Structure of weed communities occurring in monoculture and intercropping of field pea and barley

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Abstract

Weed growth suppression is an explanation of intercropping yield advantage, which can be applied to diminish herbicide use in agriculture. Intercrop effects on weed community structure, nonetheless, have been sparsely studied. The hypothesis that intercrops will produce greater changes in weed community structure than monocultures was therefore postulated. It was concurrently predicted that species diversity of the weed community will be lower in the intercropping than in the monocultures, and that winter- and spring-emerging species in intercrop will be relatively less and more abundant than in monocultures, respectively. Field experiments were carried out at Buenos Aires and Rojas (Argentina) involving monocultures, intercrops of barley and pea, and a control treatment where weeds grew without crops. Effects on weed communities were characterised in terms of growth, species diversity (richness and evenness), and floristic and functional composition. Nitrogen content of plant biomass and interception of solar radiation were also measured. The greater the crop biomass, the higher the weed suppression was. However, barley tended to greatly suppress the growth of weed and pea plants, which could be explained by the greater nitrogen accumulation in barley plants in monocultures and intercrops. Furthermore, there were apparent complementarity in nitrogen uptake between barley and pea when intercropped, since both crops use different sources of soil nitrogen. Intercrops and barley monocultures generally produced similar effects on the companion weed communities, whereas pea effects were less suppressive and more variable. However, intercrops effects appeared to be more stable across experiments. Spring-emerging species generally increased its relative importance in the intercrop weed communities; whereas winter-emerging species were usually less abundant in intercrops. Divergence in the abundance of winter and summer emerging weeds could be attributed to the different canopy dynamics of intercrop and monocultures. This work contributes to improve current understanding of how crop–weed communities are assembled and may help in developing weed management practices that are environmentally sound.

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Keywords: Competition; Intercropping; Plant functional traits; Species diversity; Weed suppression

1. Introduction

The increase in agricultural productivity during the 20th century resulted from the use of high levels of external inputs (Evans, 1998). Agricultural intensifi-
cation, however, also produced some side effects, such as soil erosion, environmental pollution by agrochemicals and fertilisers misuse, and the appearance of agrochemical-resistant populations of weeds and pests (Cox and Atkins, 1979; Jackson and Piper, 1989; Gressel, 1991; Vandermeer et al., 1998). Diversification of cropping systems, for instance, by increasing the number of crop species grown, has been proposed as a solution to some problems of modern agriculture (Vandermeer, 1995; Brummer, 1998; Vandermeer et al., 1998; Altieri, 1999). Intercropping, the practice of growing two (or more) crops simultaneously in the same land area (Willey, 1979a; Vandermeer, 1989), represents an option to diversify cropping systems (Brummer, 1998; Altieri, 1999). The most common reason for the adoption of intercropping is yield advantage, which is explained by the greater resource depletion by intercrops than monocultures, particularly when cereal and legume crops are grown together (Willey, 1979a, 1979b; Vandermeer, 1989; Ofori and Stern, 1987; Fukai and Trenbath, 1993). Weed suppression, the reduction of weed growth by crop interference, has been referred as one determinant of yield advantage of intercropping, being a viable alternative to reduce the reliance of weed management on herbicide use (Liebman, 1988; White and Scott, 1991; Liebman and Dyck, 1993; Midmore, 1993; Liebman and Davis, 2000).

Most weed research is devoted to study particular weed characteristics, mainly crop–weed competition, whereas only few studies are focused on the assemblage of multiple species communities composed of crop and weed species (Martínez-Ghersa et al., 2000). Concordantly, research on the changes in the weed community structure due to intercropping is sparse (Shetty and Rao, 1981; Janiya and Moody, 1984; Mohler and Liebman, 1987). There is some evidence supporting that crop presence modifies the species hierarchy of a weed community (i.e. the distribution of biomass among the species in the community). Mohler and Liebman (1987), in an experiment with barley and field pea, observed that the suppression of dominant weed species was greater as the crop productivity increased, even though changes were more dependent on crop dominance rather than on the number of species in the intercrop. Moreover, adding ferny Azolla (Azolla pinnata R. Br.) into rice monoculture selectively suppressed Monochoria vaginalis (Burm.f.) Presl. Solms and released Echinochloa crus-galli (L.) Beauv. from the competition of the dominant weed species (Janiya and Moody, 1984). Thus, it would be expectable that adding a second crop species to a monoculture will modify the biomass distribution among the species in a weed community.

Furthermore, since plant traits instead of species are actually adapted to a particular environment, arranging weed species into functional groups may give a better understanding of how weed communities are assembled that just using species lists (Ghersa and León, 1999; Booth and Swanton, 2002). For instance, differences in the relative abundance of both winter and spring emerging weeds between pea and wheat monocultures have been recently reported, which could be explained by the differences between crops in their patterns of resource consumption (Poggio et al., 2004). In pea–barley intercrops, it was also observed that the establishment of late-emerging species would have been modulated by the intensity of crop competition (Mohler and Liebman, 1987). Since cereals and legumes use different nitrogen sources (Tofinga et al., 1993; Snaydon, 1996; Hauggaard-Nielsen et al., 2001), and nitrogen and radiation are intimately linked with canopy dynamics (Dreccer et al., 2000), it would also be reasonable to propose that changes in the competition for nitrogen and radiation between crops and weeds grown in mixtures might also be involved in the modification of the weed community structure.

Based on the previous evidence, it can be hypothesised that the use of available resource by barley–pea intercrop is more complete than that of monocultures. Pea–barley intercrops will therefore produce greater changes than monocultures in weed community structure, characterised by its species diversity and its compositions of species and functional traits (life cycle, emergence season). These changes not only will be observed in terms of greater weed growth suppression, affecting as well, species diversity accounted by impoverishment of floristic and functional compositions. Thus, the following predictions were tested: (1) species diversity (i.e. species number and evenness) of the weed community will be lower in the pea–barley intercrop than in the monocultures, and (2) in comparison with monocultures, winter- and spring-emerging species of the intercrop will be relatively less and more abundant, respectively.
Alternatively, it can be hypothesised that resource consumption of dominant single crops is equal, or even greater, than the pea–barley intercrop; therefore, the relative dominance exerted by the crop is independent of the composition of crop species sown in monoculture or intercrop. In order to evaluate these hypotheses, field experiments were carried out in which a nitrogen-fixing species (field pea, *Pisum sativum* L.) and a cereal species (barley, *Hordeum vulgare* L.) were sown in monocultures and in mixtures and grown under field conditions allowing for the establishment of a spontaneous weed community.

### 2. Materials and methods

#### 2.1. Field experiments

Three field experiments were carried out. Two experiments were conducted in consecutive years at the campus of the Faculty of Agronomy, University of Buenos Aires (Buenos Aires, Argentina, 34°35′ latitude S, 58°35′ longitude W, 25 m a.s.l.). The other was laid in a commercial field located at Rojas (Buenos Aires, Argentina, 33°21′ latitude S, 60°45′ longitude W, 77 m a.s.l.).

The Buenos Aires experiments were sown on 1 July 1999 (experiment no. 1), and 6 August 2000 (experiment no. 2). Both experiments were carried out using a complete randomised block design with three replications. Four treatments were sown: (1) pea monoculture (Radley, Sharpes International Seed Ltd., UK); (2) barley monoculture (Busch-1614, Anheuser-Busch, USA), (3) the additive mixture of both crops; (4) a control where the weeds were allowed to grow in the absence of the crop species. Pea and barley were sown at the same density (80 seeds m⁻²) in both monoculture and additive mixtures. Pea seeds were inoculated before sowing (*Rhizobium leguminosarum* var. *pisi*, IMISA, EEA INTA Castelar, Argentina). The same agricultural management was applied at all experimental units (3 m × 4 m = 12 m² plots). The soil was a clay-loam (Vertic Argiudoll). Experimental areas were ploughed and fertilised before sowing. In the top 40 cm of the soil, the content of N-NO₃ before sowing was 2.0 g m⁻² in the experiment no. 1, and 1.2 g m⁻² in the experiment no. 2. Experiment no. 1 was fertilised with a rate of 6.4 g m⁻² of N, while 11 g m⁻² of N and was applied to experiment no. 2. Experiments were also fertilised with a rate 4.6 g m⁻² of P₂O₅. Weeds were allowed to establish and growth in all experimental units. Experiments were periodically watered.

Rojas experiment (experiment no. 3) was set in a productive paddock with the mixed grazing-cropping management which is frequently used by farmers in the Argentine Corn Belt. The experiment was started during the third of annual cropping since the preceding pasture was ploughed and after a maize crop that yielded 9400 kg ha⁻¹. The soil was a clay-loam (Typic Argiudoll). Treatments were the same four used in Buenos Aires experiments. Pea seeds were inoculated, and seeds of both pea and barley were treated before sowing with fungicides compatible with nitrogen-fixing symbionts (Carbendazim + Thiram, 0.1 L + 0.1 L a.i. L⁻¹, dose: 0.625 L per 100 kg of seed). A total herbicide (Glyphosate; 360 g a.i. L⁻¹, dose: 2.0 L per ha) was applied before sowing. Herbicide was applied in order to ensure that weeds in all plots were exclusively those established after crop sowing. No further weed control was applied during the crop cycle. Pest and disease control were not necessary. The experiment was sown on 13 July 2000 and carried out under natural rain conditions. Each treatment was sown in a strip of 9.5 m width and 110 m length using a no-tillage sowing machine (John Deere 1560, Moline, Illinois, USA). Target density of pea was 80 pl m⁻² in both monoculture and mixture, while those of barley were 160 and 80 pl m⁻² for the monoculture and the intercrop, respectively. Strips were fertilised at sowing with 98.6 kg ha⁻¹ of N and 15 kg ha⁻¹ of P₂O₅. To set the control treatment, the sowing machine passed along the strip in working position, only adding fertiliser but not sowing any crop seeds.

#### 2.2. Measurements

Interception of solar radiation and cover of crop species and weeds were measured when barley spikes emerged (hereafter referred to as crop flowering). Canopy interception of incident photosynthetically active radiation (PAR) was measured using a 1 m long photon flux sensor (LI 191 S, Licor Inc., Lincoln, Nebraska, USA). Measures were taken above and below the canopy. The fraction of the incident PAR
intercepted by the canopy (\( F_{\text{intPAR}} \)) was calculated with the following equation:

\[
F_{\text{intPAR}} = \left[ 1 - \left( \frac{\text{PAR}_{\text{below}}}{\text{PAR}_{\text{above}}} \right) \right]
\]  

(1)

Cover proportions of pea, barley and weeds in the plant canopy were obtained using an optical device developed by Beaumer and de Wit (1968). This device allows the estimation of the leaf area proportion of each component in a plant mixture. The relative leaf area (RLA) of pea, barley and weeds was obtained using the equation:

\[
\text{RLA}_i = \left( \frac{N_i}{N_{\text{total}}} \right)
\]

(2)

where \( N_i \) is the number of times that leaves of the component \( i \) were observed, and \( N_{\text{total}} \) the total number of observations.

In order to estimate the partition of the intercepted PAR among pea, barley and weeds in the plant community, both \( F_{\text{intPAR}} \) and RLA\(_i\) were combined as follow:

\[
\text{Intercepted PAR}_i \% = \left( F_{\text{intPAR}} \times \text{RLA}_i \right) \times 100
\]

(3)

All plants in a 1 m\(^2\) sample were harvested at crop maturity in each experimental unit of Buenos Aires experiments. Four 1 m\(^2\) random sub-samples were harvested in each strip at Rojas experiment. Crop and weed species were sorted from each sample and the number of weed species was counted. Plant material was dried in an oven at 60 °C during 72 h, and weighted. Percentage total nitrogen (micro-Kjeldhal) in plant tissue was determined for each crop species and for a pooled sample of weed biomass. Nitrogen content in the plant biomass was obtained by multiplying the nitrogen percentage by its respective dry matter weight.

2.3. Data analyses

Species diversity of weed community was assessed by calculating different indices. Species richness was measured by the mean number of species per treatment (Magurran, 1988). Shannon evenness (\( E \)) was used as a measure of equitability (Magurran, 1988). Berger–Parker index (\( d \)) was applied as a dominance measure, and expressed in its reciprocal form (1/\( d \)). An increase in 1/\( d \) indicates both a diversity increase and a dominance decrease (Magurran, 1988).

Rank-abundance plots were used to display species relative abundance data since abundance distributions provide a complete description of the community diversity. The relative abundance of a species indicates its degree of dominance or subordination in the plant community (i.e. the greater the relative abundance of crop in the plant community, the higher its dominance). Furthermore, rank-abundance plots simultaneously show both component of species diversity, species number and evenness, and are often a more sensitive measure of environmental effects than only using species richness (Magurran, 1988). Rank-abundance plots may be also considered as a representation of resource partitioning where the species relative abundance is analogous to the fraction of niche space pre-empted by that population (Whittaker, 1975).

Weed community structure was also analysed according to its functional composition in terms of plant functional traits. Species were classified by life cycle (annuals and perennials), and emergence seasonality (winter and spring). Life cycle represents the two contrasting reproductive strategies of weeds, annual species, which die after seed production, and perennials, which still alive after reproduction. Seasonality groups weed species according to the main season in which they establish in the field, thus, species were arranged into winter and spring emerging. Four functional groups were obtained by combination of life cycle and emergence seasonality (winter annuals, winter perennials, spring annuals, spring perennials).

The differences among treatments in PAR at weed level, nitrogen content in weeds and crops, and diversity measures were analysed by ANOVA using a mixed model (Littell et al., 1996). Blocks effects within experiments were considered as random. When the experiment by treatments interaction was significant the effect slice test was applied to calculate the simple effect of experiment within each treatment level. Significant interaction implies treatment effects may be different in some experiment whereas it may be no treatment effect in others. Then, comparison of treatment should be observed separately by experiment. Slicing produces analysis without separating the data (Schabenberger, 1998). Functional group data of each experiment were analysed by ANOVA. Means were compared with Tukey’s method (\( P < 0.05 \)) when necessary.
3. Results

3.1. Patterns of resource use and weed suppression

Barley tended to greatly suppress the growth of weed and pea plants (Table 1 and Fig. 1). More nitrogen was generally accumulated in barley biomass when grown in both monoculture and intercropping (Table 1). Accumulated nitrogen in pea biomass usually decreased in mixtures, while barley did not differ among crop treatments across experiments (Table 1). Concurrently, accumulated nitrogen in weed biomass and incident PAR at weed canopy level (%) were constrained by the crop presence (Table 2). The lowest values of these variables were, generally, observed in both intercrops and barley monocultures of all experiments, while pea crops allowed for the greatest proportion of incident PAR to reach the weeds related to the other crop treatments (Table 2). Therefore, weed growth exponentially decreased as the biomass production of crops increased, and intercrops and barley had greater suppressive effect on weeds than pea monocultures (Fig. 1, Table 2).

3.2. Weed species diversity

Species diversity of weed communities was differently modified by crop treatments. Species number and evenness were reduced by crop presence, which is showed in the rank-abundance plots (Fig. 2). The reduction of the species number (i.e. the total number of species recorded by treatment within experiment) can be observed if the last species in the ranks are projected on the species sequence axes. Intercrop species number was lower than that of pea monocultures in all experiments, whereas differences between intercrop and barley were variable across experiments (Fig. 2). Weed species richness (i.e. the mean number of species by treatment) was statistically

Table 1
Accumulated nitrogen in pea and barley biomasses (g m⁻²) corresponding to experiment carried out at Buenos Aires in 1999 and 2000 and at Rojas in 2000

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Cropping system</th>
<th>Pea</th>
<th>Barley</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buenos Aires 1999</td>
<td>Monoculture</td>
<td>22.8 a</td>
<td>15.6 ab</td>
</tr>
<tr>
<td></td>
<td>Intercrop</td>
<td>11.1 bc</td>
<td>11.6 bc</td>
</tr>
<tr>
<td>Buenos Aires 2000</td>
<td>Monoculture</td>
<td>14.2 bc</td>
<td>17.5 ab</td>
</tr>
<tr>
<td></td>
<td>Intercrop</td>
<td>6.5 cd</td>
<td>15.8 ab</td>
</tr>
<tr>
<td>Rojas 2000</td>
<td>Monoculture</td>
<td>14.3 bc</td>
<td>16.1 ab</td>
</tr>
<tr>
<td></td>
<td>Intercrop</td>
<td>3.0 d</td>
<td>12.6 bc</td>
</tr>
</tbody>
</table>

Different letters indicate significant differences within experiments or cropping systems (P < 0.05).

Table 2
Accumulated nitrogen in weed biomass (Nweed, g m⁻²), and incident of photosynthetically active radiation at weed level (PARweed, %), corresponding to experiment carried out at Buenos Aires in 1999 and 2000, and at Rojas in 2000

<table>
<thead>
<tr>
<th></th>
<th>No crop</th>
<th>Pea</th>
<th>Barley</th>
<th>Intercrop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nweed (g m⁻²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buenos Aires 1999</td>
<td>7.39 b</td>
<td>0.35 de</td>
<td>0.26 de</td>
<td>0.11 e</td>
</tr>
<tr>
<td>Buenos Aires 2000</td>
<td>10.23 a</td>
<td>2.40 cd</td>
<td>0.23 de</td>
<td>0.40 de</td>
</tr>
<tr>
<td>Rojas 2000</td>
<td>3.24 c</td>
<td>1.09 cde</td>
<td>0.03 e</td>
<td>0.04 e</td>
</tr>
<tr>
<td>PARweed (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buenos Aires 1999</td>
<td>99.0 a</td>
<td>13.6 cd</td>
<td>10.6 cd</td>
<td>0.9 d</td>
</tr>
<tr>
<td>Buenos Aires 2000</td>
<td>89.0 a</td>
<td>61.3 b</td>
<td>26.0 c</td>
<td>14.6 cd</td>
</tr>
<tr>
<td>Rojas 2000</td>
<td>100.0 a</td>
<td>67.5 b</td>
<td>17.8 cd</td>
<td>21.4 c</td>
</tr>
</tbody>
</table>

Different letters indicate significant differences among experiments and treatments (P < 0.05). Nweed (experiment × treatment): F(6,21) = 14.64 (P < 0.0001). PARweed (experiment × treatment): F(6,21) = 16.63 (P < 0.0001).
Table 3
Species richness (S), Shannon evenness index (E), and reciprocal Berger–Parker index (1/d) corresponding to experiments carried out at Buenos Aires in 1999 and in 2000, and at Rojas in 2000

<table>
<thead>
<tr>
<th></th>
<th>No crop</th>
<th>Pea</th>
<th>Barley</th>
<th>Intercrop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buenos Aires 1999</td>
<td>21.3 a</td>
<td>9.3 cde</td>
<td>13.6 bc</td>
<td>9.9 cde</td>
</tr>
<tr>
<td>Buenos Aires 2000</td>
<td>19.3 ab</td>
<td>16.9 ab</td>
<td>10.3 cd</td>
<td>10.3 cd</td>
</tr>
<tr>
<td>Rojas 2000</td>
<td>9.3 cde</td>
<td>7.3 de</td>
<td>4.3 e</td>
<td>5.3 de</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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<th>Pea</th>
<th>Barley</th>
<th>Intercrop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buenos Aires 1999</td>
<td>0.58 ab</td>
<td>0.04 c</td>
<td>0.03 c</td>
<td>0.01 c</td>
</tr>
<tr>
<td>Buenos Aires 2000</td>
<td>0.46 ab</td>
<td>0.37 b</td>
<td>0.03 c</td>
<td>0.04 c</td>
</tr>
<tr>
<td>Rojas 2000</td>
<td>0.65 a</td>
<td>0.14 c</td>
<td>0.01 c</td>
<td>0.01 c</td>
</tr>
</tbody>
</table>

1/d
<table>
<thead>
<tr>
<th></th>
<th>No crop</th>
<th>Pea</th>
<th>Barley</th>
<th>Intercrop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buenos Aires 1999</td>
<td>2.01 ab</td>
<td>1.02 d</td>
<td>1.02 d</td>
<td>1.01 d</td>
</tr>
<tr>
<td>Buenos Aires 2000</td>
<td>1.77 ab</td>
<td>1.45 bc</td>
<td>1.01 d</td>
<td>1.02 d</td>
</tr>
<tr>
<td>Rojas 2000</td>
<td>2.52 a</td>
<td>1.07 cd</td>
<td>1.00 d</td>
<td>1.00 d</td>
</tr>
</tbody>
</table>

Different letters indicate significant differences among treatments for the same variable (P > 0.05). S (experiment × treatment: F(6,21) = 5.83 (P = 0.0010), E (experiment × treatment: F(6,21) = 6.70 (P = 0.0004), 1/d (experiment × treatment: F(6,21) = 3.87 (P = 0.0093).

Table 4
Relative abundance of functional groups (%), for the experiments sown at Buenos Aires in 1999 and 2000, and at Rojas in 2000

<table>
<thead>
<tr>
<th></th>
<th>No crop</th>
<th>Pea</th>
<th>Barley</th>
<th>Intercrop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buenos Aires 1999, S.E. (P &lt; 0.05) = 12.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter annuals</td>
<td>91.0 a</td>
<td>67.0 abc</td>
<td>69.9 ab</td>
<td>53.9 abcd</td>
</tr>
<tr>
<td>Winter perennials</td>
<td>4.7 e</td>
<td>2.5 e</td>
<td>1.8 e</td>
<td>7.1 e</td>
</tr>
<tr>
<td>Spring annuals</td>
<td>3.3 e</td>
<td>6.8 e</td>
<td>20.4 de</td>
<td>12.5 de</td>
</tr>
<tr>
<td>Spring perennials</td>
<td>1.0 e</td>
<td>23.7 cde</td>
<td>7.9 de</td>
<td>26.5 bde</td>
</tr>
</tbody>
</table>

Buenos Aires 2000, S.E. (P < 0.05) = 15.44

<table>
<thead>
<tr>
<th></th>
<th>No crop</th>
<th>Pea</th>
<th>Barley</th>
<th>Intercrop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter annuals</td>
<td>95.6 a</td>
<td>88.6 a</td>
<td>52.8 ab</td>
<td>27.1 b</td>
</tr>
<tr>
<td>Winter perennials</td>
<td>0.1 b</td>
<td>0.7 b</td>
<td>1.0 b</td>
<td>1.1 b</td>
</tr>
<tr>
<td>Spring annuals</td>
<td>4.1 b</td>
<td>8.9 b</td>
<td>24.9 b</td>
<td>27.1 b</td>
</tr>
<tr>
<td>Spring perennials</td>
<td>0.2 b</td>
<td>1.8 b</td>
<td>21.3 b</td>
<td>44.7 ab</td>
</tr>
</tbody>
</table>

Rojas 2000, S.E. (P < 0.05) = 16.71

<table>
<thead>
<tr>
<th></th>
<th>No crop</th>
<th>Pea</th>
<th>Barley</th>
<th>Intercrop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter annuals</td>
<td>63.5 ab</td>
<td>14.5 abcd</td>
<td>1.6 d</td>
<td>6.4 bcd</td>
</tr>
<tr>
<td>Winter perennials</td>
<td>0.5 d</td>
<td>22.8 abcd</td>
<td>2.2 cd</td>
<td>3.2 bcd</td>
</tr>
<tr>
<td>Spring annuals</td>
<td>35.9 abcd</td>
<td>62.7 abc</td>
<td>72.2 a</td>
<td>70.9 a</td>
</tr>
<tr>
<td>Spring perennials</td>
<td>0.1 d</td>
<td>0.0 d</td>
<td>24.0 abcd</td>
<td>19.6 abcd</td>
</tr>
</tbody>
</table>

Means followed by different letters significantly differ (P < 0.05) within experiment.

3.3. Weed functional groups

Crop effects on functional groups were variable, but some coincident patterns can be identified. In two experiments, intercrops and monocultures had similar response patterns (Table 4). Winter annuals were the most abundant group in all crop treatments at experiment no. 1, but the abundance of spring perennials and winter annuals did not significantly differ between intercrop and pea (Table 4). Conversely, spring annuals were the most abundant in weed communities of all crop treatments in experiment no. 3, while spring perennials were co-dominants only in barley and intercrop. In experiment no. 2, spring perennials were the most abundant in the intercrop weed community, whereas winter annuals were the most abundant in both monocultures (Table 4).

Besides the modifications in the functional groups, floristic composition was also differently affected by crop treatments across experiments. The importance of winter-emerging species, on one hand, was reduced diverse and with high evenness than the other crop treatments, at least in one experiment (Table 3). Conversely, there were no significant differences between intercrops and barley monocultures in both, dominance and evenness indices (Table 3).
4. Discussion

Resource use by pea–barley intercropping differed from that of monocultures, and resulted in greater crop biomass production and weed growth suppression. Weed suppression by intercrops concurs with previous research using cool-season pulse and cereal crops (Mohler and Liebman, 1987; Carr et al., 1995; Bulson et al., 1997; Haymes and Lee, 1999; Hauggaard-Nielsen et al., 2001). Weed suppression variability across treatments could be explained by the different nitrogen sources used by barley and pea (Tofinga et al., 1993; Hauggaard-Nielsen et al., 2001). Nitrogen available for weeds was greater when growing with peas than when growing with intercrop and barley. Barley was identified as more competitive for nitrogen than pea, which was constrained to rely on symbiotic fixation as source of nitrogen (Tofinga et al., 1993; Hauggaard-Nielsen et al., 2001). Furthermore, solar radiation reaching weeds was modulated, at least in part, by the different ability of crop species to uptake nitrogen. The leaf area of the dominant (cereal or weed) species in the community increased when more nitrogen was available, enhancing its ability to intercept solar radiation, and therefore, to shade the subordinate species (Stern and Donald, 1962; Liebman, 1989; Liebman and Robichaux, 1990), which in turn, could reduce N-fixation even more (Fujita et al., 1992).

Interestingly, weed species diversity of intercrops was rarely lower than monocultures. This disagrees with the predicted lower diversity for intercrops. Barley alone was able to produce similar effects as the intercrop, whereas some pea monocultures had more diverse weed communities than intercrop and barley at both, plot and field experimental levels. Species richness, on one hand, did not usually differ among crop treatments. Little differences in species richness were also observed between the weed communities of intercrops and barley, while weed species richness of pea tended to be higher than that of both cropping systems (Mohler and Liebman, 1987). Similarly, the weed community of pea crops had greater species number than wheat crops at field and regional scales (Poggio et al., 2004). However, intercrops modified the evenness of weed communities by decreasing both, relative abundance of dominant weeds and number of rare species. Since the decrease of evenness necessarily implies reduction of individual plant biomass, propagule production could also be curtailed, and therefore, fewer propagules would have entered in the soil seed bank, affecting in turn species richness in the following growing seasons.

Weed diversity reduction by intercrops, surprisingly, appeared to be more stable than monocultures across experiments, despite the fact that experiments differed in the effects of cropping systems on weed communities and in their weed floras. The lack of differences in species richness and evenness of intercrops across experiments could be explained by the variability in resource use by crop species in all cropping systems and experiments. Nitrogen uptake by intercropped pea tended to increase as that of barley decreased, even though barley dominated in plant communities capturing a greater share of nitrogen in both intercropping and monoculture. This suggests an apparent complementarity between barley and pea in the combined nitrogen uptake and in the consequent growth when intercropped. Thus, intercrop may maintain a highly asymmetric competition over weeds, despite of the variation in nitrogen availability in different environments. Conversely, reductions in
nitrogen uptake and growth in some monocultures reduced the asymmetry of crop competition over weeds, thus reducing its effects on species richness and evenness. The restriction of incident PAR reaching weeds may also explain the decrease in species diversity of weed communities when shaded by taller crop individuals. Shading by a dominant crop could produce thinning mortality effects on individuals of subordinate weed species, which consequently reduces evenness among weed species richness (Goldberg and Miller, 1990; Tilman and Pacala, 1993). Shading can also inhibit the germination of some species by inducing secondary dormancy in seeds, which could be caused by the modification of either the light quality by the canopy (Górski, 1975; Silvertown, 1980; Batlla et al., 2000; Benech-Arnold et al., 2000) or the amplitude of the soil temperature (Thompson and Grime, 1983; Benech-Arnold et al., 1988, 2000).

Although functional groups of intercrop weed communities were similar to those of monocultures in some cases, spring-emerging species generally increased their relative importance in the intercrop weed communities; whereas winter-emerging species were usually less abundant in intercrops. This partially concurs with the prediction that intercropping would present lower and greater relative abundances of winter- and spring-emerging species, respectively. Once more, resource use may also explain the shift in the relative abundance of winter- and spring-emerging species by the effect of crops, as it was interpreted from previous observations in pea and wheat crops at field and regional scales (Poggio et al., 2004).

The greater ability of crops to competitively displace winter-emerging than spring-emerging weeds involves several factors. Interference between crops and winter-emerging weeds started early in their growing season as both emerge together (Joenje and Kropff, 1987; Kropff and Spitters, 1991). Canopy decay of a highly dominant crop creates open gaps at the end of its growing cycle, which allows the establishment and growth of spring-emerging species (Satorre and Ghersa, 1987). Gap availability apparently increased even more if winter-emerging weeds are highly suppressed, and therefore spring-emerging weeds were more abundant. Conversely, still green winter weeds might suppress the establishment and growth of later weeds, as observed in some monocultures and, mainly, in the no crop treatments. Facilitative effects, mediated by an introduced species, could be involved in reducing the usually larger competitive effect of dominant species (Vandermeer, 1989; Miller, 1994).

5. Conclusions

Weed growth was suppressed by all crop treatments, but barley plants tended to greatly suppress pea and weed plants in monocultures and intercrops. This could be explained by the greater nitrogen accumulation in barley plants in both cropping systems. Furthermore, complementarity in nitrogen uptake apparently occurred between barley and pea when intercropped, which would have resulted from the differences between both species in their main sources of soil nitrogen uptake. These results suggest that the design of more weed suppressive cropping system and, therefore, less dependent on herbicide use, can be achieved not only by properly combining cereal and pulse crops (e.g. choose of cultivars, relative sowing dates and sowing densities), but also by managing nutrient availability.

In relation to the changes in the weed community structure, intercrops and barley monocultures generally produced similar effects on weed communities, concurring with the alternative hypothesis. On one hand, according to the first prediction, species diversity in the intercrop was not lower than in the monoculture, particularly, in terms of species richness. However, intercrop effects appeared to be more stable than those of monoculture across the explored environments (i.e. years and sites), probably due to nitrogen complementarity between barley and pea when intercropped. On the other hand, results partially agree with the second prediction, since intercrop usually presented lower and greater abundances of winter- and spring-emerging weeds, respectively, which may be explained by the differences among crop treatments in their canopy dynamics. Furthermore, it would be reasonable to expect that reduced abundance of some weed species by the suppressive effects of crop presence could also reduce their propagule production. Thus, the observed differences among treatments in their species diversity and seasonal composition may also be reflected, and even
amplified, in the weed community structure of subsequent growing seasons. This could be used to define successional trajectories, by locally enhancing some species while excluding others. These findings have also interesting implications for developing cropping systems that are ecologically sound, especially when the aims are on reduction of agriculture pollution, as well as conservation and restoration of plant diversity.

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