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The competitive ability of pea-barley intercrops against weeds and the interactions with crop productivity and soil N availability

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Abstract

Grain legumes, such as peas (*Pisum sativum* L.), are known to be weak competitors against weeds when grown as the sole crop. In this study, the weed-suppression effect of pea-barley (*Hordeum vulgare* L.) intercropping compared to the respective sole crops was examined in organic field experiments across Western Europe (i.e., Denmark, the United Kingdom, France, Germany and Italy). Spring pea (P) and barley (B) were sown either as the sole crop, at the recommended plant density (P100 and B100, respectively), or in replacement (P50B50) or additive (P100B50) intercropping designs for three seasons (2003–2005). The weed biomass was three times higher under the pea sole crops than under both the intercrops and barley sole crops at maturity. The inclusion of joint experiments in several countries and various growing conditions showed that intercrops maintain a highly asymmetric competition over weeds, regardless of the particular weed infestation (species and productivity), the crop biomass or the soil nitrogen availability. The intercropping weed suppression was highly resilient, whereas the weed suppression in pea sole crops was lower and more variable. The pea-barley intercrops exhibited high levels of weed suppression, even with a low percentage of barley in the total biomass. Despite a reduced leaf area in the case of a low soil N availability, the barley sole crops and intercrops displayed high weed suppression, probably because of their strong competitive capability to absorb soil N. Higher soil N availabilities entailed increased leaf areas and competitive ability for light, which contributed to the overall competitive ability against weeds for all of the treatments. The contribution of the weeds in the total dry matter and soil N acquisition was higher in the pea sole crop than in the other treatments, in spite of the higher leaf areas in the pea crops.

Keywords: intercropping, weeds, nitrogen, pea, barley, organic farming

Introduction

Grain legumes, such as peas (*Pisum sativum* L.), should play a key role in organic cropping methods; they provide nitrogen (N) to the system and the soil for succeeding crops via their symbiosis with N_2-fixing bacteria, and they produce grain that is rich in protein. However, most legumes are known to have a weak competitive ability towards weeds (Wall et al., 1991; Townley-Smith and Wright, 1994; Mcdonald, 2003), and weed infestations have been shown to severely limit the N nutrition and grain yield of organically grown grain legumes (Corre-Hellou and Crozat, 2005). Weed management is a key issue in organic cropping systems, and weed control should be tackled primarily by altering the competitive balance between the crop and the weeds through such measures as the correct choice of rotation, the choice of crop species and cultivar or the appropriate sowing arrangements (Younie and Litterick, 2002). The infestation of weeds may also be markedly reduced by spatial diversification. Indeed, the results of a literature survey (Liebman and Dyck, 1993) indicated that weed density and biomass production may be markedly reduced by using intercropping. The authors noted that when intercrops were composed of two or more main crops, the weed biomass in the intercrop was shown to be lower than all of the component sole crops in twelve cases, intermediate between the component sole crops in ten cases, and higher than all of the sole crops in two cases. Several studies have demonstrated that weed biomass is often significantly reduced in intercrops compared to the legume crop alone in crop mixtures combining a cereal and a grain legume. However, it should be noted that intercrops and cereal sole crops have often displayed similar competitive abilities against weeds (Mohler and Liebman, 1987; Rauber et al., 2000; Hauggaard-Nielsen et al., 2001; Deveikyte et al., 2009).

Nevertheless, the factors that promote the greater competitive ability of intercrops compared to legume sole crops are not well known. According to Liebman and Dyck (1993), less weed growth may occur if intercrops are more effective than the sole crops in competing for resources with weeds or suppressing the weed growth through allelopathy. Moreover, intercrops may provide yield advantages without suppressing the weed growth below the levels observed in the component sole crops if the intercrops use resources that are not exploitable by weeds or convert resources more efficiently than the sole crops (Liebman and Dyck, 1993).

It is possible that intercrops promote the use of the available resources, thus, leaving less opportunity for the establishment and growth of weeds. Indeed, many crop mixtures, particularly cereal-legume combinations, show substantial yield advantages over sole crops, suggesting that the intercrops use the available resources more completely and/or effectively (Hauggaard-Nielsen et al., 2009). Some authors have studied how weed suppression is affected by an increase of biomass and the corresponding light interception for intercrops, assuming that both weeds and crops are mainly competing for aboveground resources (Carr et al., 1995; Baumann et al., 2000). However, several studies have revealed that the effect of belowground competition is often greater than that of aboveground competition (Wilson, 1988). Nevertheless, competition between species for both light and soil resources, such as N, is clearly interrelated. The solar radiation reaching weeds may be modulated, at least in part, by the different ability of a crop species to take up the soil N. The leaf area of the dominant species (crop or weed) in the community may increase when more N is available, enhancing its ability to intercept the solar radiation and, therefore, to shade the subordinate species (Corre-Hellou et al., 2006).

Although both legumes and non-legumes utilise inorganic soil resources, because of the ability of legumes to fix atmospheric N_2, in co-culture, the crops tend to balance each other in the overall N consumption. Indeed, previous studies have shown an increase of 30% in the N acquisition by cereal-legume intercrops, under various growing conditions, due to an increase in both the soil N acquisition and the N_2 fixation compared to either crop grown in sole crops (Hauggaard-Nielsen et al., 2009). A more complete soil N exploitation by the co-cultured crops probably diminishes the competitive ability of the weeds by leaving less N available (Hauggaard-Nielsen et al., 2001).

Barley is described as more competitive for inorganic soil N than pea (Jensen, 1996), likely due to a deeper root growth and a rapid early growth and N demand (Hauggaard-Nielsen et al., 2001; Bellostas et al., 2003; Corre-Hellou et al., 2007). Moreover, observed increases in the contribution of N_2 fixation to the total N accumulation are explained by the strong competition of cereals for N (Jensen, 1996). In pea monocrops, it has also been shown that the percentage of N that was derived from N_2 fixation, in relation to the N taken up by the weeds, increased with the biomass of the invading weeds (Corre-Hellou and Crozat, 2005).

The poor competitive ability of pea compared to other species (crops or weeds) could also be related to the energetic cost of nodule formation and activity.

Soil N availability has been demonstrated to increase the competitive ability of cereals for light, and their N demand then reduces the growth of the pea crop in co-culture (Jensen, 1996; Corre-Hellou et al., 2006). Because the responses to nutrient enrichment often differ among species, the increase in the soil N availability can shift the balance of competitive relationships between crops and weeds.

The aims of the study presented here were the following: i) to determine the ability of pea-barley intercrops to suppress weeds, as compared to the sole crops, under various, contrasting conditions of soil, climate, and weed potential and under different crop productivities in organic farming systems throughout a European set of trials conducted during three years in five countries; and ii) to investigate the effects on the soil N availability on the crop and weed growth in both intercrops and sole crops.

Materials and Methods

Experimental design and management practices

Field trials were carried out in 2003, 2004 and 2005 in five countries: Denmark (Taastrup, 55°40’N, 12°18’E), the UK (Reading, 51°45’N, 0’93’W), France (Thorigné d’Anjou, 47°37’N, 0°39’W), Germany (Kassel, 51°25’N, 9°25’E) and Italy (San Marco Argentano, 39°18’N, 21°12’E). For further information about the experimental conditions, see Gooding et al. (2007) and Hauggaard-Nielsen et al. (2009). In all of the countries, the crops on the experimental sites were established as the second ‘cereal’ after a fertility-building clover-rich ley. The crops were managed according to organic farming practices without pesticide or fertiliser use. No mechanical weeding was performed after sowing, and no irrigation was supplied.

Field pea (*Pisum sativum* L., cv Baccara) and spring barley (*Hordeum vulgare* L., cv Scarlett) were sown at the recommended seed density of 90 and 300 plants m^{-2} for pea (P100) and barley (B100), respectively. Row intercrops were established in an additive and a replacement design. The additive design involved the same plant population of pea in sole crops and in intercrops; this was supplemented with the barley component at a density of 150 plants m^{-2}. The replacement design involved the replacement of a proportion of the plants of one species with the other species; in the present study each species was sown at 50% of its sole crop population (P50B50). A fallow treatment was included in the experimental design specifically to assess the weed potential.

The experimental plots were drilled (125 mm row width) in a complete, one-factorial randomised design with four replicates. The experiments were arranged in a randomised block design with four replications.

Sampling and analysis

The aboveground weeds were harvested twice throughout the crop cycle. The first and the second harvests were respectively carried out at the beginning of flowering of the pea plants and at crop maturity. At each harvest, the weeds were collected on three plots of 0.25 m² per treatment and replicate to take into account the spatial distribution of the weeds. Each subsample was oven dried at 70°C to a constant weight, and the weight of the dry matter (DM) was determined. The three subsamples for each treatment and replicate were pooled for grinding. The total N content of the weeds was determined on finely ground plant material at Risø National Laboratory for Sustainable Energy (Roskilde, Denmark) using an elemental analyser (CE Instruments, EA 1110).

The most dominant weed species in terms of biomass were visually determined for each plot (Table 1). Samples of the crops were harvested on the same date as the weeds to determine the total dry matter. All of the plant materials were dried at 70°C to a constant weight to determine the total DM produced. The total N and δ^{15}N were determined at Risø National Laboratory for Sustainable Energy on 5-10 mg of the subsamples of the finely ground material using an elemental analyser (CE Instruments, EA 1110) coupled in continuous-flow mode to an isotope ratio mass spectrometer (Finnigan, MAT DeltaPlus). The leaf area index (LAI) of the pea and barley was determined at the beginning of flowering of the pea plants by measuring the green leaf area on 5 to 10 plants.

Calculations and statistics

The amount of N in the weeds (weed N) was calculated as the product of the weed dry matter (weed DM) and the %N content.

The weed suppression (WS) due to crop competition was intended to compare the weed biomass in each crop treatment and in the fallow plots. The WS characterised the ability of the crop to reduce weeds. It was determined according to the following equation:

$$\text{WS (\%)} = 100 \text{ x } \frac{\text{weed DM in fallow plots} - \text{weed DM in crop treatment}}{\text{weed DM in fallow plots}}$$

The potential soil N availability (Corre-Hellou et al., 2006) was determined as the maximum soil N acquisition obtained either in the sole crops or in the intercrops for each year and for each site.

The amount of N_2 fixed was calculated as the product of the pea biomass, %N content and the proportion of the plant N derived from N_2 fixation. The percentage of N derived from N_2 fixation (%Ndfa) was determined using the abundance of ^{15}N in the pea and the barley sole crop. Before initiating the field experiments, weed samples were harvested to measure the natural ^{15}N abundance on each site. In France and Germany, these samples indicated that the natural ^{15}N abundance in the plant-available soil N did not differ significantly from the abundance of atmospheric N_2 to allow its accurate measurement. Thus, the enrichment technique (Chalk, 1998) was used there. In the other countries, the natural abundance technique was used with the levels of barley $\delta^{15}N$ between 2.5 and 6.5‰ (for further details, see Hauggaard-Nielsen et al, 2009). The soil N acquisition in pea sole crop and pea-barley intercrops was estimated as the difference between the total N accumulated and the amount of N_2 fixed.

The stability of the competitive ability of the weeds was assessed by the coefficient of variation (CV) over the three years and different sites; the greater the CV, the lower was the stability.

Some results were analysed in relation to the different levels of potential key variables. Probabilities for significant effects were tested using an analysis of variance. The data were transformed in $\log_{10}$ values when they were not normally distributed. The differences between the treatments were evaluated using the Newman and Keuls test with a 0.05 confidence level.

Results

1. Weed suppression

1.1. Comparison of intercrops and sole crops

The weed biomass at maturity for each site was found to be significantly greater in the pea sole crops than in the barley sole crops or in the intercrops (Fig.1a). At maturity, weed biomass was, on average, three times higher for the pea sole crops than for the pea-barley intercrops (Table 2). No significant differences were observed between the barley sole crops and intercrops and between the replacement and additive designs.

Weed dry matter increased by 103% in the pea sole crops and only by 24 to 37 % in the other treatments between the time of flowering and maturity (Table 2). In the intercrops and barley sole crops, the increase in crop biomass between flowering and maturity was higher than that of the weeds, whereas in the pea sole crops, pea biomass increased at a lower rate than that of the weeds. The increase in weed biomass between flowering and maturity in the pea sole crops was quite similar to that of the fallow plots (+ 118 %, from 167 to 365g m^{-2}), whereas the increase in weed dry matter was largely reduced in the intercrops and barley sole crops.

At all of the sites, the barley sole crops and the intercrops showed a reduction in weeds, as compared with the fallow plots, which was better than the pea sole crops at the beginning of flowering and maturity (Table 2). The pea sole crops reduced weed biomass by an average of 71%, whereas the barley and pea-barley intercrops reduced weed biomass by 90% at maturity. The percentage of weed suppression was much more variable between the sites and years for P100 (cv = 28.8%), as compared to the other crop treatments (cv from 9.4 to 12.1%) at maturity.

1.2. Effect of weed potential

The treatments were compared under various conditions of weed dry matter potentials, comparing both the sites and years. The values of weed dry matter varied between 204 g m^{-2} and 688 g m^{-2} in the fallow plots at maturity. Weed suppression at maturity was higher than 80% in the intercrops, independent of the weed potential. The pea sole crops had the lowest weed-suppression effect, independent of weed potential (Fig. 2).

1.3. Effect of crop biomass

The biomass of the crops at maturity varied greatly, independent of the treatment (between 300 and 1000 g m^{-2}) among the sites and years (Fig. 3). The coefficient of variation in crop biomass among the sites and years was lower (20%) in the intercrops than in the sole crops (27% for pea and 30% for barley). Pea sole crop dry matter varied between 337 and 929 g m^{-2}, barley sole crop dry matter varied between 312 and 985, and pea-barley intercrops varied between 400 and 992 g m^{-2}.

In 73% of the cases, the pea-barley intercrops produced a greater biomass than the two sole crops.

Weed biomass tended to decrease with the level of crop biomass for each treatment (Fig. 3a). At a crop biomass of over 700 g m^{-2}, weed biomass was very low, and weed suppression was higher than 80% at maturity, independent of treatment (Fig. 3b). However, at a crop biomass below 700 g m^{-2}, weed biomass varied greatly both within a treatment and among treatments, and it was lower in the pea-barley intercrops and barley sole crops than in the pea sole crops.

Even with a very low crop biomass (<500 g m^{-2}), the barley sole crops demonstrated a high weed-suppression ability (> 80%), whereas the weed-suppression ability of the pea crops averaged only 50%.

1.4. Effect of the composition of the mixture

The percentage of barley in total dry matter accumulated at maturity varied greatly among the conditions from 17% to 82% for the replacement design and from 18 to 68% for the additive design (Hauggaard-Nielsen et al, 2009). However, weed suppression did not vary with the percentage of barley in the mixture (Fig. 4). The intercrops exhibited higher weed-suppression ability than the pea sole crops, even with a low contribution of barley to the total dry matter.

1.5. Effect of crop LAI

The pea sole crops and pea-barley intercrops produced a higher LAI at flowering than the barley sole crops in all of the situations (Table 2). The pea-barley intercrops produced a greater LAI than the pea sole crops in 20% of the situations.

A difference in weed biomass among the treatments with similar levels of LAI was observed (Fig. 5). Independent of the level of LAI, weed biomass was higher in the pea sole crops than in the pea-barley intercrops and barley sole crops. The suppression of weed dry matter was similar, independent of the levels of LAI of the pea-barley intercrops and barley sole crops, whereas weed dry matter suppression tended to increase with LAI of the pea sole crops.

2. Interactions between intercrop effects on weed growth and soil N availability

2.1. Nitrogen accumulation and weed suppression

The total weed N accumulation at maturity for each site was found to be significantly greater under the pea sole crops than under the barley sole crops or intercrops (Fig. 1b). The weeds accumulated an average of 2.2 g N m^{-2} in their aboveground parts under the pea sole-crop condition, as compared to 0.6 g N m^{-2} under the barley sole-crop condition and 0.7 g N m^{-2} under the pea-barley intercrop condition (Table 3).

In the intercrops and barley sole crops, on average, 90% of the soil N was used by the crops, and only 10% was used by weeds, whereas the pea sole crops used only an average of 70% of the N, leaving at least 30% for the weeds (up to 65%) (Table 3).

2.2. Effect of soil N availability on crop and weed growth

Soil N availability varied greatly among both the sites and years (Hauggaard-Nielsen et al, 2009). Low crop LAIs were obtained under low soil N conditions, especially in the barley sole crops (Fig. 6a). Higher soil N availabilities tended to increase crop LAI and crop biomass values and decrease the contribution of weeds in the total DM for the barley sole crops and intercrops (Fig. 6b). The barley sole crops had a lower LAI than the pea sole crops and intercrops, regardless of soil N availabilities. Nevertheless, the highest contribution of weeds in DM and soil N accumulation was in the pea sole crops (Fig 6b and 6c).

3. Effect of weeds on crop biomass

For all of the treatments, crop biomass tended to be lower when weed biomass in the crops was high (Table 4). However, crop biomass of the intercrops tended to be less affected by weed infestation (-20% in P50B50 and -25% in P100B50, between low and high weed infestations) than the sole crops (-31% in P100 and -33% in B100). Thus, the differences in crop biomass between the intercrops and the sole crops tended to be higher under a high weed infestation.

Discussion

The weed-suppression effect and interactions with crop biomass

This work demonstrates that pea-barley intercropping is a relevant strategy when trying to reduce weed infestations in organic farming systems. Our results are consistent with previously published studies (e.g., Hauggard-Nielsen et al., 2001; Bulson et al., 1997). Peas have a relatively low competitive strength towards weeds and intercropping can be a way to successfully produce peas in organic farming. The use of joint experiments, conducted under various growing conditions across Europe, showed the general ability of pea-barley intercrops to maintain a highly asymmetric competition over weeds (Fig. 1), despite variation in weed infestation (species and productivity) (Fig. 2), crop biomass (Fig. 3), and soil N availability (Fig. 6). The weed suppression of intercropping was highly resilient, whereas the weed suppression of the pea sole crops was lower and displayed a higher variability.

The barley and pea crops had a synergistic effect on the weed populations when intercropped, as shown by the replacement intercrop with a lower weed biomass than the average biomass of the two corresponding sole crops (Table 2). Moreover, a difference in weed biomass was observed between intercrops and sole crops with similar biomasses. Compared to the pea sole crops, the addition of barley (additive design) increased the crop biomass by 22% and decreased the weed biomass by 72%.

Crop biomass is often considered as a key factor that explains differences between species in their competitive abilities toward weeds (Mohler and Liebman, 1987; Poggio, 2005). However, in most of these studies, different species were rarely compared at the same level of crop productivity, thus preventing the isolation of other main factors. In our study, crop biomass was not the main factor explaining the differences in competitive ability between the intercrops and sole crops and within the treatments. The intercrops had a high weed-suppression effect, even with a low crop biomass (approximately 500 g m^{-2}). The pea sole crops may have obtained a weed suppression comparable to the intercrops and barley sole crops if its productivity had been higher than 700 g m^{-2}. However, such pea growth is only rarely obtained in organic cropping systems (Hauggaard-Nielsen et al., 2009). A crop biomass threshold of approximately 700 g m^{-2} is consistent with the results of Poggio et al. (2005) regarding the relationship between the crop biomass and weed biomass using the same species (peas and barley) under conditions different than those presented here.

The weed-suppression effect was not correlated with the percentage of barley in the total biomass. Even with a low percentage of barley (20%) in the total crop biomass, the weed biomass was reduced by 90% (Fig. 4). The percentage of each species in a crop mixture is usually quite variable and poorly correlated with plant densities at sowing, as was confirmed in this study. Thus, it is difficult for farmers to predict the final composition. However, this study revealed that the efficiency of pea-barley intercrops against weeds was not influenced by variability in the contribution of each species.

The control of weeds was relatively similar in the replacement and additive designs. Over the three years and five experimental sites, only one case was reported (in Denmark, 2003) where the additive intercrop had less weed dry-matter accumulation at maturity than the replacement design (data not shown). In that particular situation, the weed biomasses were particularly high, irrespective of the crop treatment, which suggests that the additive intercrop may control weeds better than the replacement design in the presence of highly competitive weeds.

At pea flowering, the weed biomass in the pea sole crops was, on average, twice that of the barley crops and intercrops, independent of the design. Pea has been reported to exhibit a low competitive ability against weeds at the beginning of the crop cycle (Hauggaard-Nielsen et al., 2001). Furthermore, the weed biomass increased significantly between the flowering and maturity stages in the pea sole crops, in contrast to the weed biomass in the other treatments, which remained quite constant after the flowering stage. In addition, the pea sole crops had high LAIs at flowering compared to the other treatments. Nevertheless, the pea sole crops were sensitive to lodging, in contrast to the pea intercropped with barley, likely allowing a higher growth of weeds at the end of the crop cycle**.** Apart from contributing to yield loss, greater weed growth at the end of the cycle will exacerbate weed problems for subsequent crops through increased seed production. Following organic farming principles, such temporal patterns need to be dealt with, and intercropping seems to be a cropping strategy worth considering.

Interactions with the soil N availability and N acquisition

Even with a low leaf area, a high weed-suppression effect was observed in the intercrops and barley sole crops compared to the pea sole crops. The leaf area of the barley was particularly low when the soil N availability was low (Fig. 6). At a low soil N availability, light is probably not the main factor limiting weed growth, whereas the competition for N probably is the driving force; under such conditions, barley has a competitive advantage. Pea crops are known to be less competitive than barley crops for soil N, probably due to their shallow rooting depth and low N demand, especially at the beginning of the crop cycle when soil N availability is low (Corre-Hellou et al., 2007). In our experiments, we observed that the weeds took advantage of the low soil N uptake of the pea plants.

The competition for light and N has been proposed to be interrelated (Corre-Hellou et al., 2006). At high soil N availabilities, leaf area and crop biomass increased, regardless of the treatment, likely creating a stronger competition for light that partly drove the competitive abilities of the crops against the weeds. Under such conditions, the percentage of weeds in DM and N acquisition tended to decrease in the barley sole crops and intercrops, yet this percentage remained high for the pea sole crops. Although the pea plants had a higher leaf area, they displayed a lower weed-suppression capability.

Weeds with a high growth rate at early stages can gain an initial advantage, and small competitive advantages during growth early in the season can translate into large differences in size and light-interception ability later in the season. Pea, which is known to have a slow crop establishment (shoot and root growth), is probably affected very early by weed pressure, whereas, at flowering, it appeared to have a high competitive ability for light, as shown by its high LAI. Early responses to soil conditions can be critical for determining competitive interactions between weeds and crops. Further experiments will be needed to characterise the early growth of crops and weeds in their interactions with soil N availabilities and the consequences to interspecific competition.

Weed species differ in their responses to N (Blackshaw et al., 2003). The nitrogen requirements of *Chenopodium album*, one of the major species in our experiments, were observed to be relatively low, in comparison with both other weed species and barley (Jornsgard et al., 1996), perhaps explaining its low competitive ability with crops when N availability increased.

The amount of soil N that is available and the dynamic of soil N availability during the crop cycle have been shown to affect the dominance of pea and cereal in intercrops (Naudin et al., 2010) and may also affect weed dominance. We found that availability of soil N was one main factor that influenced the interactions of the species in the intercrops; however, other factors, such as water deficits, may have limited weed and crop growth at several of the sites because no irrigation was applied in these experiments. Low soil N availability was probably linked to a low water availability at several of the sites, partly explaining the decrease in pea growth with decreased soil N availability. Pea plants are usually unaffected by soil N availability because of their complementary use of inorganic N and atmospheric N (i.e., soil N and N_2) (Voisin et al, 2002). Our results were clearly obtained under the limiting growth conditions that are usually observed in organic cropping systems. The range of crop biomass that we observed was particularly low, as compared to previously published results that were obtained using the same species, but with N as the only limiting factor (e.g., Corre-Hellou et al., 2006).

Tolerance to weed competition

This study was mainly focused on the effect of crops on weed suppression, whereas the effect of weeds on crop growth was less investigated. Indeed, these two effects are rarely studied separately in the same study. However, differences in tolerance to weed competition may be expected between intercrops and sole crops (Liebman and Dyck, 1993), thus increasing the advantages of the intercrops in the case of excessive weed infestations. In our experiments, the pea sole crops had a lower weed-suppression effect than the intercrops and also tended to have a lower tolerance to weed competition. We found that high weed infestation caused a greater decrease in the biomass of the pea sole crops (Table 4). Moreover, the intercrops and barley sole crops demonstrated similar weed-suppression abilities; however, under a high weed infestation, the intercrops in the replacement design, in particular, seemed more tolerant to weeds than the barley sole crops. Nevertheless, a control setting with no weeds growing with the crops would be needed to investigate more precisely the differences in tolerance to weeds between treatments.

Other studies have also investigated the effect of intercrops on weed composition. It has been reported that diversity of weeds tended to decrease in intercrops, in comparison with sole crops (Mohler and Liebman, 1987; Poggio, 2005; Gharineh and Moosavi, 2010). These studies have demonstrated that species richness paralleled weed productivity, with the fewest species in the barley sole crops and the highest in the pea sole crops; in general, the most dominant species were more suppressed than the other species as crop biomass increased. Furthermore, the reduction in weed diversity appears to be more stable in intercrops than in pea sole crops (Mohler and Liebman, 1987; Poggio, 2005).

Conclusion

The study presented here reveals the high resilience of intercrops in the suppression of weeds. Moreover, this work contributes to the expansion of our current understanding of how crops and weeds may interact in both cereal-pea intercrops and in the corresponding sole crops in low input systems, and it may help in developing weed-management practices that are environmentally sound. Weed suppression effects and the dynamic use of light and N sources in cereal-legume intercrops were shown to be interrelated. Some of the hypotheses emerging from this network should be further investigated. Intercrops offer additional ecological services (such as reduction of pests and diseases), which need to be studied together with their weed-suppression ability in order to clarify the benefits for farmers and improve the development of such cropping strategies.

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Table 1. The dominant weed species observed each year (recurrent species) or in particular years, at the five experimental sites in Denmark (DK), the United Kingdom (UK), France (FR), Germany (GER) and Italy (IT).

	Recurrent species	Other species, according to year
DK	*Sinapis arvensis*	*Cerastium fontanum, Cirsium arvense* (2004) *Matricaria discoidea, Stellaria media* (2004-2005)
UK		*Chenopodium album, Viola arvensis, Polygonum aviculare, Chrysanthemum segetum* (2003)
FR	*Chenopodium album*	*Stellaria media* (2003-2005) *Atriplex patula* (2004) *Viola arvensis* (2005)
GER	*Chenopodium album*	*Thlaspi arvense, Cirsium arvense* (2003) *Matricaria chamomilla, Stellaria media* (2004)
IT	*Chenopodium album*	*Xanthium strumarium* (2003) *Cirsium arvense, Datura stramonium* (2004)

Table 2. Crop and weed growth at the beginning of pea flowering (BF) and at maturity and weed dry matter suppression for the pea sole crops (P100), barley sole crops (B100) and pea-barley intercrops (additive design, P100B50 and replacement design, P50B50). Values are the mean (n = 60, 3 years, 5 sites, 4 replicates per site), and the treatments with the same letter within each line were not significantly different using Tukey's Studentised Range (HSD). CV: coefficient of variation.

	P100		P100B50		P50B50		B100	
Weed dry matter at BF (g m^{-2})	48.5	a	21.7	b	27.3	b	19.1	b
Weed dry matter suppression at BF (%)	66.9	a	82.5	b	80.1	b	84.8	b
CV of weed dry matter suppression at BF	33.6		23.7		23.1		19.4	
Weed dry matter at maturity (g m^{-2})	98.5	a	27.9	b	33.9	b	26.2	b
Weed dry matter suppression at maturity (%)	71.0	a	91.3	b	89.5	b	91.9	b
CV of weed dry matter suppression at maturity	28.8		10.4		12.1		9.4	
Crop dry matter at BF (g m^{-2})	316.9	a	427.0	b	383.6	ab	315.4	a
Crop dry matter at maturity (g m^{-2})	574.2	a	704.3	ab	659.6	ab	590.6	a
Crop LAI at BF	4.7	b	5.6	b	4.3	b	2.7	a

Table 3. Soil N accumulated by weeds and crops at maturity. Values for the pea sole crops (P100), barley sole crops (B100) and pea-barley intercrops (additive design: P100B50 and replacement design: P50B50) are given. Values are mean (n = 60, 3 years, 5 sites, 4 replicates per site), and the treatments with the same letter within each line were not significantly different using Tukey's Studentised Range (HSD).

	P100		P100B50		P50B50		B100	
Weed N at BF (g m^{-2})	1.1	a	0.4	b	0.6	b	0.4	b
Weed N at maturity (g m^{-2})	2.2	a	0.7	b	0.7	b	0.6	b
Soil N accumulated by the crop at maturity (g m^{-2})	5.1	a	7.1	b	6.5	b	6.4	b
% of the soil N accumulated by weeds at maturity (g m^{-2})	33.2	a	8.5	b	9.9	b	9.8	b

Table 4. Crop biomass (dry matter g m-2) at maturity according to the level of weed infestation under the pea sole crops (P100), barley sole crops (B100) and pea-barley intercrops (additive design, P100B50 and replacement design, P50B50). Low: weed dry matter < 12 g m^{-2}; medium: 12-36 g m^{-2}; high: > 36 g m^{-2}. The means per class and standard errors (*se*) are given.

	weed pressure at pea flowering					
	low		medium		high	
	mean	se	mean	se	mean	se
P100	730.6	*140.4*	649.6	*114.2*	505.6	*111.4*
P100-B50	775.5	*101.2*	667.6	*121.3*	580.5	*150.0*
P50-B50	716.1	*149.1*	638.4	*61.5*	576.0	*128.3*
B100	623.5	*239.4*	594.2	*101.3*	420.3	*22.5*

Figure 1. Weed dry matter (g m^{-2}) (a) and weed nitrogen accumulation (g m^{-2}) (b) in the pea sole crops (P100), barley sole crops (B100) and pea-barley intercrops (additive design, P100B50 and replacement design, P50B50). Values are the mean (n = 12 for each site), and the columns with the same letter within each individual diagram were not significantly different using Tukey's Studentised Range (HSD).

Figure 2. Weed potential (weed dry matter at maturity on a fallow treatment) and weed dry matter suppression of the pea sole crops (P100), barley sole crops (B100) and pea-barley intercrops (additive design, P100B50 and replacement design, P50B50) at maturity. Mean and standard error per class are given.

Figure 3. Effect of crop biomass on weed dry matter (a) and weed dry matter suppression at maturity (b) for the pea sole crops (P100), barley sole crops (B100) and pea-barley intercrops (additive design, P100B50 and replacement design, P50B50). Mean and standard error per class are given.

Figure 4. Effect of the percentage of barley in the crop biomass of the intercrops (additive design, P100B50 and replacement design, P50B50) on weed dry matter suppression at maturity.

Figure 5. Effect of crop leaf area index (LAI) on weed dry matter suppression at the beginning of flowering for the pea sole crops (P100), barley sole crops (B100) and pea-barley intercrops (additive design, P100B50 and replacement design, P50B50). Mean and standard error per class are given.

Figure 6. Effect of soil N availability on leaf area index (LAI) at the beginning of pea flowering (a), percentage of weeds in the total dry matter (b) and percentage of weeds in total soil N acquisition (c) at maturity for the pea sole crops (P100), barley sole crops (B100) and pea-barley intercrops (additive design, P100B50 and replacement design, P50B50). Mean and standard error per class are given.

Fig 1.

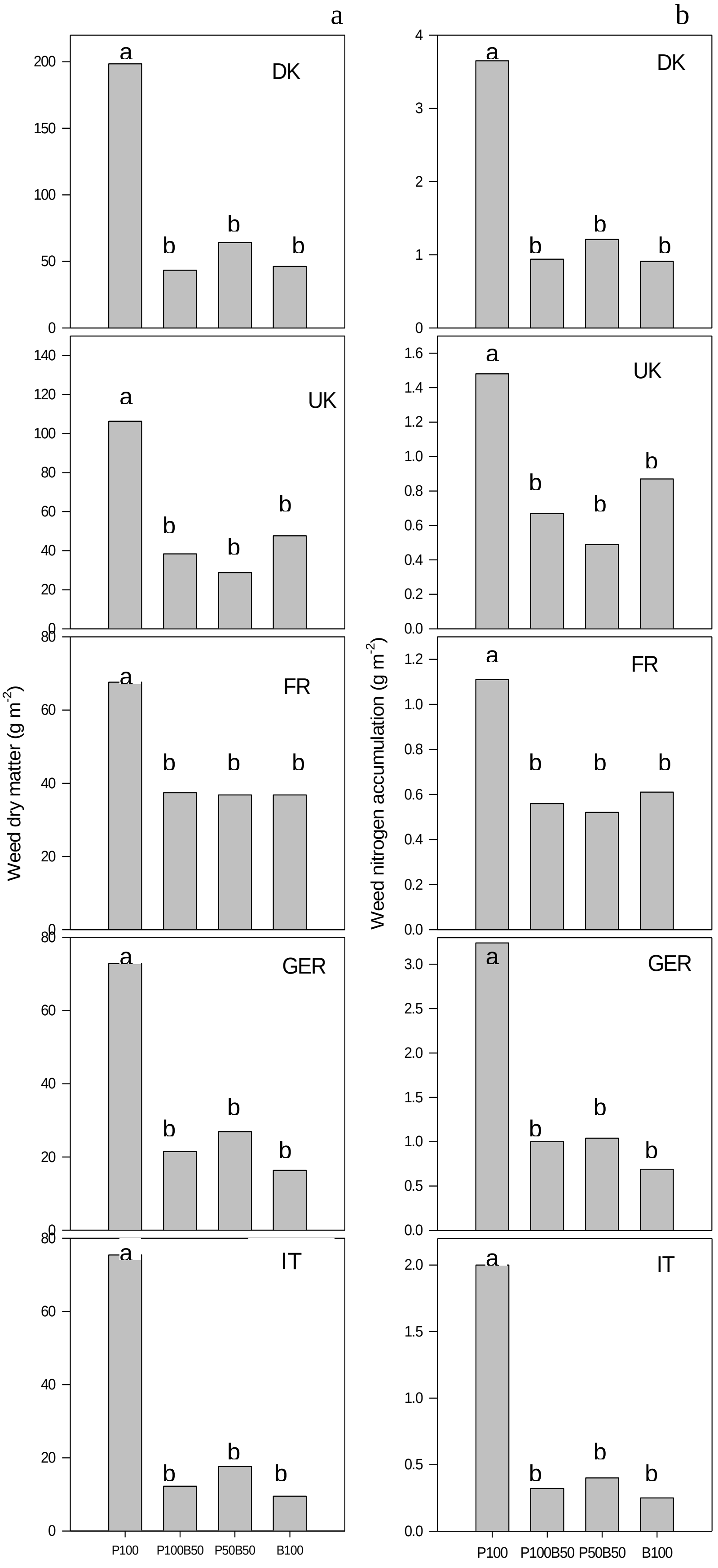

a
b
DK
UK
FR
GER
IT
Weed dry matter (g m-2)
Weed nitrogen accumulation (g m-2)
0
50
100
150
200
20
40
60
80
100
120
140
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0.5
1.5
2.0
2.5
3.0
1
2
3
4
a
b
P100
P100B50
P50B50
B100

Fig 2

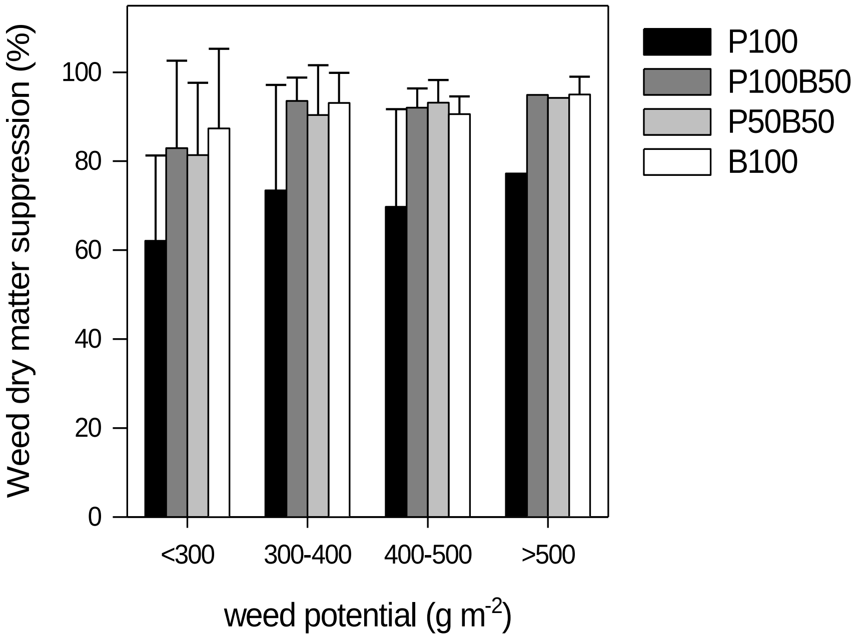
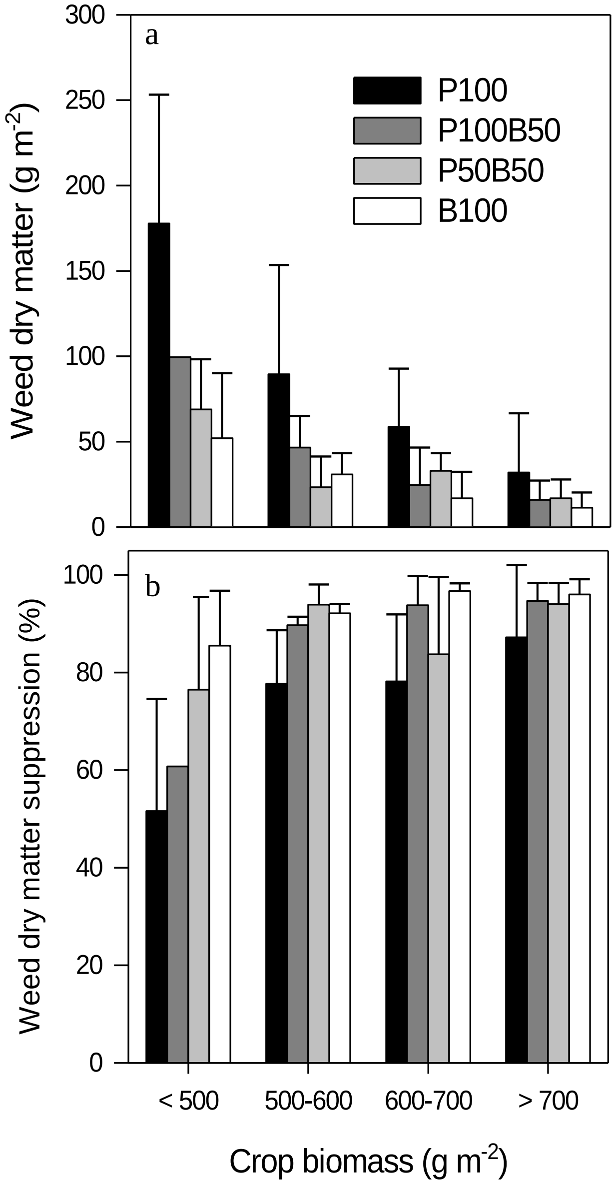
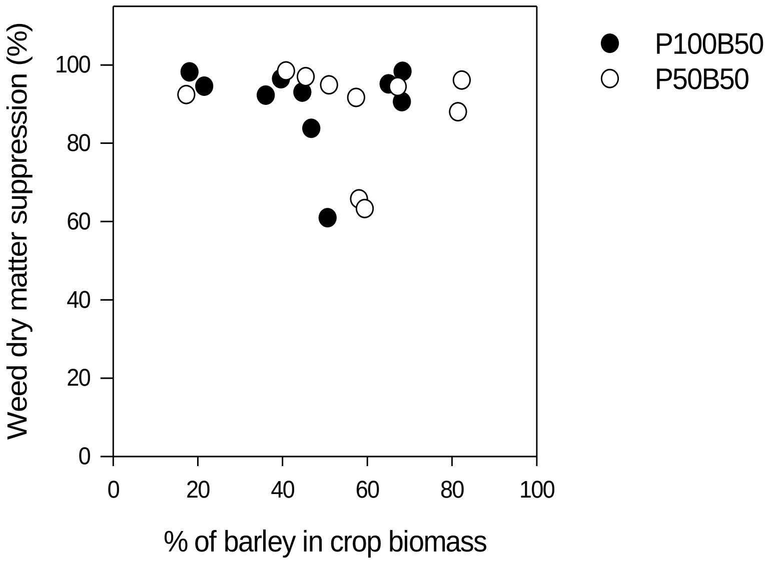

Weed dry matter suppression (%)
0
20
40
60
80
100
<300
300-400
400-500
>500
weed potential (g m-2)
P100
P100B50
P50B50
B100

Fig 3


a
P100
P100B50
P50B50
B100
Weed dry matter (g m^{-2})
0
50
100
150
200
250
300
b
Weed dry matter suppression (%)
0
20
40
60
80
100
< 500
500-600
600-700
> 700
Crop biomass (g m^{-2})

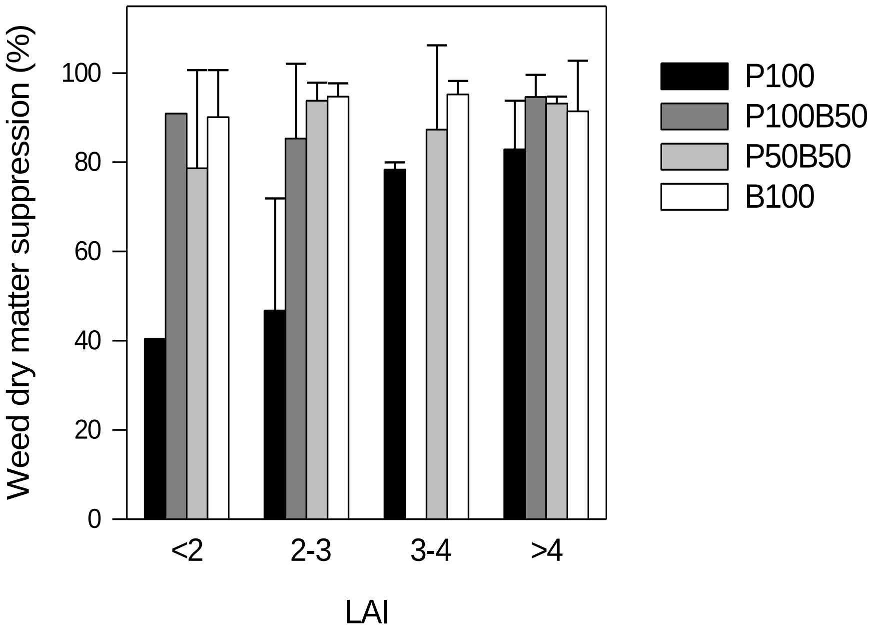
592

Fig 4


Weed dry matter suppression (%)
0
20
40
60
80
100
0
20
40
60
80
100
% of barley in crop biomass
● P100B50
○ P50B50

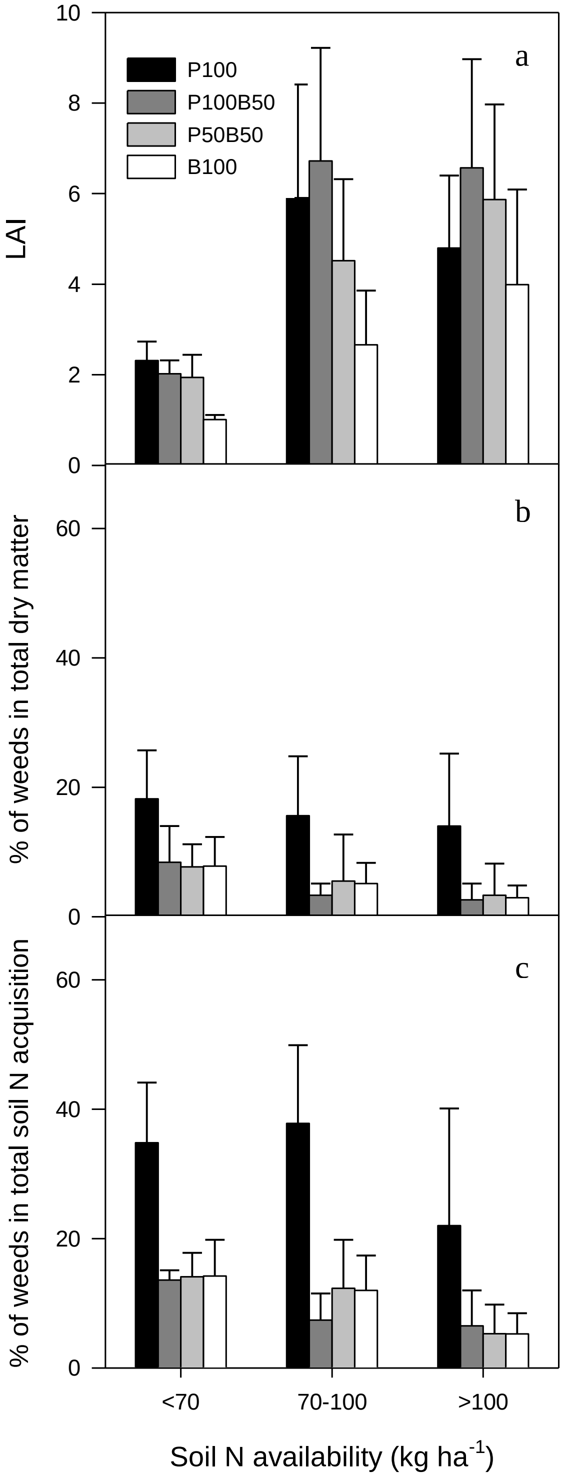
594

Fig 5


Weed dry matter suppression (%)
0
20
40
60
80
100
<2
2-3
3-4
>4
LAI
P100
P100B50
P50B50
B100

604

Fig6



10
8
6
4
2
0
LAI
a
P100
P100B50
P50B50
B100
b
60
40
20
0
% of weeds in total dry matter
c
% of weeds in total soil N acquisition
<70
70-100
>100
Soil N availability (kg ha-1)

606