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

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Abstract

20 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
22 (*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,
24 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)
26 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
28 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
30 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
32 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
34 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
36 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
38 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
40 treatments, in spite of the higher leaf areas in the pea crops.

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

42 **Introduction**

44 Grain legumes, such as peas (*Pisum sativum* L.), should play a key role in organic cropping
46 methods; they provide nitrogen (N) to the system and the soil for succeeding crops via their
48 symbiosis with N₂-fixing bacteria, and they produce grain that is rich in protein. However,
50 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
52 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
54 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
56 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
58 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
60 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
62 displayed similar competitive abilities against weeds (Mohler and Liebman, 1987; Rauber et
al., 2000; Hauggaard-Nielsen et al., 2001; Deveikyte et al., 2009).

64 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
66 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,
68 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
70 exploitable by weeds or convert resources more efficiently than the sole crops (Liebman and
Dyck, 1993).

72 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,
74 particularly cereal-legume combinations, show substantial yield advantages over sole crops,
suggesting that the intercrops use the available resources more completely and/or effectively
76 (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,
78 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
80 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,
82 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
84 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
86 (Corre-Hellou et al., 2006).

Although both legumes and non-legumes utilise inorganic soil resources, because of the
88 ability of legumes to fix atmospheric N₂, 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
90 acquisition by cereal-legume intercrops, under various growing conditions, due to an increase
in both the soil N acquisition and the N₂ fixation compared to either crop grown in sole crops
92 (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
94 (Hauggaard-Nielsen et al., 2001).

Barley is described as more competitive for inorganic soil N than pea (Jensen, 1996), likely
96 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
98 the contribution of N₂ 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
100 percentage of N that was derived from N₂ fixation, in relation to the N taken up by the weeds,
increased with the biomass of the invading weeds (Corre-Hellou and Crozat, 2005).

102 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.

104 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;
106 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
108 relationships between crops and weeds.

The aims of the study presented here were the following: i) to determine the ability of pea-
110 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
112 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
114 growth in both intercrops and sole crops.

116 **Materials and Methods**

Experimental design and management practices

118 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,
120 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
122 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
124 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
126 supplied.

Field pea (*Pisum sativum* L., cv Baccara) and spring barley (*Hordeum vulgare* L., cv Scarlett)
128 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
130 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.
132 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
134 population (P50B50). A fallow treatment was included in the experimental design specifically
to assess the weed potential.

136 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
138 block design with four replications.

Sampling and analysis

140 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
142 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
144 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
146 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
148 analyser (CE Instruments, EA 1110).

The most dominant weed species in terms of biomass were visually determined for each plot
150 (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
152 determine the total DM produced. The total N and $\delta^{15}\text{N}$ were determined at Risø National
Laboratory for Sustainable Energy on 5-10 mg of the subsamples of the finely ground
154 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
156 (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.

158 Calculations and statistics

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

The weed suppression (WS) due to crop competition was intended to compare the weed
162 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:

164

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

166

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

170 The amount of N₂ fixed was calculated as the product of the pea biomass, %N content and the
proportion of the plant N derived from N₂ fixation. The percentage of N derived from N₂
172 fixation (%Ndfa) was determined using the abundance of ¹⁵N in the pea and the barley sole
crop. Before initiating the field experiments, weed samples were harvested to measure the
174 natural ¹⁵N abundance on each site. In France and Germany, these samples indicated that the
natural ¹⁵N abundance in the plant-available soil N did not differ significantly from the
176 abundance of atmospheric N₂ to allow its accurate measurement. Thus, the enrichment
technique (Chalk, 1998) was used there. In the other countries, the natural abundance
178 technique was used with the levels of barley δ¹⁵N 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
180 intercrops was estimated as the difference between the total N accumulated and the amount of
N₂ fixed.

182 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
184 stability.

Some results were analysed in relation to the different levels of potential key variables.

186 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
188 the treatments were evaluated using the Newman and Keuls test with a 0.05 confidence level.

190 **Results**

1. Weed suppression

192 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
194 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
196 intercrops (Table 2). No significant differences were observed between the barley sole crops
and intercrops and between the replacement and additive designs.

198 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
200 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
202 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
204 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
206 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
208 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
210 P100 (cv = 28.8%), as compared to the other crop treatments (cv from 9.4 to 12.1%) at
maturity.

212 1.2. Effect of weed potential

The treatments were compared under various conditions of weed dry matter potentials,
214 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
216 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).

218 1.3. Effect of crop biomass

The biomass of the crops at maturity varied greatly, independent of the treatment (between
220 300 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
222 (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
224 between 400 and 992 g m⁻².

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

Weed biomass tended to decrease with the level of crop biomass for each treatment (Fig. 3a).
228 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
230 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.

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

1.4. Effect of the composition of the mixture

236 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
238 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
240 ability than the pea sole crops, even with a low contribution of barley to the total dry matter.

1.5. Effect of crop LAI

242 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
244 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
246 (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
248 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.

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

2.1. Nitrogen accumulation and weed suppression

252 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
254 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}
256 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,
258 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).

260 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,
262 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
264 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
266 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).

268 **3. Effect of weeds on crop biomass**

For all of the treatments, crop biomass tended to be lower when weed biomass in the crops
270 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
272 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
274 infestation.

Discussion

276 **The weed-suppression effect and interactions with crop biomass**

278 This work demonstrates that pea-barley intercropping is a relevant strategy when trying to
280 reduce weed infestations in organic farming systems. Our results are consistent with
282 previously published studies (e.g., Hauggard-Nielsen et al., 2001; Bulson et al., 1997). Peas
284 have a relatively low competitive strength towards weeds and intercropping can be a way to
286 successfully produce peas in organic farming. The use of joint experiments, conducted under
288 various growing conditions across Europe, showed the general ability of pea-barley intercrops
290 to maintain a highly asymmetric competition over weeds (Fig. 1), despite variation in weed
292 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

300 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
302 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)
304 regarding the relationship between the crop biomass and weed biomass using the same
species (peas and barley) under conditions different than those presented here.

306 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
308 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
310 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
312 by variability in the contribution of each species.

The control of weeds was relatively similar in the replacement and additive designs. Over the
314 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
316 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
318 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
320 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
322 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,
324 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
326 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,
328 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
330 patterns need to be dealt with, and intercropping seems to be a cropping strategy worth
considering.

332 **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
334 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
336 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
338 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
340 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.

342 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
344 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
346 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
348 area, they displayed a lower weed-suppression capability.

Weeds with a high growth rate at early stages can gain an initial advantage, and small
350 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
352 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
354 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
356 early growth of crops and weeds in their interactions with soil N availabilities and the
consequences to interspecific competition.

358 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
360 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
362 availability increased.

The amount of soil N that is available and the dynamic of soil N availability during the crop
364 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
366 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
368 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
370 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
372 and N₂) (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

374 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
376 al., 2006).

Tolerance to weed competition

378 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
380 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
382 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
384 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
386 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
388 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
390 weeds between treatments.

Other studies have also investigated the effect of intercrops on weed composition. It has been
392 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
394 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
396 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
398 pea sole crops (Mohler and Liebman, 1987; Poggio, 2005).

400 **Conclusion**

The study presented here reveals the high resilience of intercrops in the suppression of weeds.
402 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
404 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
406 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
408 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
410 development of such cropping strategies.

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Wilson, J. B., 1988. Shoot competition and root competition. *J. Appl. Ecol.* 25, 279-296.
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488 Table 1. The dominant weed species observed each year (recurrent species) or in particular years, at
 490 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	<i>Sinapis arvensis</i>	<i>Cerastium fontanum</i> , <i>Cirsium arvense</i> (2004) <i>Matricaria discoidea</i> , <i>Stellaria media</i> (2004-2005)
UK		<i>Chenopodium album</i> , <i>Viola arvensis</i> , <i>Polygonum aviculare</i> , <i>Chrysanthemum segetum</i> (2003)
FR	<i>Chenopodium album</i>	<i>Stellaria media</i> (2003-2005) <i>Atriplex patula</i> (2004) <i>Viola arvensis</i> (2005)
GER	<i>Chenopodium album</i>	<i>Thlaspi arvense</i> , <i>Cirsium arvense</i> (2003) <i>Matricaria chamomilla</i> , <i>Stellaria media</i> (2004)
IT	<i>Chenopodium album</i>	<i>Xanthium strumarium</i> (2003) <i>Cirsium arvense</i> , <i>Datura stramonium</i> (2004)

492

494 Table 2. Crop and weed growth at the beginning of pea flowering (BF) and at maturity and
 496 weed dry matter suppression for the pea sole crops (P100), barley sole crops (B100) and pea-
 498 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.

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	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

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506 Table 3. Soil N accumulated by weeds and crops at maturity. Values for the pea sole crops
 508 (P100), barley sole crops (B100) and pea-barley intercrops (additive design: P100B50 and
 510 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).

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	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

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542 Table 4. Crop biomass (dry matter g m⁻²) at maturity according to the level of weed
544 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

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554 Figure 1. Weed dry matter (g m^{-2}) (a) and weed nitrogen accumulation (g m^{-2}) (b) in the pea
556 sole crops (P100), barley sole crops (B100) and pea-barley intercrops (additive design,
558 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).

560 Figure 2. Weed potential (weed dry matter at maturity on a fallow treatment) and weed dry
562 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.

564 Figure 3. Effect of crop biomass on weed dry matter (a) and weed dry matter suppression at
566 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.

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

572 Figure 5. Effect of crop leaf area index (LAI) on weed dry matter suppression at the
574 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
576 error per class are given.

578 Figure 6. Effect of soil N availability on leaf area index (LAI) at the beginning of pea
580 flowering (a), percentage of weeds in the total dry matter (b) and percentage of weeds in total
582 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.

584

Fig 1.

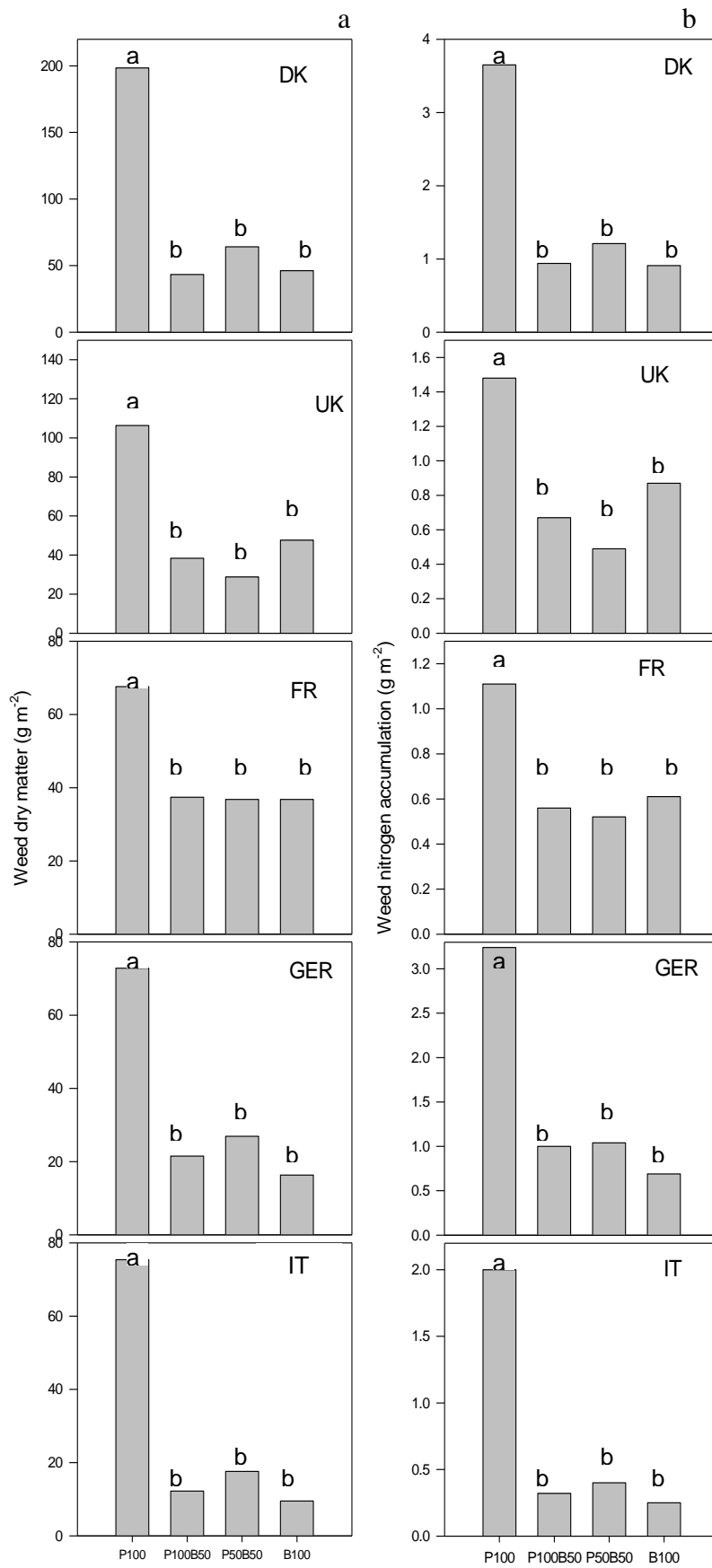


Fig 2

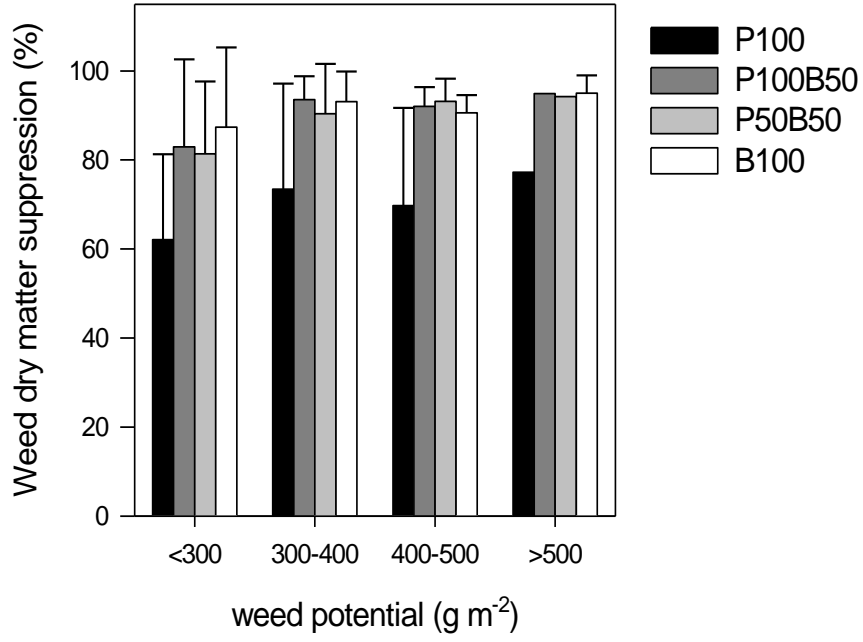


Fig 3

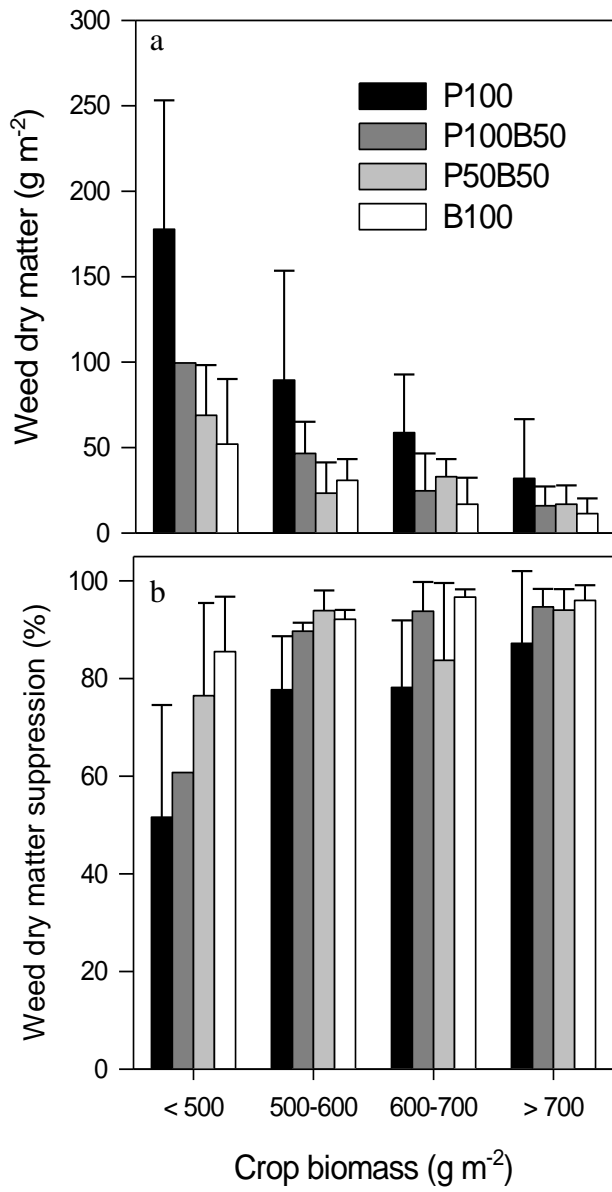
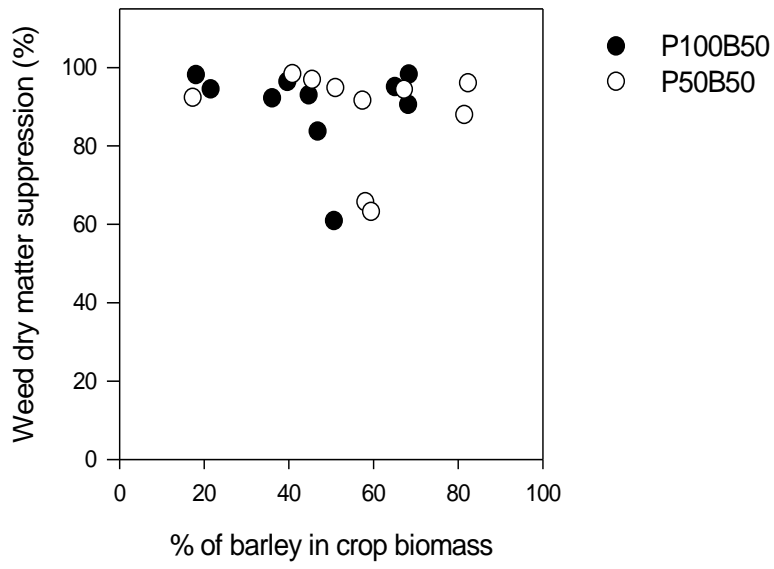
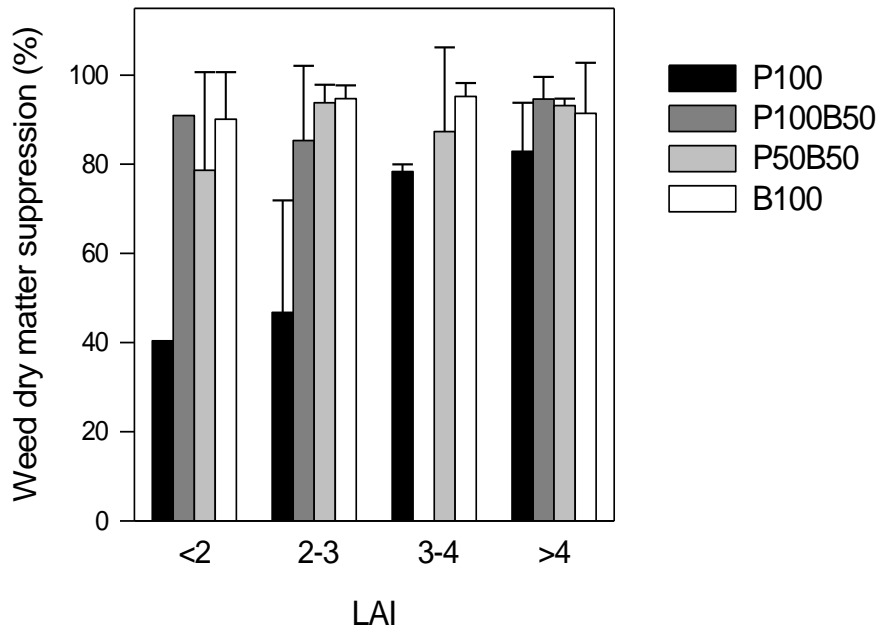


Fig 4



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Fig 5



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Fig6

