show some indications that intercropping is useful to provide more N at the end of autumn growth and might be useful to be able to reduce the use of N fertilizers. This thesis also shows signs that the sowing date is of great importance for the interspecific competition between WOR, CC, and weeds. Despite these variable results, intercropping still indicate that it could be a possible solution for organic cultivation to mitigate the impact of agriculture on the environment.

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Populärvetenskaplig sammanfattning

I alla ekosystem finns det en naturlig konkurrens mellan alla växter, djur och småkryp om de tillgängliga resurser som finns inom systemet. För växter gäller detta bland annat ljus, vatten och näringsämnen. Denna konkurrens kan medföra nackdelar för vissa växter men kan vara fördelaktig för andra. Samodling av jordbruksgrödor kan ge bättre konkurrens mot ogräs, sjukdomar och skadeinsekter. Baljväxter utgör en bra mellangröda i ett samodlingssystem eftersom de kan använda sig av symbiotiskt fixerat kväve från luften i stället för det kväve som finns i marken. Växter som är fördelaktiga i samodling kallas för kompanjongrödor.

Denna studie har undersökt fältförsök från två olika år där höstraps och baljväxter har samodlats, där två olika radavstånd (12.5 cm och 50 cm) och fyra olika baljväxter som kompanjongrödor (åkerböna, lupin, vicker och klöver) har jämförts. Hypotesen var att höstrapsen skulle få större biomassa, högre kväveinnehåll och mindre ogräs om den samodlas med baljväxter, och även att dessa faktorer kommer skilja mellan olika kompanjongrödor, plats och år.

Resultatet visar att det finns mer kväve i den höstraps som odlats tillsammans med en baljväxt och mindre kväve i den ensamma grödan, vilket tyder på att samodling med baljväxter gör det möjligt att öka tillgängligheten på kväve för höstraps. Dock visade resultaten inga tecken på att samodling leder till större biomassa av raps eller större rapsplantor. I stället verkar en försenad sådd minska konkurrenskraften hos höstraps och resultera i att det blir mindre biomassa om den odlas tillsammans med en kompanjongröda. Ogräsmängden verkar inte bli mindre om höstrapsens biomassa ökar, snarare verkar den öka i stället, vilket kan bero på att ogräsen tävlar med höstraps och baljväxter om de tillgängliga resurserna snarare än att ge upp.

Olika studier visar olika resultat av samodling. Denna studie visar tecken på att samodling av höstraps och baljväxter skulle kunna öka tillgängligheten på kväve till höstrapsen på hösten, men verkar inte ha någon effekt på vare sig biomassa eller ogräs. I och med detta verkar det finnas potential till att samodling av baljväxter kan vara gynnsamt i ekologisk odling och minska behovet att gödselmedel.

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Appendix 1

Results from analyses of soil samples from experimental site of the original project from 2021-08-24, Örebro county. Analyses of three different soil depths: 0-30 cm, 30-60 cm, and 60-90 cm. Results including pH, nutrient contents, soil organic matter (SOM), soil type, and nitrogen contents. Swedish classification for K and P (I-IVA).

		0-30 cm	**30-60 cm**	**60-90 cm**
pH		5.9	6.1	6.1
P-AL	*mg/100g*	10.0 (IVA)	3.0 (II)	2.0 (II)
K-AL	*mg/100g*	12.9 (III)	7.4 (II)	5.3 (II)
Mg-AL	*mg/100g*	5.0	2.4	1.9
K/Mg-AL		2.6	3.1	2.8
Ca-AL	*mg/100g*	55	25	19
Al-AL	*mg/100g*	53	69	48
Fe-AL	*mg/100g*	18	27	29
K-HCl	*mg/100g*	37.2 (I)	32.6 (I)	29.8 (I)
P-HCl	*mg/100g*	48.2 (III)	27.7 (II)	25.6 (II)
Cu-HCl	*mg/Kg*	2.8	1.5	1.4
SOM	*%*	3.8	1.3	0.9
Soil type		Silty loam	Sandy loam	Sandy loam
Clay	*%*	7	6	5
Silt	*%*	29	26	23
Sand	*%*	59	67	71
TS	*%*	81.0	84.6	84.1
NO3-N	*mg/100g TS*	0.31	0.20	0.13
NH4-N	*mg/100g TS*	0.09	0.05	0.02
NO3-N	*kg/ha*	12.3	8.9	5.8
NH4-N	*kg/ha*	3.6	2.1	0.8
N-MIN	*kg/ha*	15.9	11.0	6.5

Appendix 2

Results from soil mapping made in 2021, regarding the field from the original project sown in 2022, Lidköping, Västra Götaland County (personal reference). For the field, there were eight samples in total (the total of 8 ha), with the results presented of an average of these samples. Results including pH, nutrient contents, soil organic matter (SOM), and clay content. Swedish classification for K (IV) and P (II).

pH		6.5
P-AL	*mg/100 g*	2.6 (II)
K-AL	*mg/100 g*	17.6 (IV)
Mg-AL	*mg/100 g*	24.3
K/Mg-AL		1.0
SOM	*%*	2.9
Soil type		Clay loam*
Clay	*%*	35-40

* estimated from the clay content

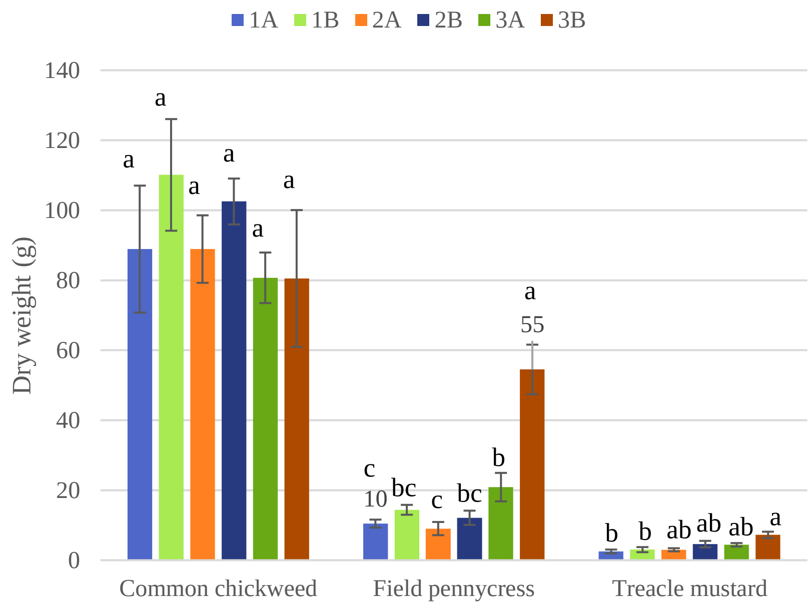
Appendix 3

Results from regression analyses between biomass of winter oilseed rape (WOR) for different treatments (sole crop, WOR + faba bean, WOR + blue lupin, WOR + common vetch, and WOR + clover mixture) and biomass of weeds for 2021 (Örebro county) and 2022 (Västra Götaland county). Biomass was presented in the form of wet weight of both WOR and weeds. Adjusted R^2. Degrees of freedom = 1. Statistical significance when *p*-value < 0.05, indicated by*.

	***p*-value**	**T-value**	**R^2 (%)**
2021			
WOR	0.019 *	3.78	72.67
WOR + faba bean	0.418	0.90	0.00
WOR + blue lupin	0.659	0.48	0.00
WOR + common vetch	0.081	2.32	46.62
WOR + clover mixture	0.027 *	3.40	67.90
2022			
WOR	0.349	-1.06	2.41
WOR + faba bean	0.193	1.56	22.41
WOR + blue lupin	0.323	-1.13	5.06
WOR + common vetch	0.548	0.66	0.00
WOR + clover mixture	0.746	0.35	0.00

Appendix 4

Dry weight (mean ± SE) of common chickweed (*Stellaria media*), field pennycress (*Thlaspi arvense*), and treacle mustard (*Erysimum cheiranthoides*) for each repeat of the field trial, Lidköping, November 2022. Each repeat contains one replicate of each treatment (WOR, WOR + faba bean, WOR + blue lupin, WOR + common vetch, and WOR + clover mixture), five in total. For the repeats, the numbers (1-3) represent the blocks, and the capital letters (A-B) represent the different row spacings (A 12.5 cm, and B 50 cm). Lowercase letters (a-c) represent significant differences from Tukey's pairwise comparison.



Results from statistical analyses, analysis of variance with a general linear model. Repeats (1A, 1B, 2A, 2B, 3A, 3B) represent different blocks (1-3) and different row spacings (A 12.5 cm and B 50 cm), Lidköping, November 2022. Treatments represent the different combinations of winter oilseed rape (WOR) and companion crops (WOR, WOR + faba bean, WOR + blue lupin, WOR + common vetch, WOR + clover mixture). Significant difference between the repeats for field pennycress and treacle mustard since *p*-value < 0.05, indicated by*.

		Common Chickweed		**Field Pennycress**		**Treacle Mustard**	
	DF	*F-value*	*p-value*	*F-value*	*p-value*	*F-value*	*p-value*
Repeats	5	0.65	0.663	20.85	0 *	4.10	0.010 *
Treatments	4	0.24	0.908	1.99	0.126	0.16	0.957

Appendix 5

Plant densities (%) of WOR and plants per m^2 for WOR (2021 and 2022) and legumes (2022) in November 2022, DC15. The letters (A-B) represent the different row spacings (A 12.5 cm, B 50 cm). The numbers (1-5) represent the different treatments (1 WOR, 2 WOR + faba bean, 3 WOR + blue lupin, 4 WOR + common vetch, 5 WOR + clover mixture). Data from the original project.

		2021		**2022**		
		Density *%*	*WOR* *Plants/m^2*	*Density* *%*	*WOR* *Plants/m^2*	*Legumes* *Plants/m^2*
A	**1**	-	-	85	40	-
	2	93	34	92	39	16
	3	92	59	90	36	4
	4	92	48	87	44	11
	5	-	-	88	42	-
B	**1**	-	-	87	33	-
	2	93	45	87	31	21
	3	95	61	88	28	2
	4	95	57	92	30	12
	5	-	-	90	28	-

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