Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Faculty of Natural Resources and
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Weed suppressive ability of crop mixtures

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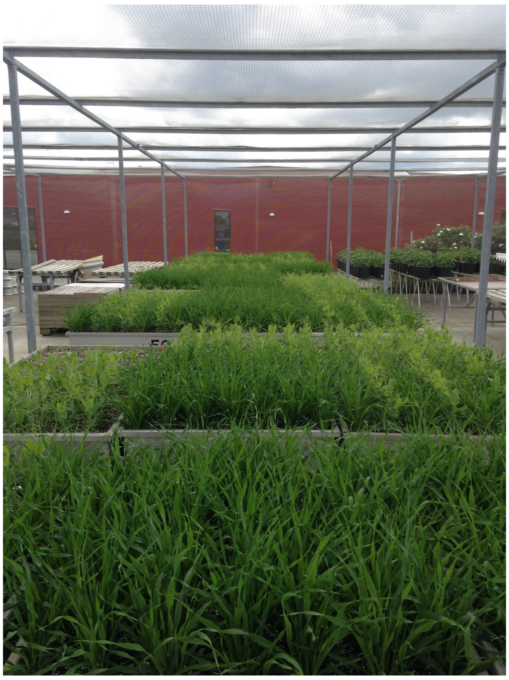

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Anna Pers Berglund

Supervisor:	Theo Verwijst, Swedish University of Agricultural Sciences SLU, Department of Crop Production Ecology
Assistant Supervisor:	Anneli Lundkvist, Swedish University of Agricultural Sciences SLU, Department of Crop Production Ecology
Examiner:	Henrik Eckersten, Swedish University of Agricultural Sciences SLU, Department of Crop Production Ecology

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Abstract

In order to assess the weed suppressive ability of a pea/barley crop mixture and the component crops in sole cropping, a controlled outdoor experiment was performed at The Swedish University of Agricultural Sciences, Ultuna, Sweden, in the summer of 2015. A substitutive completely randomized experimental design was used with seven treatments and six replicates. The weed species planted in the experiment was *Elytrigia repens* (L.) Desv. ex Nevski. At three occasions leaf area index (LAI) was optically measured using a LAI-2200C Plant Canopy Analyzer. Two destructive harvests were taken in order to assess the biomass of different plant parts from each of the component species. At the first harvest leaf area was measured in order to calibrate the optical LAI data. The results revealed a good correlation between optically obtained LAI and LAI data from the destructive harvest; pea had the highest LAI and the intercrop was intermediate to the component crops in monoculture. Presence of a crop (sole crop or intercrop) significantly diminished the growth of *E. repens* but there were no differences between sole crops and intercrop. Sole cropped pea and barley showed ability to compete against weeds at the first and the second harvest respectively whereas the intercrop showed an ability to compete at both harvests indicating an advantage of the crop mixture in terms of weed suppression.

Keywords: Elytrigia repens (L.) Desv. ex Nevski, intercropping, LAI, LAI-2200C Plant Canopy Analyzer, leaf area index, pea, spring barley, weed, weed tolerance

Sammanfattning

Ogräsen har gjort sig kända som viktiga skördesänkare inom växtproduktion på åkermark. Inom ekologisk odling finns en uppsjö metoder för att på mer eller mindre lång sikt kontrollera detta problem. Den här uppsatsen grundar sig på ett experiment som finansierats av EU-pengar i forskningsprogrammet PRODIVA. En mycket kort beskrivning av idén och syftet med PRODIVA är att man vill kartlägga vikten av diversifieringen på våra åkrar för att minska ogräsens negativa inverkan. Alltså, om man odlar olika grödor tillsammans, samtidigt och har en större artrikedom på åkrarna, kan man då minska ogräsens makt över marken?

För att ta utvärdera konkurrensförmågan gentemot ogräset kvickrot hos ärt, korn och en blandning av dem, jämfört med ingen gröda alls så utfördes under sommaren 2015 ett odlingsexperiment. Grödornas förmåga att konkurrera om ljuset med ogräset skulle undersökas. Experimentet utfördes i odlingslådor utomhus i en nätgård på Sveriges Lantbruksuniversitet, SLU, Ultuna och bestod av sju olika led: 1 kvickrot i renbestånd (ogräs); 2 korn; 3 ärt; 4 korn och kvickrot; 5 ärt och kvickrot; 6 korn och ärt; 7 korn, ärt och kvickrot. Alla arter i rena bestånd och i alla möjliga kombinationer. Alla led upprepades sex gånger och antalet odlingslådor, eller experimentella enheter, var 42.

Vid tre tillfällen i juli mättes ljusgenomsläppet i varje odlingslåda med ett optiskt instrument, LAI2200C, som jämför ljuset som går in i grödan med det som når botten på beståndet. Apparaten räknar sedan ut ett värde på bladyteindex (LAI) baserat på ljusmätningen. Två destruktiva skördar togs för att ta reda på biomassan hos de olika växtdelarna ur respektive art. En i slutet av juli och en i slutet av augusti, halva experimentet åt gången. Vid den första skörden gjordes dessutom en bladytemätning av alla blad från fem plantor per art ur varje skördad låda. Bladytemätningen användes sedan dels för att kalibrera de optiska mätningarna mot uppmätt bladyteindex, dels för att räkna ut termen specifik bladyta (SLA) som anger bladets yta per viktenhet. Ett blad som är skuggat brer ut sig mer än ett blad i direkt solsken, antalet kvadratcentimeter per gram ökar.

Resultaten visade att närvaro av en gröda gör att ogräsen minskar och med tiden blir denna effekt starkare. Ogräsens tillväxt mellan första och andra skörden var mycket kraftigare i ledet utan gröda än i leden med en eller två grödor. Vidare kunde vi se att kvickroten var påverkad av ljuskonkurrensen från grödorna. Ärten skuggade mest, kornet minst och grödblandningen låg mittemellan. Termen Ability to compete (AC) anger andelen ogräsbiomassa av total biomassa i en experimentell enhet. När vi räknade ut AC för korn, ärt och grödblandningen vid de olika skördetillfällena så visade det sig att ärt konkurrerade mot ogräs vid det första skördetillfället, korn vid det andra och grödblandningen hade konkurrensförmåga vid båda skördarna. I och med det resultatet har grödblandningen en fördel som ogräskonkurrent. I experimentet hade ogräsen ingen inverkan på grödan.

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Abbreviations

AC	Ability to compete
AWC	Ability to withstand competition
B	Barley
BP	Barley and Pea
BPW	Barley, pea and weed
BW	Barley and weed
CM	Crop Mixture
IC/I	Intercrop
LAD	Leaf Area Duration
LAI	Leaf Area Index
P	Pea
PW	Pea and weed
RWB	Relative Weed Biomass
SC/M	Sole Crop/Monoculture
SLA	Specific Leaf Area
W	Weed
WSA	Weed Suppressive Ability
WT	Weed Tolerance

1 Introduction

Intensification of the production on arable land to feed a growing world population has raised a call for sustainable cropping systems. Increasing yields has been the primary goal and has been made possible through external inputs such as agro-chemicals, fertilizers and up scaling of farm sizes. The agribusiness where a few crops are grown in large scale has, though, led to increasing problems with pests, diseases and weeds. The latter is considered a great constraint to food production (FAO 1, n.d.). As stated by the Food and Agriculture Organization of the UN (FAO), herbicides are very useful to control weeds but the extended use has given new problems such as ground water pollution and the spreading of herbicide resistant weeds (Taberner Palou et al., 2008).

In Western Europe the environmental concerns have resulted in EU policies for biological control and Integrated Pest Management (IPM) of weeds (Anonymous, 2009; FAO, 2006). Within the IPM of weeds, preventive methods such as choice of plant material, crop rotation and soil management are implemented. Moreover, herbicides should be used according to a need and making use of crop-weed competition is part of the weed control. The crops should use the resources well enough to restrain the weed populations' uptake of light, water and nutrients. It is done by choosing plants with a quick emergence, high nutrient use efficiency and quick canopy closure (Anonymous, 2009; Jordbruksverket, 2015; Lundkvist, 2014).

Whilst the IPM methods for weed control allow herbicide use to a certain extent, the organic production struggles to maintain profitable yields keeping weed populations under control without chemical input. Organic production is nothing new but the concept as such has developed from the choice not to use agrichemicals nor fertilizers when they entered the market in the mid1900s (Källander and Ögren, 2005; Lundkvist, 2014). Organic farming is, according to Bárberi (2002), a slower system where the time at which one expects to see an effect of a measure needs to be longer than in conventional farming where direct methods such as chemical control of weeds gives a kind of instant relief. Further, all direct and indirect methods must be seen as flexible components to be used to keep weed populations under control. In order to break dominance of a few weed species the cropping system must contain many and diverse means of control that are allowed to change over time (Bàrberi, 2002).

This thesis is done within the PRODIVA project which is a European Union financed research program aiming at providing organic farmers with knowledge and guidelines about weed management through crop diversification. One of the goals of the project is to investigate the effect of crop mixtures on weed suppression in controlled experiments and field trials (Anonymous, 2015).

The objective of this thesis is to evaluate the impact of a crop mixture on weeds compared to i) pure stands of any of the component crops and ii) to weeds in absence of crops; with a focus on leaf area index and light extinction by the crop/-s. Furthermore, the thesis should give a literature background containing relevant theory on the subjects treated in the experiment and discussed in the thesis. The hypotheses are:

- Presence of weeds suppresses crops
- The intercrop of pea and barley supresses weeds to a larger extent than their sole crops
- A crop's ability to shade is important for weed suppression

2 Background

2.1 State of the art – a brief on the current use of crop mixtures in Sweden

Sweden's most common crop mixture (leys not included) is the cereal/legume mixture with more than 50 % cereal and it is grown on around 0.5 % of the total arable land in the country (table 1). It constitutes a little over 1 % of the green fodder and ley production area (production of maize (*Zea mays* L.) not included). The second most common intercrop is the cereal mixture (cereals only) cultivated on nearly 0.5 % of the arable land and only on a little more than 1 % of the area of cereal production. The third type of mixture is the one called protein crops (cereal/legumes) with unknown percentages of cereal and legume content, produced on nearly 1 % of the green-fodder and lay area (Statistics Sweden, 2014).

The two big seed traders in Sweden, Lantmännen Lantbruk and Svenska Foder, have a few crop mixtures for sale (table 2) where the most common is the oat/pea mixture (Personal communication, Lantmännen lantbruk and Svenska Foder, 2015-02-15). The mixtures contain a legume, pea (*Pisum sativum* L.) (most commonly used) or field bean (*Vicia faba* L.) and a cereal, which is oat (*Avena sativa* L.), spring barley (*Hordeum vulgare* L.) or spring wheat (*Triticum aestivum* L.). Only one mixture contains two cereals – oat and spring barley. There are slight differences in the proportions of the component crops in the mixtures. According to Svenska Foder there are also a few farmers that use a cereal/lupin (*Lupinus* sp.) mixture but the mixture is then composed at the farm and is not sold by the company (Personal communication, Svenska Foder 2015-02-15).

*Table 1. Total number of hectares used for crop mixtures in Sweden, % of areas used for crop mixture production out of the total area of arable land, and proportion of crop mixtures in each group of production. The two main groups of crop-mixture production are: cereal/legume production and green fodder- and ley production (Statistics Sweden, 2014). * 3 047 400 ha. ** 984 500 ha. # 37 450 ha (maize not included).*

Mixture type	Number of hectares	% of total arable land*	% of total cereal area**	% of tot. green fodder and ley area#
Cereal mixtures	13 568	0.45	1.38	-
Cereal/legumes (>50% cereal)	15 832	0.52	-	1.34
Protein crops (legume/cereal)	9 368	0.31	-	0.80
Total	37 768	1.3		3.20

Table 2. Crop mixtures for sale in Sweden according to the seed traders Lantmännen Lantbruk and Svenska Foder. - : no information available.

Seed company	Crops	Percentage of each crop
Lantmännen Lantbruk	Oat/pea	50/50
	Barley/pea	50/50
	Spring wheat/field bean	30/70
	Spring wheat/pea	50/50
	Oat/barley	50/50
Svenska Foder	Oat/pea	40/60
	Barley/pea	40/60
	Spring wheat/field bean	30/70
	(Lupin/cereal)	-

2.2 General concepts

In a literature review made by Liebman and Dyck (1993), it was found that, out of 24 intercropping studies where all component crops were considered main crops, in 50 % of the cases the weed biomass reduction was greater in the intercrop than in sole crops of all component species. In 42 % the intercrop was intermediate to the component crops regarding weed suppression and in 8 % the intercrop was weaker than the component crops in sole cropping.

According to Larsson (1990) mixing species can be an effective way to prevent nutrient leakage and weed growth since the component species have different ranges of uptake and make a good combination for competition against weeds. The most common crop mixture in Sweden is grass ley or grass/clover ley for fodder production (Statistics Sweden, 2014). Crop mixtures can also consist of two or more different cereals or cereals and legumes (Kaut et al., 2008; Nelson et al., 2012). Larsson (1990) states that not only can a crop mixture contribute to weed control; it can also give more stable yields of a sensitive crop, one example being pea where a cereal contributes to the structural stability of the crop stand and the diminishing of crop disease. Pea can be added to a cereal in order to increase the protein content of animal feed (Larsson, 1990).

The most basic understanding of intercropping (IC) is a mix of two or more crops, also called multi-cropping or poly-culture and it is opposed to monoculture (M) or sole cropping (SC) where only one species is cultivated. Second, the mix i.e. the crop diversification can be done in time and/or in space (Vandermeer, 1989). A crop mixture in a field gives the space diversification whereas a crop rotation is a diversification over time (Liebman and Dyck, 1993). The time- and space-aspects of diversification can be combined if the crops are sown at the same time and harvested at different occasions (Bergkvist et al., 2010). Increasing the diversity of species at a site has many times showed to increase the total yield compared to a monocrop community (Malézieux et al., 2009). This can be derived from the complementarity hypothesis that suggests that each species added to a community will add to *community function*, for example the resource capturing capability of that community (Cain et al., 2008).

The design of an intercrop can be additive or substitutive. An additive design means adding one crop at a decided seed rate to the other, whose seed rate is not changed due to addition of the other. Hence, the plant density increases. A substitutive design means that the crops are partly exchanged with each other keeping the plant density at the original level of one of the component crops. There are however all sorts of intercropping designs in between these two types (Vandermeer, 1989). The data analyses of intercropping experiments have to take into account the type of design in order not to misinterpret the results (Harper, 1977).

There are many ecological theories treated in intercropping literature and only a few can be considered the scope of this thesis. The ecological niche of a species is the physical and biological conditions it needs to survive, grow and reproduce (Cain et al., 2008). The niche can be *fundamental* or *realized* where the first one denotes a species' niche when undisturbed and the second is the niche of a species when in interaction with another or other species. The realized niche is a result of the effect-response process (Vandermeer, 1989). It means that the environment has an impact on the plant/plants, which in turn has/have an impact on the environment. This is somehow very similar to what Harper (1977) denominates interference, which includes any kind of change in the environment brought about by another species (resource capture, production of toxins etc.). The effect-response might be positive (facilitation) or negative (competition/competitive interference). Plant population dynamics and intercropping also include the theory of asymmetric and symmetric competition. Symmetric competition is due to size differences whereas the asymmetric competition is not (Weiner, 1990). Competition has been defined in the literature by both Vandermeer (1989) and Harper (1977) where the former states:

> *'Competition (interference) is the process in which two individual plants or two populations of plants interact such that at least one exerts a negative effect on the other' (Vandermeer, 1989).*

And the latter declares:

> *'Competitive interference is the process whereby one species directly affects the growth of the other by competing for a resource or resources potentially available equally to both' (Harper, 1977).*

In an intercrop the ratio of competition or facilitation of one crop on the other is a matter of density of the component crops and the aim is to reach facilitation at least for one of them (Vandermeer, 1989). Moreover, if facilitation dominates competition, the realized niche will be broader than the fundamental one. Hence, the facilitation is of interest for the yield of an intercrop but the competitive ability of a crop or intercrop is of interest when dealing with weeds (Vandermeer, 1989).

The interference between (inter)crop and weed can be accounted for by looking at the (inter)crop's ability to compete (AC) and its ability to withstand competition (AWC). There are also the terms weed tolerance (WT) and weed suppressive ability (WSA). WT is the same as AWC and refers to a crop's ability to yield equally regardless of competition from weeds whereas the AC and WSA both denotes the crop's capability to weaken the growth of weeds (Nelson et al., 2012). Szumigalski and Van Acker (2005) calculated the ability to compete and the ability to withstand competition in the following way:

$$AC = 100 - ((b_w/b_t)*100) \quad [1]$$

$$AWC = (Cb_w/Cb_{wf})*100 \quad [2]$$

AC is the weed biomass weight out of the total plant biomass weight in one experimental unit and AWC compares the crop biomass weight in presence of weeds to the crop biomass weight in absence of weeds. The same authors used their data to investigate the possible synergistic effects of an intercrop on the weed biomass; a term denoted relative weed biomass, RWB.

$$\mathrm{RWB} = \mathrm{Ib}/(\Sigma \mathrm{Sb}_{i \ldots n}/n) \qquad [3]$$

RWB compares the weight of the weed biomass in an intercrop with the average weight of weed biomass in the sole cropped component crops. An RWB < 1 indicates that there might be synergistic weed suppressive effects of an intercrop (Szumigalski and Van Acker, 2005). Relative Weed Biomass and Ability to Compete answer the same question about Weed Suppressive Ability using different data in their formulas (Nelson et al., 2012).

2.3 Barley, pea and their intercrops

In the experiment of this thesis three species were used. The two crops were barley and pea and the weed *Elytrigia repens*. This sub-chapter treats pea and barley and studies on their intercrop, and the next will briefly describe the possible methods of controlling *Elytrigia repens* and studies thereof.

Barley (*Hordeum vulgare* L.) is abundant worldwide and variation within the species is large. Spring barley is the second most commonly grown cereal crop in Sweden, with an average yield of 4000 to 5000 kg ha^{-1} (Statistics Sweden, 2014). Spring barley is cultivated in all parts of the country whereas autumn sown varieties are concentrated to the southern parts (Fogelfors, 2015). The fertilizing scheme reaches from 55-125 kg N ha^{-1} depending on expected yield (Albertsson et al., 2014). Barley has a fast emergence and growth and is capable of vigorous tillering, traits that make it a good competitor against spring emerging weeds (Fogelfors, 2015).

Pea (*Pisum sativum* L.), just like barley, is cultivated all over the world except for the warmest areas of the tropics. In symbiosis with rhizobium bacteria on its roots pea can fix nitrogen from the air and is hence not in any particular need for nitrogen fertilizing (Fogelfors, 2015). It even contributes with nitrogen to the soil for the subsequent crop to take up (Albertsson et al., 2014). Pea can be sown early in the season since it starts growing already at low temperatures (1-3°C) but is sensitive regarding soil structure and water conditions. The scarce tillering of modern cultivars of pea makes a fast and early emergence important to obtain a good competitive ability against weeds. Normal yield of pea in Sweden if harvested ripe is 3000 kg ha^{-1} (Fogelfors, 2015).

It has been showed by a number of studies that pea suppresses weeds to a lesser extent than barley and their intercrop (Corre-Hellou et al., 2011; Deveikyte et al., 2009; Hauggaard-Nielsen et al., 2001; Mohler and Liebman, 1987; Poggio, 2005). This is an overall conclusion from experiments done mainly with different plant densities and nitrogen applications as treatments. Due to a more efficient resource capture the intercrops suppressed weeds to a greater extent than the different sole crops of pea and barley in a study by Hauggaard-Nielsen et al. (2008).

Mohler and Liebman (1987) observed in their work with barley, pea, annual weeds and *E. repens,* that weed density decreased with increasing crop density and that the barley/pea intercrop did not show any advantage regarding weed suppression compared to sole cropped barley. Biomass production of the stands was barley > intercrop > pea for all treatments and the weed biomass showed the inverted results, i.e. weed only > pea > intercrop > barley. This is in line with the results of Corre-Hellou et al. (2011) and Poggio (2005). Weed suppressive ability of pea seemed most effective in cases where it germinated faster than the dominating weed (Mohler and Liebman, 1987).

Corre-Hellou et al. (2011) performed an intercropping experiment in four European countries. Barley and pea were the component crops that were cultivated in organic farming conditions. Neither irrigation nor mechanical weeding was done after sowing. For the intercrops there was both a replacement- and an additive design with varying amounts of barley (Corre-Hellou et al., 2011). Data collection was done on three main parameters: biomass production, leaf area index (LAI) and nitrogen content. From the first harvest to the second there was a doubling in weed dry matter in pea SC but only a 24-37% increase in barley SC and intercrops. Weed suppression by the IC was in level with barley SC even at low plant density of barley. No significant differences were found between barley and intercrop or between additive and replacement design. In 73% of the cases the IC produced a larger amount of biomass than the sole crops. The total crop biomass was less influenced by weed infestation in intercrops than in SC of any of the component crops, which indicates a greater *weed suppression stability* of the IC (Corre-Hellou et al., 2011). This is also described by Poggio (2005) whose results showed similar weed suppression of barley SC and the IC of barley and pea where the IC's weed suppression was more stable across sites and years and complementarity was the explanation (Poggio, 2005).

Corre-Hellou et al. (2011) further showed that pea SC and intercrops had higher LAIs than barley SC. In 20% of the cases, an IC produced a higher LAI than a pea SC. Barley LAI was coupled to nitrogen: lower LAI at lower soil N availability. An increase in LAI of a pea SC led to increased weed suppression. Regardless of LAI, pea SC plots contained more weed biomass than ICs and barley SC. The decrease in weed dry matter was similar for barley SC and ICs independently of their LAI (Corre-Hellou et al., 2011).

Liebman and Robichaux (1990) showed though that shading by the crops (pea and barley) became less important as a competitive parameter against weeds at high fertilization and that the competitive advantage of their pea/barley-intercrop was greater at the low fertilization rate. The canopy's importance for weed suppression was further studied by Liebman (1989) who showed that the pea leaves' ability to shade does become important at well-fertilized conditions.

2.4 Control of *Elytrigia repens* (L.) Desv. ex Nevski

Elytrigia repens (L.) Desv. ex Nevski, or couchgrass, is a perennial weed propagating by its relatively shallow rhizomes and by seed production. It thrives on all kinds of soils and in well-fertilized environments. It is tolerant to shading but sensitive to repeated tillage although the rhizomes can be boosted to new shoots if disturbed to a lesser extent (Håkansson, 2003; Lundkvist, 2014). Harrowing or ploughing at its compensation point (3-4 leaves) is a powerful setback for *E. repens*. The most effective mechanical control measures have shown to be combined stubble cultivation and ploughing in the autumn as well as black fallow (Håkansson, 2003; Lundkvist, 2014). The rhizomes grow from the underground stem base of an aboveground shoot and will only start to grow once there are photosynthates in surplus. New aerial shoots will then appear from the nodes or apices of the rhizomes, or from the stems of older shoots. Rhizomes will grow continuously throughout the season, branching mainly horizontally (Håkansson, 2003).

In an experiment by Rasmussen et al. (2014) done on coarse sand the repeated mechanical destruction of rhizomes and shoots both pre- and post-harvest as well as during the season was effective against *E. repens*. It was also shown that inclusion of manure did not enhance growth of *E. repens* and that the preceding crop is important for the population of *E. repens* in the current one (Rasmussen et al., 2014). From experiments with autumn measurements to control *E. repens* it was concluded that an early post-harvest prevention of growth of *E. repens* was more important than repeated cultivation to starve the rhizomes (Ringselle et al., 2016).

Bergkvist et al. (2010) utilized niche differentiation and competitive ability in a crop mixture to prolong the period of competition against *E. repens*. Winter wheat (*Triticum aestivum* L.) was under-sown with red fescue (*Festuca rubra*) and the latter was left to grow after harvest of wheat. Red fescue did then reduce the growth of rhizomes significantly. Further, as shown by Ringselle et al. (2015) a grass-clover cover crop can decrease the above ground shooting of *E. repens* during autumn as well as increase the yield of the subsequent crop. The number of shoots of *E. repens* during autumn did also decrease using a cover crop and a single duck foot cultivation although the long term effects of this combination of measures have not been verified (Aronsson et al., 2015).

Chemical control of *E. repens* is mainly done by using glyphosate and in 2014 researchers looked into the possible event of resistance development to that substance (Espeby et al., 2014). Sixty-nine clones of *E. repens* were collected from different locations in Sweden and no past selection for resistance could be found. However, the susceptibility varied to a large extent, which points in the direction of possible such selection in the future (Espeby et al., 2014).

2.5 Leaf Area Index and light extinction measurement

The evaluation of competition for light in the experiment in this thesis was done through optical measurements of light extinction at three occasions and one leaf area measurement at the first harvest.

Leaf area index (LAI) is a measure of total leaf area per m^2 ground, i.e. the total area of assimilation over 1 m^2. Leaf area index can be measured indirectly using optical methods or directly through a destructive harvest where leaves are taken off the plants to measure their area. The methods can also be combined in order to calibrate the optical method (Fang et al., 2014; Malone et al., 2002). The optical instrument calculates LAI from measurements of the light extinction of a crop stand (LI-COR Inc., 2013). Malone et al. (2002) found no or little (2-15%) difference between the estimated LAI from the optical instrument LAI-2000 and the leaf area index obtained from a destructive harvest of soybean stands. In the same study it was concluded from measurements of defoliated stands that the optical instrument does include other parts than leaves since an LAI value was also obtained from plants left with stems and pods only (Malone et al., 2002).

Leaves developing in a shaded environment become thinner than leaves exposed to a lot of light. This is explained by a lower number of light absorbing cells in a leaf where light is scarce than in a leaf in direct sun (Fogelfors, 2015). This can be described and quantified using the term specific leaf area (SLA), unit area per unit weight of a leaves, since shading gives a rapid increase in the leaf area to leaf weight ratio (Harper, 1977).

According to Fogelfors (2015) the LAI for most crops in Swedish conditions is somewhere between 4 and 6. LAI in cereals should not be lower than 3 to fully utilize the incoming radiation. A maximum LAI much higher than 3 is not necessary, more important is the Leaf Area Duration (LAD), which is LAI over time and is strongly correlated to grain yield (Fogelfors, 2015; Liu et al., 2005).

Hay and Porter (2006) showed the LAI development of barley at different target plant densities. LAI reaches maximum earlier the more dense the crop and at 200 plants/m^2 peak LAI is around 4 at the beginning of July whereas the density of 400 plants/m^2 is 5 at the same point of time (Hay and Porter, 2006). Further they explain the reason behind a higher LAI value than the seemingly optimal 3 by pointing out that later emerging leaves tend to stay green and assimilating longer than leaves at lower strata in the canopy. Therefore the LAI can exceed 3 due to the leaf-ages overlapping each other in a canopy (Hay and Porter, 2006)

3 Materials and Methods

In order to evaluate the impact on weeds from i) an intercrop and ii) its two component species in sole cropping with a focus on leaf area index and light extinction by the crop/-s, a controlled outdoor box experiment was performed during the summer of 2015. Data was collected from the two harvests, the optical measurements of light extinction by the canopy and estimation of leaf area index through a destructive harvest. The degree of competition from the different crop stands was then assessed using statistical analyses.

3.1 Box experiment

The box experiment was performed in an outdoor netting enclosure at SLU, Ultuna close to Uppsala in Sweden (59°48'N, 17°39'E). The experiment consisted of seven treatments, described in table 3, and six replicates – a total of 42 boxes – in a complete randomized design.

Each box measured 80 cm x 80 cm x 20 cm giving an area of 0.64 m^2 and a volume of 128 litres. The boxes, consisting of a bottom and a frame allowing for drainage around the edges, were filled with soil consisting of 85% moderately decomposed peat and 15% sand, which was watered thoroughly before sowing.

The component crops of the experiment were spring barley (*Hordeum vulgare var. distichon*) SW Vilgott, field pea (*Pisum sativum*) SW Clara, and weed species used was *Elytrigia repens* (L) Desv. ex Nevski. The rhizomes of *E. repens* were harvested from a rhizome bank kept at SLU, Ultuna. Each planted rhizome piece had two nodes. Six such pieces were planted in each box of treatments containing weed, an amount assumed to give rise to significant weed pressure.

The number of seeds per box (n) was calculated by multiplying the most commonly used number of seeds per square meter in conventional farming (spring barley sole crop (SC): 350 seeds m^{-2}, pea SC: 100 seeds m^{-2}) with the box area (0.64 m^{-2}) (equation 4), see table 3.

$$n = (\text{Number of seed m}^{-2}) \times 0.64 \qquad [\text{no m}^{-2}] \qquad [4]$$

Table 3. Experimental design of the box experiment. Numbers of seeds box^{-1} of spring barley and pea were calculated by using equation 4: n = (Number of seeds m^{-2}) x 0.64 where n is the number of seeds per box.

Treatment		Abbreviations	No of seeds, box^{-1}		No of rhizomes, box^{-1}
			Spring barley	Pea	*E. repens*
1	*E. repens*	W	-	-	6 pieces
2	Spring barley	B	224 seeds	-	-
3	Pea	P	-	64 seeds	-
4	Spring barley + *E. repens*	BW	224 seeds	-	6 pieces
5	Pea + *E. repens*	PW	-	64 seeds	6 pieces
6	Spring barley + Pea	BP	112 seeds	32 seeds	-
7	Spring barley + Pea + *E. repens*	BPW	112 seeds	32 seeds	6 pieces

3.1.1 Preparations, sowing and maintenance

Before the experiment was started one indoor and two outdoors emergence tests were performed and for each component crop the weight of a hundred seeds (HSW) were noted and used to calculate the amount of seed in grams for each box of the experiment. The number of seeds box^{-1} (n) (table 3) divided by 100 was multiplied with the weight of a hundred seeds (HSW) (equation 5).

$$\text{Grams of seed} = (n/100) \times \text{HSW} \qquad [\text{g box}^{-1}] \qquad [5]$$

The experiment was sown on 25 May 2015, with a sowing depth of 3 cm and a row spacing of 12 cm. This gave seven crop rows with four cm spacing between the box frame and the rows on the edges. Two rows with 3 pieces of *E. repens* rhizomes were planted in treatments 1, 4, 5 and 7. In the intercrop treatments (6 and 7), spring barley and pea were sown in a 50/50 replacement design with the component crops in different rows. After sowing, the experiment was watered and continued to be so whenever the weather conditions made it necessary. The experiment was fertilized 23 June with about 60 kg nitrogen ha^{-1} at developmental stage DC 24 for barley and DC 35 for pea (Zadoks et al., 1974). On 7 July, boxes with pure *E. repens* (treatment 1), were moved to form a separate group since barley and pea in adjacent boxes shaded the pure stands of *E. repens*.

3.2 Leaf area index (LAI) - Optical measurements

At three occasions, 17, 21, and 25 July, Leaf area index (LAI) was optically measured. The instrument used for the experiment was a LAI-2200C Plant Canopy Analyzer which estimates LAI of a canopy by comparing the incident light at 320-490 nm (blue wavelength) above the canopy with the light at the bottom of the crop stand looking upwards. The LAI-2200C uses a “fish-eye”-lens in five concentric rings to estimate the leaf area of a stand. The optical ring 4 and 5 of the sensor were masked since the size of the boxes undercut the minimum size in relation to the canopy height according to the manual (LI-COR Inc., 2013). For each box the instrument was programmed to do a controlled sequence of one measurement above the canopy and three subsequent ones below, i.e. at the bottom of the stand. Barley was in developmental stage DC 69 at the first measurement and DC 71 for the second and third. Pea had reached DC 59, 61 and 65 at the three occasions respectively. All measurements were done at overcast conditions in order to get the best results according to the manual of the LAI-2200C (LI-COR Inc., 2013).

3.3 Harvests and weed assessments

3.3.1 Harvest 1 (27-31 July)

Three boxes within each treatment, a total of 21 boxes, were randomly chosen and harvested 27-31 July for assessment of leaf area and biomass production. Spring barley was in developmental stage DC 77 and pea in stage DC 67-71. The plant stand was cut 4 cm above the soil surface and separated into component species (spring barley, pea, *E. repens*). From each species five shoots were randomly picked for analyses of leaf area, dry weights of leaves, stems and tendrils. The remaining plants of each species were dried to constant weight. Rhizomes from *E. repens* (treatments 1, 4, 5, and 7) were washed and dried to constant weight. In all boxes a number of weed species apart from *E. repens* had appeared. The weeds (denoted “weeds” or “remaining weeds”) were harvested and accounted for in the same manner as the crops and *E. repens*.

3.3.2 Harvest 2 (24-28 August)

All remaining boxes in the experiment were harvested 24-28 August. Barley was in developmental stage DC 91-92 and pea in DC 81-85. The procedure of harvest 2 was the same as for harvest 1 with the exception for the leaf area measurements, which were not done at harvest 2.

3.4 Data analyses and statistics

Analyses of data and construction of graphs (means with error plots) were done by means of the Dell Statistica Software (DELL INC., 2015). The LAI calibration was performed by the nonlinear estimation procedure, using an exponential zero-intercept model. Ability to compete (AWC) and Relative weed biomass (RWB) were calculated according to Goodman (1960). Other comparisons of treatments and of treatments over time were made by the Factorial ANOVA Procedure (DELL INC., 2015).

4 Results

4.1 Emergence tests

In both the indoor and the outdoors tests, spring barley and *E. repens* emerged 1-2 days faster than pea. The emergence rate for all three species was 100% indoors, while the emergence rate was 100%, 90%, and 80% for pea, spring barley and *E. repens*, respectively, outdoors.

4.2 Optical measurements of light extinction and Leaf area index

The optical data from 25 July was scattered and calibrated using an exponential zero-intercept model with the leaf area index (LAI) calculated from data obtained from the first destructive harvest. The scatterplot, figure 1, shows that the optical measurements correlated well, R^2=0.69, with the data from the destructive harvest. At lower LAI values the LAI-2200C Plant Canopy Analyzer gave an overestimation of the LAI, which is expected since the optical instrument does not discriminate between leaves, stems and pea tendrils. At lower LAI the stems and tendrils contribute to the crop's light extinction relatively more than at higher LAI. The data from LAI-2200C and the destructive harvest coincided at an LAI of about 7.

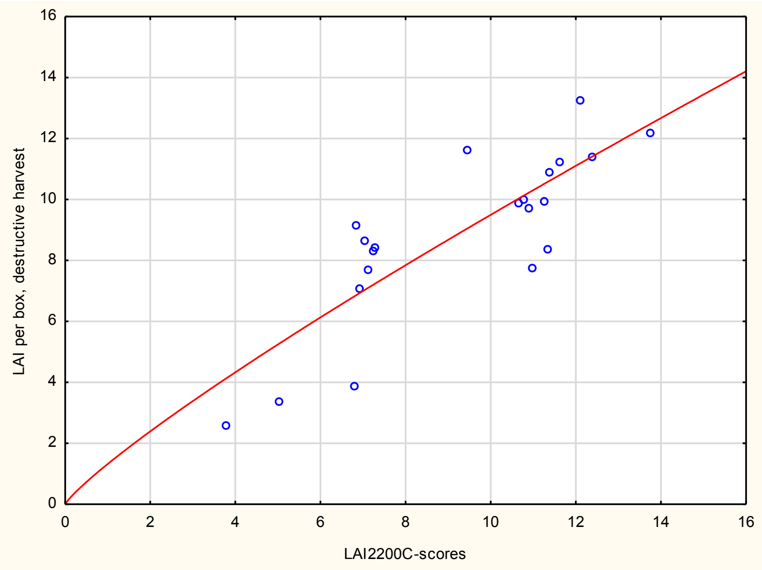

Figure 1. LAI-2200C-scores as a function of measured LAI at harvest 1. The LAI-2200C measurements used in the graph were taken on 25 July, 2015. Calibration was done with an exponential zero-intercept model giving an R^2-value of 0.69.

The calibrated data from LAI-2200C were then plotted to display the development over the three occasions of optical measuring, figure 2. Between the three measurements the LAI in treatment 1 (weeds only) increased whereas for the treatments 2 (barley) and 4 (barley and *E. repens*) the LAI decreased. The remaining treatments showed no significant changes in LAI between the three measurements, table 4.

Treatments with SC barley (2 and 4) had a lower LAI than the intercrop, treatments with SC pea (3 and 5) had a higher LAI than the intercrop and LAI of the intercrop (6 and 7) was intermediate compared to the different sole cropped stands (figure 2). Data in figure 2 is based on LAI per box including LAI of all weeds. This is a reasonable approximation since weeds contributed with 0.07-2.28 % to the total LAI in treatment 2-7.

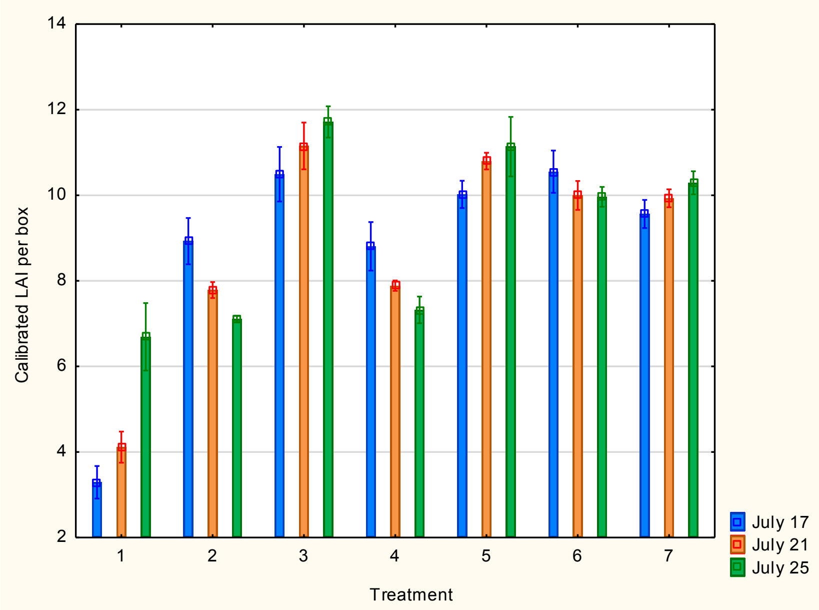

Figure 2. Calibrated LAI values for the different treatments measured with LAI-2200C at three different occasions: 17 July; 21 July; and 25 July 2015.

Table 4. ANOVA results of the changes in LAI over time as displayed in figure 2. The p-values indicate an increase (treatment 1), a decrease (treatments 2 and 4) or NONE meaning no significant change (treatments 3, 5, 6, 7).

Treatment	p-value	direction
1 W	0.0014	increase
2 B	0.0053	decrease
3 P	0.2920	NONE
4 BW	0.0437	decrease
5 PW	0.2390	NONE
6 BP	0.4690	NONE
7 BPW	0.2052	NONE

4.3 Effect on weeds from crops and crop mixtures

4.3.1 *Elytrigia repens* – Leaf area index (LAI) and Specific leaf area (SLA)

Leaf Area Index (LAI) and Specific Leaf Area (SLA) changed significantly when crops were present. In figure 3 the LAI of *E. repens* is shown with a significant (*p*-value of 0.006) difference between treatment 1 where no crop was present and the remaining treatments containing one or two crops and *E. repens*. There were no significant differences between treatments with one or two crops, i.e. treatments 4 (BW), 5 (PW) and 7 (BPW).

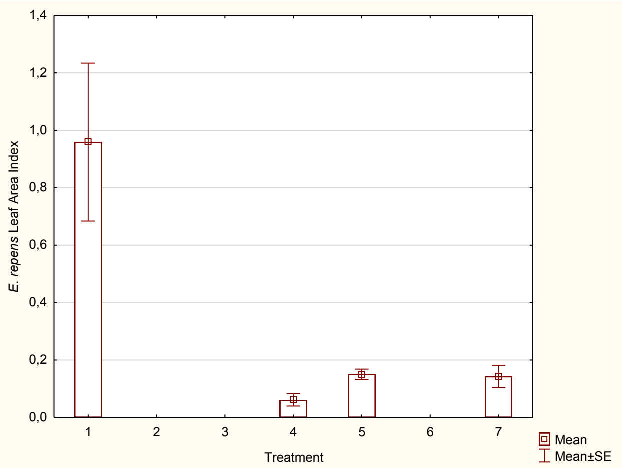

Figure 3. LAI of *E. repens* (*p*-value 0,006). Values from harvest 1, 27-31 July with mean and SE indicated. Treatments: 1 W, 2 B, 3 P, 4 BW, 5 PW, 6 BP, 7 BPW.

The SLA of *E. repens* is shown as a function of treatment in figure 4. There are significant differences between treatments 1 and the other treatments (4 BW, 5 PW, 7 BPW) (*p*-value 0.0005) as well as between treatments 4, 5 and 7 (*p*-value 0.0019. The highest SLA of *E. repens* was found in treatment 5 (PW) whereas the lowest was found in treatment 4 (BW). Values from treatment 7 (BPW) are in between the ones from treatment 4 and 5.

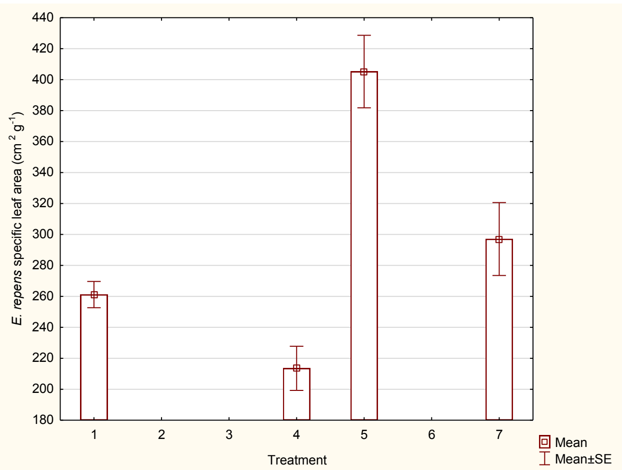

Figure 4. Specific Leaf Area ($cm^2\ g^{-1}$) of *E. repens* in the different treatments. Significant differences between treatments 1 (W), 4 (BW), 5 (PW), and 7 (BPW (*p*-value 0.0005) and between treatments 4, 5 and 7 (*p*-value 0.0019).

4.3.2 *Elytrigia repens* – Growth and reproduction

The average proportion of *E. repens* aboveground weight over total weight (above/(above + below-ground)) is 0.64 ±0.019 (mean ± SE). Neither harvest time nor treatment had an effect on this proportion. The biomass of *E. repens* (above-ground and rhizomes) decreased when any component crop or intercrop was present, figure 5. There was also a significant interaction between treatment and time, *p*-value 0.000007, the relative increment of *E. repens* over time being much lower in the treatments containing a crop, compared to the sole weed treatment. No significant differences were found between *E. repens'* biomass in treatments with crops, i.e. 4 (BW), 5 (PW) and 7 (BPW).

The same pattern of reduced biomass, harvest time x treatment interaction and lack of difference between treatment 4, 5 and 7 is valid for the rhizomes of *E. repens* as well as of production of spikes and seeds.

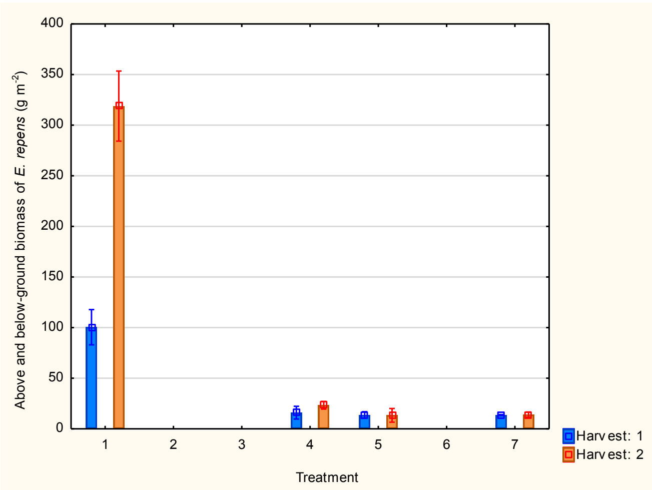

Figure 5. Biomass of *E. repens* in the different treatments of the experiment, mean values from harvest 1 and 2 and standard error indicated. Treatments: 1 W, 2 B, 3 P, 4 BW, 5 PW, 6 BP, 7 BPW.

4.3.3 *Elytrigia repens* – Relative weed biomass (RWB)

The relative weed biomass (RWB) for *E. repens* was calculated for harvests 1 and 2, using equation 3 and standard errors according to Goodman (1960) table 5. The results showed no significant differences between the two harvests.

Table 5. Relative weed biomass (RWB) calculated according to equation 3: RWB = Ib/(ΣSb$_{i...n}$/n) with no significant differences.

	Harvest 1	Harvest 2
RWB ± SE	0.92 ± 0.45	0.77 ± 0.41

4.3.4 Other weeds – biomass production

Weeds other than *E. repens* appeared in the boxes without being sown or planted. The following species were identified: *Salix viminalis* L., *Salix sp, Polygonium sp, Taraxacum vulgare* L., *Tussilago farfara* L. and *Senecio sp.* At both harvests the biomass of those weeds was relatively high in treatment 1 (no crop) compared to the other treatments. This is illustrated in figure 6 where data from both harvests are included with mean values and standard error displayed in the graph. The graph also indicates that time had an impact on the effect of treatment, i.e. there was a harvest time x treatment interaction.

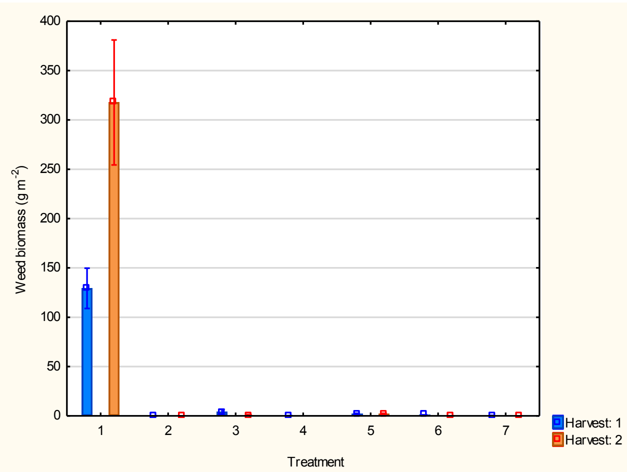

Figure 6. Biomass of weeds (*E. repens* not included) in the different treatments for harvest 1 and 2. Mean values and standard error are shown for each treatment. There is a significant difference between treatment 1 and the other treatments and a time x treatment interaction. Treatments: 1 W, 2 B, 3 P, 4 BW, 5 PW, 6 BP, 7 BPW.

In figure 7, treatment 1 (W) is excluded in order to illustrate the effect of sole crops and intercrop. It reveals that at harvest 2, barley was a better competitor than pea with a *p*-value of 0.0025, and that the intercrop was intermediate to the sole cropped component crops. At harvest 1 there was no significant difference between treatments 2-7. This further indicates a harvest time x treatment interaction.

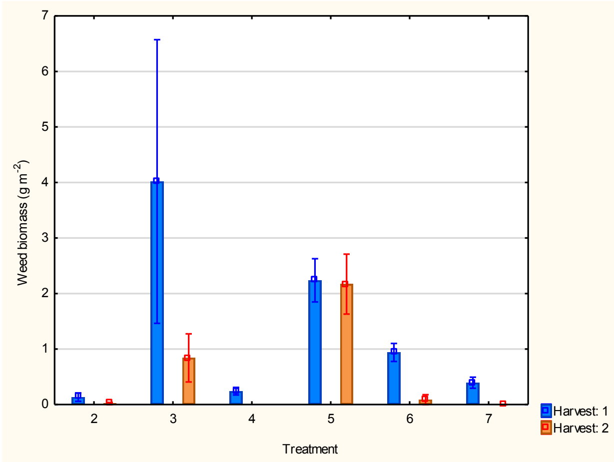

Figure 7. Weed biomass (*E. repens* not included) per treatment and harvest with treatment 1 (W) excluded. Significant differences in weed biomass between treatments for harvest 2 (p = 0.0025), but not for harvest 1. Treatments: 1 W, 2 B, 3 P, 4 BW, 5 PW, 6 BP, 7 BPW.

4.3.5 *Elytrigia repens* and other weeds – Ability to compete (AC)

The ability to compete (AC) was calculated using equation 1. There were significant results of AC for treatment 4 (BW), harvest 2; treatment 5 (PW), harvest 1; and treatment 7 (BPW), harvest 1 and 2, table 6.

*Table 6. Ability to compete (AC) according to equation 1: AC = 100 – ((b_w/b_t)*100). The respective bt-input (total biomass) include the aboveground biomass of all weeds as well as crop biomass and the term bw (weed biomass) denotes either all weed biomass including the rhizomes of E. repens; the above- and belowground biomass of E. repens; or the aboveground biomass of E. repens and the other weeds. Only significant results are shown in the table.*

		AC ± SE	
	bw includes	Harvest 1	Harvest 2
Barley	All*		98.65 ± 0.30
	*E*ab**		9865 ± 0.30
	*E*a+W***		99.24 ± 0.17
Pea	All	98.85 ± 0.20	
	*E*ab	99.02 ± 0.22	
	*E*a+W	99.19 ± 0.14	
IC	All	98.91 ± 0.05	99.06 ± 0.22
	*E*ab	98.94 ± 0.05	99.06 ± 0.22
	*E*a+W	99.26 ± 0.10	99.37 ± 0.13

* *Elytrigia repens* aboveground and belowground biomass and other weeds
** *Elytrigia repens* aboveground and belowground biomass
*** *Elytrigia repens* aboveground and other weeds

4.4 Effect of weeds on crop

4.4.1 Crops and crop mixtures – biomass production

The effect of *E. repens* and the other weeds on the biomass of sole cropped and intercropped pea and barley was not significant.

4.4.2 Crops and crop mixtures - Ability to withstand competition (AWC)

The ability to withstand competition (AWC) was calculated using equation 2. AWC values are not significant, table 7.

Table 7. Ability to withstand competition (AWC) calculated using the equation AWC = (Cb_w/Cb_{wf}) 100 and standard errors (SE) according to Goodman (1960). Results are not significant.*

	AWC ± SE	
	Harvest 1	Harvest 2
Barley	106.63 ± 9.91	96.45 ± 10.29
Pea	115.63 ± 9.19	99.19 ± 5.17
IC	99.04 ± 8.67	92.77 ± 5.27

5 Discussion

The first hypothesis of this theses stated, “Presence of weeds suppresses crops”. In this experiment there was no effect from the weeds on any of the crops, be it a sole crop or an intercrop. The lack of effect from the weeds is likely to be a result of scarce weed presence and quick and vigorous emergence and growth by the crops, factors that can be reverse in field production making weeds a concern as stated in the introduction.

The presence of pea and/or barley had a significant decreasing effect on weed biomass; consequently the weed community decreased and would not be as big and vigorous in a subsequent crop. Bàrberi (2002) suggests that organic farming systems have to be seen as slower and the expected time of effect from a measure has to be longer than for commercial farming with the instant help from agrochemicals. Since the sole presence of a crop in the experiment at Ultuna did have a diminishing effect on the biomass of *E. repens* there is both a “direct” effect on the weed biomass during one season and the long-term effect of a weakened weed population.

The second hypothesis declares “The intercrop of pea and barley supresses weeds to a larger extent than their sole crops”. Out of the comparisons of weed tolerance and weed suppressive ability between treatments there were only significant results in ability to compete (AC). The ability to compete of pea was significant earlier (harvest 1) than the AC of barley (harvest 2). In addition, the intercrop had a significant ability to compete at both harvests, revealing a prolonged (or combined) weed suppressive ability in the intercrop. A longer weed suppression period and weed control measures late in the season are important in order to diminish the population of *E. repens* (Bergkvist et al., 2010; Lundkvist, 2014) making the significant values of AC in the intercrop interesting.

The third hypothesis, “A crop’s ability to shade is important for weed suppression”, was answered by calculating the specific leaf area of *Elytrigia repens* of the different treatments. Shading by a crop showed to have an importance for weed suppression since the specific leaf area of *Elytrigia repens* was larger in treatments with pea than without pea. Barley suppressed weeds to a larger extent regarding biomass and was hence the best competitor out of the two component crops. For a crop like pea that is not a strong competitor, shading becomes an important ability for weed suppression.

The relative weed biomass (RWB) did not give significant results despite of the statement by Nelson et al. (2012) that the AC and RWB both answer the question about weed suppressive ability. RWB compares weed presence of different treatments whereas AC compares weed biomass with total biomass for each experimental unit. In the present case where the experimental design was completely randomized, calculations of RWB had to be done using averages of data for crops and weeds from different experimental units (boxes), while AC –calculations were done using averages of crop and weed data from the same experimental units, the latter giving a more fine meshed analysis. The two terms AC and RWB do give answers to the same issue but the experimental design has an impact on the answers.

In this thesis the calibration of the optically measured data of LAI with the LAI from the destructive harvest was done as an evaluation of the optical method. The optical instrument measures the light extinction and uses a model to calculate the LAI-values. Calibrated data from the three occasions of optical measurements was then used to illustrate the development of LAI over time for the three occasions. Due to logistic issues the optical measurements could not start until mid July and a more complete series of data from the beginning of the season (at an LAI of 0) until somewhere beyond LAI maximum would have been interesting.

For the optical measuring the LAI2200C was programmed according to the manual and the two outer rings of the fish eye lens were masked in order to obtain a higher accuracy since the boxes and the crop stands covered a smaller area than the uptake of a fully open lens. If the optically obtained data is to be compared to a leaf area index obtained at a destructive harvest, the data could maybe have correlated even better if more rings had been masked.

The exponential zero-intercept model used for the calibrating of data from LAI2200C was used since it gave a slightly higher R^2-value than a Pearsson correlation, and a zero-intercept is likely to be true for a crop stand: if no leaves are present the leaf area index will be zero. An alternative could be not to extrapolate the data into a zero-intercept and instead look for the correlation of existing data.

The calibration where the optical data is compared to LAI from the destructive harvest does not lead to any conclusion on the degree of competition for light in the experiment. Regarding light extinction and competition for light, not only do the leaves play a role but pea tendrils, pea pods, stems, spikes and straws also contribute. Light extinction by the crop stand as a whole, rather than by the leaves only, is the explanation when the weeds have suffered from shading in the experiment. The LAI calculated by the LAI2200C might not be true values of leaf area index but the numbers per se could be used as valuation of light extinction by a crop stand.

Can the results of this study be generalized? The experiment showed that presence of a crop strongly inhibits weed growth and competition from a crop is an effective measure to diminish weeds. As stated above the diversification of crops, i.e. the intercrop, gave a prolonged weed suppression adding on to the weed control. Further, a small population of weeds doe not necessarily suppress the growth of a crop. Hence, one can accept the presence of some weeds in a crop and maybe even see it as part of the diversification of species in a field where no weed species is let dominate.

Why would it be interesting to look at the results from a small controlled experiment when weed issues are a global concern in field production? This question is dealt with by Bàrberi (2002) who discusses the reductionist versus holistic approach to research on weed management in organic farming. The author states that if one is to resolve a problem emerging within a specific farming system the method to solve it is probably not by the same means that have created it and certainly not by looking at an isolated occasion – the reductionist approach – but rather the system as a whole – the holistic approach. The arguments seem accurate but the paper later points out that reductionist and holistic approaches can exist mutually and overlap (Bàrberi, 2002). Hence, a controlled box experiment using fertilizer within a program of research on weed control in organic farming could work as a compass or point of departure for more holistic research and field trials where organic farming methods are implemented. Also, the experiment treated in this thesis focused on a specific issue within weed management: the competition for light and its role in weed suppression. In order to look into one isolated function it is important to design an experiment that excludes as many potential side effects and co-factors as possible.

Suggestions for further research are to perform an experiment using an additive design or a substitutive with a set plant density. With a constant density it would be possible to calculate the Land equivalency ratio to evaluate if an intercrop of pea and barley can result in over yielding, as a result of the complementarity effect of a crop mixture (Harper, 1977; Vandermeer, 1989). Further the weed pressure should be higher, i.e. if *E. repens* is the weed of interest it should be planted in greater amounts and/or be given an advantage by planting it a couple of days before the crops are sown. These design parameters would possibly give greater distinctions between the weed suppressive ability and weed tolerance of sole crops and their intercrop.

Corre-Hellou et al. (2011) found that the weed suppressive ability of a pea/barley intercrop increased even at a small addition of barley to pea. An experiment with an additive design could investigate the effect of 1-n added plants of one of the component species to the other. If pea is able to shade better than barley and barley is the better over-all competitor - at what amount of barley would the crops' weed suppressive abilities be used to their respective maximum?

An experiment with a more limited fertilization or no fertilization could give distinct results from the ones in the present study. Liebman and Robichaux (1990) found that the competitive advantage of an intercrop was significant at a low fertilization rate. An experiment with low or no fertilization would also correspond to the organic farming systems where the research results from the PRODIVA project is meant to end up as useful information and guidance.

The results from the experiment and the discussion lead to the following conclusions:

- A small population of weeds does not suppress a strong crop.
- The presence of one or two crops suppressed the biomass production of the weeds in the experiment.
- Production of biomass of *Elytrigia repens* was suppressed by the presence of one or two crops and therefore the reproduction of the population was diminished.
- Competition for light was present in the experiment judging from the specific leaf area of *E. repens*: pea shaded more than barley and their intercrop was intermediate to sole cropped pea and barley.
- The intercrop of barley and pea had the combined ability to compete (AC) against weeds of both pea and barley and was able to suppress weeds during a longer period than either of the sole cropped component crops.
- The LAI-2200C gives estimates of the LAI not too far from the leaf area index measured in a destructive harvest.
- Competition for light is a matter of light extinction by the crop stand as a whole, not only by the leaves.

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