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Productivity of FieldPea (*Pisumsativum* L.) and Spring Oat (*Avena sativa* L.) Grown as Sole and Intercrops Under Different Nitrogen Levels

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Abstract

Intercropping cereal grains and legumes has potential as an alternative cool-season forage cropin low-input farming systems. The objectives of this study were to quantify the effects of density, species proportion and nitrogen (N) supply on the biomass accumulation of field pea and spring oat grown as sole or intercrops. Greenhouse experiments were conducted using an additive series experimental design. Treatments included threefertilizer Nrates and 20 density/proportion combinationsin a randomized complete block with four replications. Sole plant densities included 2, 3, 4, 5 plants of each species pot^{-1} (16 cm in diameter, 16 cm in height). The species ratios per pot for the intercrop included 1:1, 1:2, 1:3, 1:4, 2:2, 2:3, and 3:5 and their reciprocals. Nitrogentreatments included urea at 0, 0.2, or 1.0 g N pot^{-1} in a split application. Plants were harvested and oven dried to constant weight at 46 days after planting. As density increased, sole cropped oat and fieldpea biomass increased. In the intercrop, oat showed greater biomass accumulation at higher N levels, whereas field pea biomass was reduced at the highest N level. In both sole and intercrop, oat was more sensitive to intraspecific competition than field pea. Niche differentiation was only observed at the highest N level. At higher N and lower total density, mixtures yielded more than monocultures, indicating that intercropping of field pea and spring oat may be beneficial. Results from this study can aid in future field research to determine optimum density for each species and N rates to be applied in field pea-oat intercropping systems.

Keywords: field pea (*Pisumsativum* L.), spring oat (*Avena sativa* L.), intercrop advantage, interplant competition, niche differentiation, overyielding, land equivalent ratio, relative yield total

1. Introduction

Intensive management of large-scale plantings of genetically homogeneous crops has been linked to reductions in soil and water quality and ecosystem services (Malézieux et al., 2009). There is general public interest in implementing alternative agronomic practices to reduce the impact of agriculture on the environment. One possible alternative is to grow crops as intercrops, where more than one crop species are grown in the same field for a significant period of the crops' life cycle (Ofori & Stern, 1987; Willey, 1979). Intercropping can be beneficial if the practiceresults in niche differentiation, weed suppression, or resource use-sharing. In addition, increasing diversity through intercropping may reduce pest and disease incidence leading to less pesticide application, increased habitat for beneficial insects and microorganisms, and an overall reduction in farm inputs (Kontturi et al., 2011). Intercropping may also help facilitate nutrient and water acquisition (Hauggaard-Nielsen, Jornsgaard, Kinane, & Jensen, 2008), which may increase crop biomass and grain yield, and improve crop quality and ecosystem sustainability (Malezieux et al., 2009).

The greatest benefits of intercropping often occur when the mixed crop species differ markedly in morphology, phenology or physiology, thereby increasing the potential for niche differentiation and beneficial symbiotic

relationships (Andersen, Hauggaard-Nielsen, Weiner, & Jensen, 2007). Plant density, species proportion, spatial arrangement, crop architecture, species life cycle, and the relative roles of intra- and interspecific competition must be taken into consideration when selecting species for an intercropping system to ensure that crops have adequate resources to maximize growth and minimize competition (Andersen et al., 2007; Anil, Park, Phipps, & Miller, 1998; Brisson, Bussiere, Ozier-Lafontaine, Tournebize, & Sinoquet, 2004; Malezieux et al., 2009; Molla & Sharaiha, 2010; Neumann, Schmidtke, & Rauber, 2007).

Cereal grains and legumes are someof the most commonly promoted species for intercropping (Anil et al., 1998; Arlauskiene et al., 2011; Hauggaard-Nielsen & Andersen, 2000; Hauggaard-Nielsen et al., 2008; Kadziuliene et al., 2009; Konturri et al., 2011; Ofori & Stern, 1987; Sarunaite, Deveikyte, & Kadziuliene, 2010). Legumes, including field pea (*Pisumsativum* L.), have the ability to fix atmospheric nitrogen (N), thereby increasing soil inorganic N. Cereal crops planted alongside legumes may be able to exploit this increase in soil N and growers, in turn, may reduce their reliance on inorganic fertilizer and fossil energy resources (Neumann et al., 2007). Moreover, application of fertilizer N has a direct deleterious effect on symbiotic N fixation because it is thought that nitrate disrupts O_2 diffusion in the bacterial symbiont, which in turn decreases nitrogenase activity (Luciński, Polcyn, & Ratajczak, 2002). Thus, N application benefits the cereal crop in a legume-cereal intercropping system, but not the legume (Naudin, Corre-Hellou, Pineau, Crozat, & Jeuffroy, 2010). Additional benefits associated with legume-cereal intercropping include: *i)* increased biomass and grain yield (Carr, Gardner, Schatz, Zwinger, & Guldan, 1995; Jensen, 1996), *ii)* higher N content in fodder (Cowell, Bremer & Van Kessel, 1989; Droushiotis, 1989) and better feed value (Begna, Fielding, Tsegaye, Van Veldhuizen, Angadi, & Smith, 2011), *iii*) more efficient use of limited resources (Spitters, 1983; Wilson, 1988), and iv) weed suppression (Hauggaard-Nielsen, Ambus, & Jensen, 2001).

Research designed to optimize the intercrop advantage typically uses a replacement series experimental design, where total plant density is held constant and the relative proportion of each species in the mixture is varied (Bedoussac & Justes, 2011). This allows the researcher to assess the quantity of overyielding in mixture relative to the monoculture at the same density. This overyielding has also been referred to as the land equivalent ratio (LER; Willey, & Osiru, 1972) and the relative yield total (RYT; Spitters, 1983). The problem with the replacement series experimental design is that it does not allow one to identify the optimum planting density and proportion of the two species in mixture. To accomplish the latter, an additive series experimental design is needed, where both total stand density and species proportion are varied and yield is assessed using a response-surface analysis.

Although numerous studies have been conducted on legume-cereal intercrops, relatively few have used the additive series approach. Thus, the objective of this greenhouse study was to use an additive series design to quantify the density and species proportionsof field pea and spring oat that result in optimum biomass production of the intercrop as influenced by nitrogen supply. Our hypotheses were that *i*) an increase in plant density will result in greater total biomass, *ii*) increase in N will increase oat biomass but not field pea, *iii*) niche differentiation,or overyielding, will be greater at lower N levels at the same final density (same number of plants per pot).

2. Materials and Methods

2.1 Greenhouse Experiment and Data Collection

A greenhouseexperiment was conducted at the University of Nebraska-Lincoln to quantify the effects of density, species proportion, and nitrogen supply on the biomass accumulation of field pea (*Pisumsativum* L.) and spring oat (*Avena sativa* L.) grown as sole or intercrops. Field pea (cultivar‘4010’) and spring oat (cultivar ‘Jerry’) were grown in plastic pots (16 cm in diameter, 16 cm in height) filled with 2.1 L of an 8:1:1 mixture of soil:sand:vermiculite. The soil used was a Sharpsburg silty clay loam and the mixture contained 92 ppm N, 39 ppm P, and 249 ppm K, with a pH of 6.3 and 2.5% OM. The experiment was designed as an additive series, where both total density and species proportion varied simultaneously (Gibson, Conolly, Harnett, & Weidenhamer, 1999). The treatment design was a factorial with three fertilizer N rates and 20 density combinationsin a randomized complete block with four replications. Field pea and oatplants were grown as sole crops (SC) at 2, 3, 4 and 5 plants per pot or intercropped (IC) with 1:1, 1:2, 1:3, 1:4, 2:2, 2:3, and 3:5 plants of each species per pot, and their reciprocals (total of 2, 3, 4, 5, 4, 5, and 8 plants per pot for the IC, respectively). Nitrogen was applied to each pot in the form of urea at a rate of 0, 0.2, or 1 g N pot^{-1}. Pots were spaced 15 cm apart on the greenhouse bench.

Uninoculated seeds were planted on January 19, 2012, at 2 cm depth with two seeds in each hole to increase probability of emergence. Plants were uniformly distributed at each density treatment. Seedlings of both species emerged within one week and were thinned to the treatment density at 12 days after planting (DAP). Half of the N was applied at 14 DAP and the second half was applied at 21 DAP to avoid fertilizer injury. Each dose of urea was

dissolved in 250 ml of water, and the 0 g N pots received 250 ml of water. Pots were watered on a daily basis. Greenhouse temperatures were set at 24/19 C day/night, respectively. In addition to natural radiation, supplemental lighting was providedfrom 6 to 8 am and 6 to 8 pm to ensure a 14 hr day. Field peas showed symptoms of fusarium root rot (wilting and curling of the leaves) at about 30 DAP, so all pots were treated with the fungicide thiophanate-methyl (T-Methyl SPC 4.5 F; Nufarm Americas Inc. Burr Ridge, IL) applied as a drench (75 ml of solution per pot) at 36 DAP, resulting in 0.057 ml of commercial product per pot. At 45 DAP the first flowers on both field pea and oat plants were observed, and at 46 DAP the experiment was harvested by clipping plants at the soil surface. Field pea and oat plants in the intercrop treatments were separated and bagged individually and dried to constant weight at 60 C.

2.2 Data Analysis

The Spitters (1983) response surface analysis approach was used to quantify intra- and interspecific competition in the present study. The reciprocal mass of individual plants (1/w) was regressed on density of each species for each of the three N treatments (Spitters, 1983):

$$1/w_p = b_{p,0} + b_{p,p}D_p \quad (1)$$

$$1/w_o = b_{o,0} + b_{o,o}D_o \quad (2)$$

$$1/w_p = b_{p,0} + b_{p,p}D_p + b_{p,o}D_o \quad (3)$$

$$1/w_o = b_{o,0} + b_{o,o}D_o + b_{o,p}D_p \quad (4)$$

where the regression coefficients $b_{p,0}$ and $b_{o,0}$ represent the y-intercept, or the reciprocal of maximum biomass for individual plants of field pea and oat, respectively; $b_{p,p}$ and $b_{o,o}$ are the coefficients of intraspecific competitionfor field pea and oat, respectively; $b_{p,o}$ and $b_{o,p}$ are the coefficients of interspecific competition for field pea and oat, respectively; and D_p and D_o represent the density of field pea and oat plants, respectively.

Intraspecific competition was quantified at each N level as $b_{p,p}/b_{p,0}$ and $b_{o,o}/b_{o,0}$ from Equations 1 and 2 for field pea and oat, respectively.Interspecific competition was quantified as $b_{p,p}/ b_{p,o}$ and $b_{o,o}/ b_{o,p}$from Equations 3 and 4 for field pea and oat, respectively.

This approach assumes *i)* constant final yield and *ii)* additivity. The assumption of constant final yield in sole crop was evaluated by fitting (Weiner & Freckleton, 2010):

$$Y = N / (A + BD) \quad (5)$$

where Y is total yield (g pot^{-1}), D is density (plants pot^{-1}), and A and B are parameter estimates. If the yield-density relationship begins to plateau, constant final yield is reached. The assumption of additivity was evaluated by including an interaction term (D_pD_o) in Equations 3 and 4. If the parameter estimate on the interaction term was not significant, the effect of each species in competition is additive.

To determine if field pea and oat were competing for the same resources, the niche differentiation index (NDI) was calculated for each N treatment using estimates from Equations 3 and 4 (Spitters, 1983):

$$NDI = (b_{p,p}/ b_{p,o}) * (b_{o,o} / b_{o,p}) \quad (6)$$

where NDI > 1 indicates that species were not competing or limited by the same resource, whereas NDI < 1 indicates that species were competing or limited by the same resource. Spitters (1983) argued that the NDI provides a more robust estimate of intercrop potential because it is essentially equivalent to the relative yield total or land equivalent ratio, but calculated from parameter estimates obtained across a full range of species proportions and total densities in mixture. Therefore, an NDI > 1 also indicates intercrop advantage.

Equations 1-5 were fitted to the data and parameter estimates obtained using the REG and NLIN procedures in SAS (SAS Institute, Cary, NC).

3. Results and Discussion

3.1 Aboveground Biomass of Sole Cropped Field Pea and Oat

Oat biomass in sole crop was greater than field pea at all densities and N levels (Figure 1). The interaction between plant density and N supply was not significant for either species. Shoot biomass increased with increasing density for both species ($P < 0.0001$ and $= 0.0098$ for field pea and oat, respectively), but appeared to plateau at 4 to 5 plants per pot. Therefore, both species approached constant final yield in all N treatments. Increasing N resulted in an increase in oat biomass (Figure 1, Table 1), but the opposite was true for field pea. Similarly, Marshall, Kolb & Roth (1987) and Cowell et al. (1989) reported that spring oat grain and biomass yield increased as N rate increased and Hauggar-Nielsen and Jensen (2001) showed that when sole cropped, different field pea cultivar yields were

either similar or reduced when N was applied. Moreover, Clayton et al. (2004) reported a reduction in field pea nodulation when high rates of urea-N were applied in the field, indicating N application did not benefit this crop.

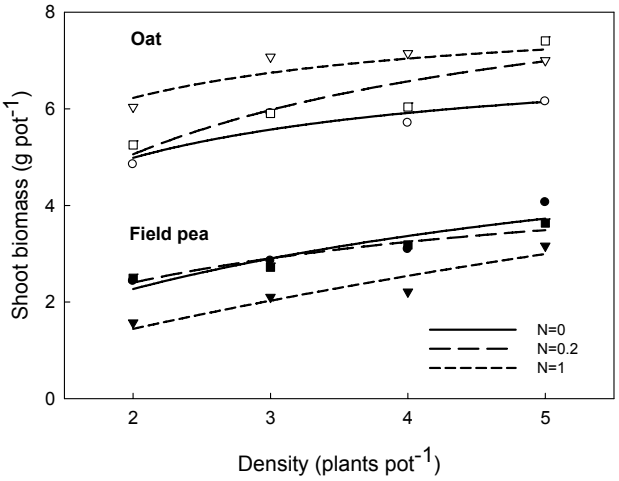

Figure 1. Total shoot biomass (g pot^{-1}) of field pea (closed symbols) and oat (open symbols) planted as sole crops at different final densities (plants pot^{-1}) and nitrogen levels. Lines represent the best fit of equation 5 to the data.

3.2 Intraspecific Competition in Field Pea and Oat

Coefficient values of the fit of reciprocal per plant yield on plant density using Equations 1 and 2 and their use for quantifying intraspecific competitive ability for field pea ($IntraCA_p$) and oat ($IntraCA_o$) in sole crops at different levels of N, are presented in Table 1. Results indicate that oat wasa stronger competitor with itself than field pea. Greatest $IntraCA_o$ was observed in the highest N treatment (1 g N pot^{-1}), indicating that N addition enhanced oat growth and intraspecific competition. Whereas field pea biomass declined with increasing N addition, the effect of adding each additional field pea plant on reciprocal field pea yield was still greater as N addition increased, indicating N addition enhanced intraspecific competition in field pea. If N application results in reduced nodulation and N fixation, it may be expected that field pea were dependent on applied inorganic N and plants were competing for that N.

Table 1. Estimates of regression coefficients for the best fit of Equations 1 and 2 to reciprocal of per plant field pea or oat yield on plant density in sole crop and their use for quantifying intraspecific competition

Nitrogen g N pot^{-1}	$b_{p,O}$	$b_{o,O}$	$b_{p,p}$	$b_{o,o}$	r^2_p	$P\text{-value}_p$	r^2_o	$P\text{-value}_o$	$IntraCA_p$	$IntraCA_o$
0	0.607	0.128	0.151	0.140	0.434	0.0055	0.756	<.0001	0.249	1.094
0.2	0.497	0.208	0.189	0.103	0.589	0.0005	0.646	0.0002	0.380	0.496
1.0	0.579	0.052	0.260	0.132	0.526	0.0010	0.873	<.0001	0.450	2.514

Notes:

$b_{p,O}$ and $b_{o,O}$ are the intercepts for field pea and oat, respectively;

$b_{p,p}$ and $b_{o,o}$ are the coefficients of intraspecific competition for field pea and oat, respectively;

r^2 is the coefficient of determination of the regression and P-value is for the overall fit of the regression model;

$IntraCA_p$ and $IntraCA_o$ are calculated as $b_{p,p}/b_{p,0}$ and $b_{o,o}/b_{o,0}$, respectively.

3.3 Interspecific Competition of Field Pea and Oat in Mixture

Coefficient values of the fit of reciprocal per plant yield on plant density using Equations 3 and 4 and their use for quantifying interspecific competitive abilityfor field pea and oat are presented in Table 2. Addition of an interaction term (D_pD_o) in Equations 3 and 4 resulted in non-significant parameter estimates (P = 0.659, 0.549, and

0.492 for field peas treated with 0, 0.2, and 1 g N pot^{-1}, respectively, and P = 0.711, 0.252, and 0.097 for oats treated with 0, 0.2, and 1 g N pot^{-1}, respectively). Therefore, the effect of each species in competition was additive. Both field pea and oat were more competitive with increasing N addition.The interspecific competitive ability of oat (CA_o) was much greater than field pea (CA_p). Oat produced more biomass in the sole crop (Figure 1), so it was expected that it also would be dominant in the intercrop. The estimate of CA indicates the relative impact of adding a plant of each species in mixture (Spitters, 1983). For example, the effect of adding one field pea plant on field pea shoot mass was equal to the addition of 0.13 plants of oat in the 0 g N pot^{-1} treatment. Conversely, the effect of adding one oat plant on oat shoot mass was equal to the addition of 1.62 field pea plants. Hauggaard-Nielsen et al. (2001) and Hauggaard-Nielsen and Jensen (2001) showed that field pea was consistently the dominated species in barley-field pea mixtures, indicating the low competitive ability of this legume.

Table 2. Estimates of regression coefficients for the best fit of Equations 3 and 4 to reciprocal of per plant field pea and oat biomass on plant density in mixture and their use for quantifying interspecific competition and the niche differentiation index (NDI)

N	$b_{p,O}$	$b_{o,O}$	$b_{p,p}$	$b_{o,o}$	$b_{p,o}$	$b_{o,p}$	r_p^2	P-value$_p$	r^2_o	P-value$_o$	CA_p	CA_o	NDI
0	1.017	0.247	0.040	0.114	0.302	0.071	0.399	<0.0001	0.293	<0.0001	0.132	1.618	0.214
0.2	0.629	0.148	0.144	0.118	0.324	0.069	0.542	<0.0001	0.601	<0.0001	0.443	1.718	0.761
1.0	1.013	0.049	0.141	0.127	0.226	0.060	0.301	<0.0001	0.646	<0.0001	0.625	2.121	1.326

Notes:

$b_{p,O}$ and $b_{o,O}$ are the intercepts for field pea and oat, respectively;

$b_{p,p}$ and $b_{o,o}$ are the coefficients of intraspecific competition for field pea and oat, respectively;

$b_{p,o}$ and $b_{o,p}$ are the coefficients of interspecific competition for field pea and oat, respectively;

r^2 is the coefficient of determination of the regression and P-value is for the overall fit of the regression model;

CA_p and CA_o are calculated as $b_{p,p}/ b_{p,o}$ and $b_{o,o}/ b_{o,p}$ from Equations 3 and 4 for field pea and oat, respectively;

NDI was calculated as $(b_{p,p}/ b_{p,o}) * (b_{o,o} / b_{o,p})$.

3.4 Niche Differentiation of Field Pea and Oat

Estimates of the niche differentiation index (NDI)at different N levels are shown in Table 2. When an intercrop advantage is observed, NDI >1, indicating that species are not limited or competing for the same resource (Spitters, 1983). In the present study, NDI > 1 was only detected at the highest N level (1 g N pot^{-1}). At 0 and 0.2 g N pot^{-1}, NDI was < 1, indicating these species were limited by, or competing for, the same resource. We had hypothesized that niche differentiation would occur only at low N, but found the opposite effect. As with the sole crop treatments, N addition to intercropped treatments had little impact on field pea biomass, but very large effects on oat biomass, resulting in greater total biomass than expected in mixture. Li et al. (2011) also found that N addition alleviated competition among intercrop species and optimized intercrop advantage.

3.5 Optimum Total Plant Density and Species Proportion

Our third hypothesis was that intercropped field pea and oat will produce more biomass than either sole crop at equivalent total density, especially at low N addition. Figure 2 shows a more traditional approach to assessing intercrop advantage by comparing observed total shoot biomass of field peaand oatin the intercrop with that expected based on sole crop biomass. If the top line in each frame (the relative yield total, RYT) exceeds the 1.0 line, then overyielding occurs and there is an intercrop advantage. If the RYT line falls below 1.0, then interplant competition makes the intercrop less productive than the respective sole crop at equivalent density. In agreement with the niche differentiation index, overyielding occurred at all total plant densities in the high N treatment, though it appears that overyielding is greatest at the lower total mixture densities. In contrast, Willey and Osiru (1972) found that higher plant densities in mixture had the greatest yield in a field study.

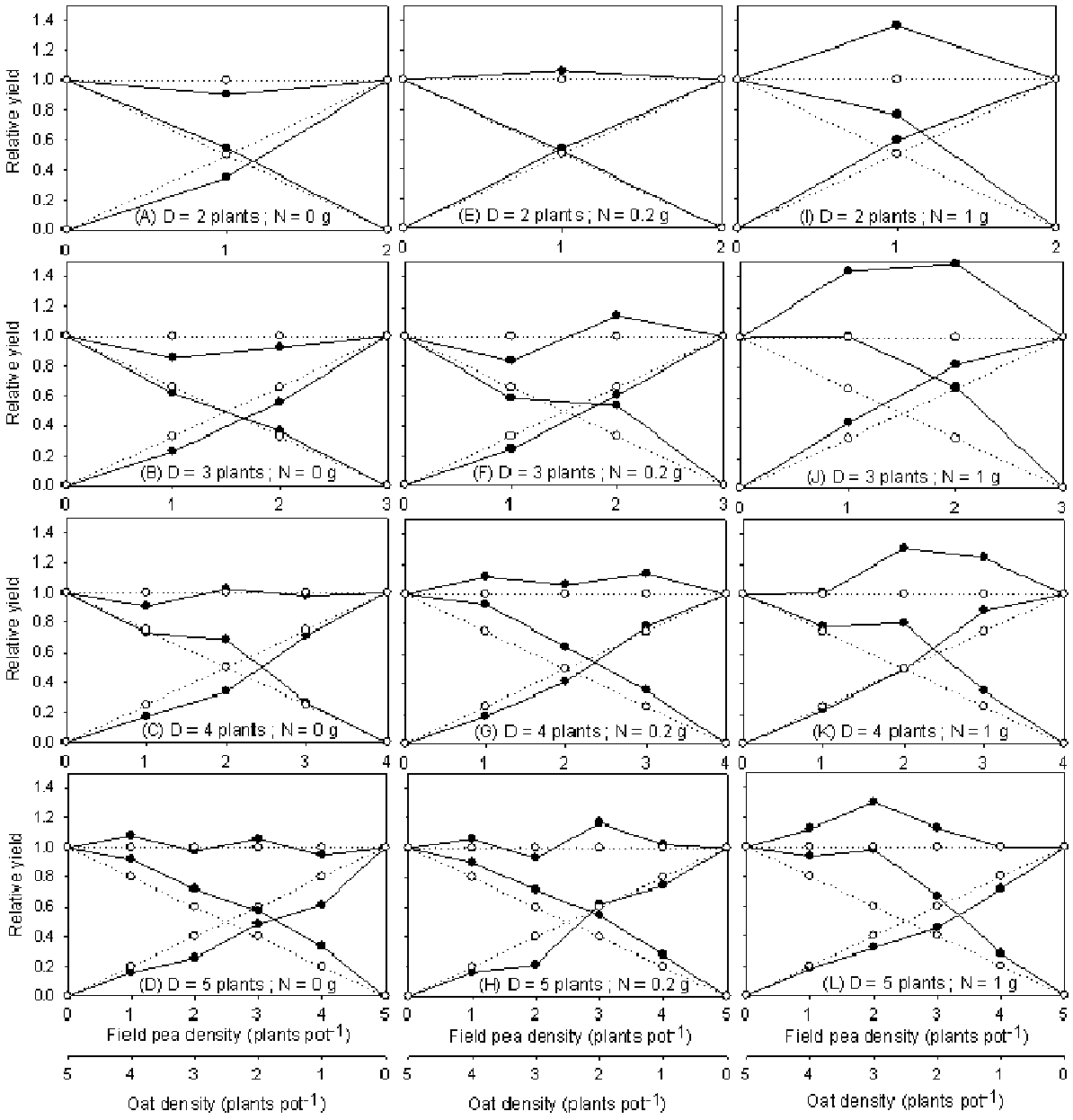

Figure 2.Traditional replacement series analysis of field pea and oat relative yield in relation to the proportion of each species in the mixture

Solid lines and symbols show the actual relative yield trends, dotted lines and open symbols represent the expected relative yield based on the proportion of plants in the mixture. The top line represents the relative yield total or the degree of overyielding occurring for the intercrop.

3.6 Conclusions

Overall, the greater the N supply, the greater the biomass produced by oat in sole crop and both species in the intercrop. Field pea sole crop biomass responded negatively to increasing N, but when intercropped with oats, field pea was able to produce more biomass, suggesting that the presence of oat reduced the detrimental effect of urea-Non field pea.The greater performance of oat in the intercrop was expectedbecausefield pea has been shown to be less competitive than cereal grains.

In general, the field pea and oat intercrop overyieldedonly in the highest N treatment(1 g N pot^{-1}). This

corroborates the results of the niche differentiation analysis. The greatest intercrop advantage occurred in the treatment with two field pea and one oat plant per pot and 1 g N pot^{-1}. This research was conducted under controlled conditions and in order to validate our findings the next step would be to conduct research under field conditions. Whereas this research could be used to identify total plant densities and species proportions to be evaluated, field experiments on oat and field pea densities that optimize intercrop advantage are still needed since stand density in a greenhouse pot study is not necessarily the same as density in the field.

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