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Effect of seed rate on the seed yields in wheat/faba bean intercropping system: a competition approach

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Abstract

Five experiments agronomically managed differently investigated yield-density relationships in wheat /faba bean (bean) intercropping system. For the wheat sole crop, seed yield (SY) ranged from 102 g/m^2 to 734 g/m^2. Intercropping reduced wheat SY but this did not always depend on wheat seed rate (wsr). Standard intra-specific and/or inter-specific yield-density equations derived from the literature and others modified here were used to quantify the SYs (as was applicable). For the majority of the experiments wheat SYs, whether sole cropped or intercropped responded asymptotically as wsr increased. The maximum bean sole crop SY was 392 g/m^2: bean SY declined as wsr increased. The total intercrop (wheat + bean) SY response to wsr was asymptotic in at least two of the experiments, following similar pattern as the wheat. Although, for the mean effects of intercropping the total intercrop SYs was substantial in three experiments; the total intercrop did not produce significantly greater SY than the wheat sole crop as wsr increased. Moreover, maximum wheat sole crop and wheat intercrop SYs were significantly greater under the organically-managed experiment than the conventional-managed one, even though they were both established in the same cropping year. Similarly, as regards wheat SYs, comparisons of spring-sown with the winter-sown crops established in the same cropping year indicate that the former performed better than the latter. Nevertheless, for most of the experiments investigated here, this research indicates that 100-wheat seeds/m^2 or lower may be appropriate to intercrop with bean at 30 to 40-bean seeds/m^2 to reduce competition and improve productivity.

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Introduction

In the United Kingdom (UK), wheat (Triticum aestivum L.) and faba bean (bean; *Vicia faba* L.) are the most important cereal and pulse crops respectively

(Nix, 2009; Yahuza, 2011a). For wheat/bean intercrop combinations, the benefit of intercropping compare to sole cropping was demonstrated in the UK and elsewhere previously (Ghanbari-Bonjar and Lee, 2002; Pristeri *et al.,* 2006), but the seed yields (SY) response to plant population density (p) or seed rate (sr) have rarely been analysed using competition approaches (Helenius and Jokinen, 1994 ; Park *et al.,* 2002). In any case, given the deficiency of analyses of variance procedure in some cases (Yahuza, 2011b), such analyses are more efficient when meaningful yield-density equations (YDE) (Willey and Heath, 1969; Neumann *et al.,* 2009) are applied. In addition, though both Wright (1981) and Dolman (1985) have made substantial contributions as regards developing inter-specific YDE for application to intercropping; to date no one has applied these equations in quantifying SY in wheat/bean intercropping system. Similarly, Counce (1987) proposed a simple equation for determining the optimum sr in situation where the yield response to density is asymptotic (Mligo and Craufurd, 2007), but the equation has rarely been applied widely even under sole cropping. From the foregoing, it is obvious that for wheat/bean intercrop combination, SY competition analyses based on the application of YDE approaches has rarely been carried out previously. Thus, there is a need to compare the SY of this intercrop combination based on competition approach using both the intra-specific (Bleasdale, 1984) and the inter-specific YDEs (Park *et al.,* 2002).

Moreover, though wheat/bean intercropping system had been studied under conventional (Hongo, 1995; Haymes and Lee, 1999) and organic (Bulson, 1991; Gooding et al., 2007) management systems, the SYs of this intercrop combination under these contrasting management conditions were not compared in the same study in the same season. Yield-density relationships (Shirtliffe and Johnston, 2002) may be different for wheat/bean intercrop between the two systems given that under organic system synthetic inputs such as fertilizers and pesticides are not allowed (Stolze and Lampkin, 2009). Therefore, it is necessary to compare the SYs of wheat/bean intercropping system in response to sr under both the conventional and organic systems and for the crop that is grown in the same season. In addition, though a few studies had compared winter-sown with the spring-sown wheat/bean intercrop previously (Bulson *et al.,* 1997; Haymes and Lee, 1999; Gooding *et al.,* 2007), the Sys were rarely analysed using the competition approaches in those investigations. Thus, further investigations on the effects of sr on the SY of this intercrop combinations based on competition analyses under the two seasons are necessary.

Irrespective of cropping system involved and/or sowing season, it is well documented that intercropping reduces SY (Hongo, 1995; Pristeri *et al.,* 2006). Hence, the recommended sr for the sole crop may not be applicable to the intercrops. For wheat/bean intercrop, such yield losses had been reported in both conventional (Haymes and Lee, 1999) and organic systems (Bulson *et al.,* 1997). Similarly, for this intercrop combination, it had been reported that intercropping reduced SY of the two component crops irrespective of season of sowing (Bulson *et al.,* 1997; Haymes and Lee, 1999). However, most previous studies have rarely presented detailed data on such yield losses due to intercropping. Consequently, there is a need to investigate the yield losses and/or facilitations due to intercropping as may be influenced by different management conditions.

This investigation was carried out with the following objectives. i. To quantify SY response to sr using the competition approach (es). ii. To compare SYs in response to sr across the experiments and/or cropping years. iii. To compare SYs as is influenced by sr and cropping system (organic versus conventional). iv. To compare SYs as is influenced by sr and sowing season (spring-sowing versus winter-sowing). v. To give estimates of SYs losses and/or facilitations due to intercropping.

Materials and methods

Study area

All the experiments reported in this paper were carried out at the University of Reading's Crop Research Unit, Sonning, Berkshire, UK (0^{o} 56ʹ W, 51^{o} 27ʹ N). The long-term mean monthly rainfall, solar radiation and temperature for the site ranges from 40.1-67.3 mm, 2-17.5 MJ/m²/day and 5.1-17.3 °C respectively (Yahuza, 2012a; Table 1). The study location had a land area of 10 hectares (ha), with a portion (2.5 ha) that is not a certified organic field (*sensu stricto* organic) but since 2001 had been managed organically (Yahuza, 2012a). The soil at the experimental field had been categorized as a free-draining sandy-loam of Sonning Series (Gooding *et al.,* 2002). For the purpose of these investigations, each cropping year soil samples were taken at the end of February at random locations in the field using a using a soil corer. Soils were collected from 0-90 cm depth. Samples were then bulked and analyzed for pH, phosphorus (P), potassium (K), magnesium (Mg), available nitrogen (N) and sulphate (Table 2).

Experimental design, treatments and crop management

Experiment 1 (autumn-sown conventional experiment 2005-2006) was a complete factorial combination of five wheat seed rate (wsr) (0, 10, 50,100,200 seeds/m²) with or without 40 seeds/m² of bean randomized in four blocks with wsr as the main plot factor and bean treatment as the split-plot factor. Experiment 2 (autumn-sown organic experiment 2005-2006), was similar to Experiment 1 in design, except that this experiment was managed organically. However, in addition, the two experiments were further complicated by sulphur treatment as was detailed in Yahuza (2012a). Other details regarding the design, treatments and crop management of Experiments 1 and 2 were presented in Yahuza (2012a). However, unlike in Yahuza (2012a), for each of the two experiments, here the effects of sulphur were blocked.

Experiment 3 consist of spring wheat (cv. Paragon) sr (0, 30, 75, 200, 400 and 650) seeds/m² with or without 40 seeds/m² spring bean (cv. Hobbit) randomized in four blocks in a split-plot with wsr as the main plot and the bean treatment as the subplot factor. Other details regarding this experiment were presented in Yahuza (2012b). Experiment 4 consist of five wheat (cv Mallaca) sr (0, 25, 75, 150, 400 seeds/m²) with or without 30 seeds/m² bean (cv Clipper) treatment as affected by three bean sowing dates (BSD; Yahuza, 2012c). Other details regarding this experiment were presented in Yahuza (2012c). However, unlike in Yahuza (2012c), here means presented are averages across the 3 BSD.

Experiment 5 was based on a conventional response surface design (RSD) (Neuman *et al.,* 2009), and was laid down in a randomized complete block design. The experiment consists of complete factorial combination of five wheat (cv. Mallaca) sr (0, 25, 100, 200, 400 wheat seeds/m²) and five bean (cv. Clipper) sr (0, 5, 20, 40, 80 bean seeds/ m²) randomized in 3 bocks with a total of 25 plots in each block measuring 10m x 2m. The experiment was drilled on 6 November 2007 and rolled on 7 November 2007. Both bean and wheat were sown on the same row in contrast to the earlier experiments. On 7 November 2007 the experiment was sprayed with BASF 'claymore' (pendimethalin) at a rate of 3.3 litres per ha in 200 litres of water. On 8 April 2008, Folicur (tebuconazole) was applied at 1 litre per ha, Cleancrop (fenpropimorph) at 1 litre per ha and Clortosip (chlorothalonil) at 2 litres per ha all in 210 litres per ha of water. The application were made with nozzles arranged on hand-held booms under 200-250 Pa pressure which produced a spray of medium droplet size. Similarly, on 23 March 2008, at GS 30 (Zadoks *et al.,* 1974), 348 kg/ha, Nitram (ammonium nitrate granules, (34.5%N)) was applied per hectare. This was equivalent to 120 kg of N per ha.

For each of the Experiments 1, 2, 3 and 5 the final harvest was carried out with a combine harvester (Wintersteiger Nursery Master Elite, Inkreis, Austria). The central 1.25m of each plot was harvested. Both wheat and bean were harvested simultaneously. The two outer rows and the destructive sampling areas were left as discards. The length of the harvested plot was then measured. Details for Experiments 1 and 2, and 3 were presented in Yahuza (2012a) and Yahuza (2012b) respectively. In Experiment 5, the final harvest was delayed until 17 September 2008 because the summer for that year was very wet with rains falling almost every 2-3 days (Table 1). The approximate harvested area was 1.25m x 7m per plot. On the other hand, Experiment 4 was hand harvested as detailed in Yahuza (2012c). For all the experiments, wheat and bean SYs were then separated in the laboratory with the aid of different sieves. Later the SYs were adjusted to 15% moisture content.

Statistical analyses

In general, data were analysed using GENSTAT (Genstat 8.1 release, Rothamsted UK). Generally, the following were considered in the analysis of variance (ANOVA). For analysing wheat variables, plots with 0-wheat seeds/m^2 were restricted in the analyses. Similarly, in the case of bean variables, plots with no bean sowing were restricted from the analyses to get the sole and intercrop values. For combined wheat + bean (henceforth to be referred to as total intercrop or total) analyses were done mostly with no restriction. For each of Experiments 1, 2 and 3, the analyses were done using the General ANOVA. The treatment structure was pol (wsr; 3) x bean treatment with all interactions. The block structure was replications/wsr/bean with all interactions. In Experiment 4 similar procedures used for Experiments 1, 2 and 3 were employed, except for the further complication of the BSD factor. The variables was analysed using the General ANOVA with the treatment structure given as pol (wsr; 3) x (bean/BSD). The block structure was replications. This means that the BSD factor was nested within the bean treatment. However, as stated earlier in this paper means presented were averages across the three BSD. The effects of BSD were presented in Yahuza (2012c). In Experiment 5, the analytical procedure differs slightly from that of the previous experiments because the bean seed rate (bsr) was also varied. The variables were analysed using the General ANOVA with the treatment structure given as pol (wsr; 3) x pol (bsr; 3). The block structure was replications.

Regressions mainly using hyperbolic YDE (Willey and Heath, 1969; Bleasdale, 1984; Yahuza, 2011b) were performed across wsr particularly for wheat SYs where the response to wsr deviated from linearity. Hence, for all the data sets for which the regression were performed, the adjusted R^2 was compared with equation 1 to determine whether it fitted better when the response to wsr deviated significantly from linearity.

$$Y = \frac{wsr}{a_w + b_w} \qquad 1$$

In equation 1, Y = yield (g/m^2), a_w and b_w are constants that defines yield per plant in a competition free environment and maximum yield potential of the environment respectively (Willey and Heath, 1969) and wsr refers to the wheat sowing rate (seeds/m^2).

Where equation 1 holds, Counce (1987) proposed that it is possible to determine 99% of the predicted yield (optimum yield) at the maximum density of an experiment using equation 2.

$$wsr_{crit} = (a_w 0.99 y_{max}) \big/ (c - b_w 0.99 y_{max}) \qquad 2$$

In equation 2, c is a unit dependent constant (c = 1 when yield and density are expressed on the same area basis), a_w and b_w are as defined in equations 1, y_{max} (for an experiment with an asymptotic response to wsr) is predicted yield at the maximum wheat seed rate, wsr_{crit} is population at $0.99y_{max}$.

However, besides applying more complicated equations other than equation 1 to quantify the SYs, in some cases new equations were proposed and applied as was detailed in Yahuza (2012b). In addition, for Experiment 5, the inter-specific YDE (Park *et al.,* 2002) were applied to quantify the wheat and total intercrop SYs.

Some abbreviations used in the paper explained

In some cases (particularly in the text) wheat sole crop, wheat intercrop, bean sole crop, bean intercrop and the total intercrop are referred to simply as the WSC, WIC, BSC, BIC and TIC respectively. Similarly, in some cases (particularly in the tables) the actual results are referred to as observed WSC SY (OWSSY), observed WIC SY (OWISY), observed BSC SY (OBSSY), observed BIC SY (OBISY) or simply observed SY (OSY). Other terms associated with the results includes OSY reductions due to intercropping (OSYR), percentage of OSY reduction due to intercropping (OSYR %), observed wheat SY reductions due to intercropping (OWSYR), percentage of OWSYR (OWSYR %), observed bean SY reductions due to intercropping (OBSYR) and percentage of OBSYR (OBSYR %).

As for the results, abbreviations used for fitted yields (particularly in the tables) include fitted WSC SY (FWSSY), fitted WIC SY (FWISY), seed yields simultaneously fitted using equations 3, 1 and 4 (FSY), fitted BSC SY (FBSSY), and fitted BIC SY (FBISY). Other terms associated with fitted values includes fitted wheat SY reductions due to intercropping (FWSYR), percentage of FWSYR (FWSYR %), fitted bean seed yields reductions due to intercropping (FBSYR), percentage of FBSYR (FBSYR%), fitted seed yields reduction due to intercropping (FSYR) and percentage of FSYR (FSYR %).

Results

Weather data

Weather data during the growing period for Experiments 1 and 2 were discussed in Yahuza (2012a). Since Experiment 3, though spring-sown, was established in the same cropping year as Experiments 1 and 2, with the details given for this experiment in Yahuza (2012b), the weather data can be easily deduced in Yahuza (2012a). On the other hand, the weather data for Experiment 4 was presented in Yahuza (2012c). During the growing season for Experiment 5 the mean air monthly temperatures particularly during winter (Table 1) was comparatively greater than the 37-year long-term average for the site (Yahuza, 2012a). Compared to the long-term average for the site (Yahuza, 2012a), there was no definite pattern of rainfall received over the growing season. Although the mean monthly rainfall obtained was mostly greater than that of the 47-year long-term average for the site (Yahuza, 2012a), occasionally lower values were obtained (Table 1). However, the mean monthly solar radiations received (Table 1), were mostly similar to the long-term average for the site (Yahuza, 2012a). Despite the fact that the weather data for Experiments 1, 2, 3 and 4 were not repeated here, it is possible to make comparison across the experiments/cropping years with the data presented elsewhere (Yahuza, 2012a; b; c).

Seed yields for experiment 1 (conventionally managed, 2005-2006)

In Experiment 1, as wsr was increased so did WSC SY increase (P = 0.004 for quadratic effect) up to a maximum level even though asymptote does not appear to be reached (Fig. 1). For the WSC SY, equation 1 was fitted (Fig. 1), the predicted asymptotic yield for WSC SY (i.e. $1/b_w$) was 604 g/m² but the observed maximum yield was 490 g/m² obtained at 200-wheat seeds/m². The parameter values for quantifying yields using equation 1 were presented in Yahuza (2012b). Note that for OWSSY there was no significant difference with 425 g/m² SY obtained at 100-wheat seeds/m². The disparity between the predicted asymptotic yield and the maximum OWSSY suggests that yields may be described using a simpler equation. However, given the significant deviation from linearity as indicated by ANOVA outputs, the curvilinear response was found to be more appropriate. Hence, the application of equation 1 was justified. Using equation 2, the optimum sr for the WSC was determined as 189-wheat seeds/m².

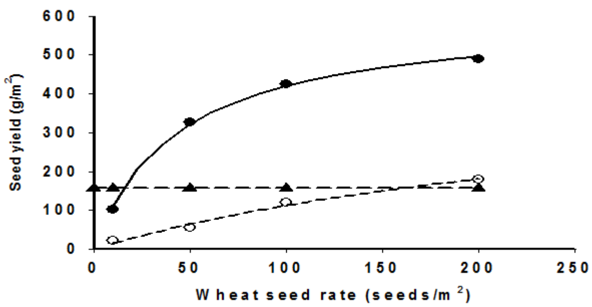

Fig. 1. Effect of wheat seed rate (wsr) on the seed yields for winter wheat (cv. Mallaca) sole crop ● (solid curve), wheat intercrop ○ (broken curve) and mean winter faba bean (cv Clipper) averaged across wsr ▲ (broken line) for Experiment 1. For the beans, see Table 4 for mean SY at each wsr. The fitted equations are described in the text.

Averaged across wsr intercropping significantly reduced wheat SY ($P < 0.001$). For the mean effect of bean treatment, wheat SY were 336 g/m² and 94 g/m² for the 0 bean seeds/m² and 40 bean seeds/m² respectively (SED = 22.3, DF = 12; Table 3). As was the case with the WSC, wheat intercrop SY increases with increase in wsr. There was an interactive effect of wsr and intercropping ($P = 0.024$ for quadratic wsr x bean treatment). Equation 1 quantified WIC SY (Fig. 1), and further details were provided in Yahuza (2012b). Intercropping decreased the predicted asymptotic yield to 450 g/m². From 50 wheat seeds/m² or more WSC significantly produced more SY than the intercrops as wsr increased. The maximum WIC SY of 179 g/m² obtained at 200-wheat seeds/m² combinations was lower than the predicted value. Note that there was no significant difference between the maximum WIC SY and the 120 g/m² WIC SY obtained at 100-wheat seeds/m². Compared at each level, intercropping reduced wheat SY by as much as 311 g/m² as wsr increased. This was equivalent to wheat SY decline of about 63 % at 200-wheat seeds/m² (Table 3). See the materials and methods for explanation on the abbreviations used in Table 3 and all the subsequent tables presented in the paper. The disparity between the observed maximum WIC SY and the predicted asymptotic SY was as explained earlier. The optimal wsr for the wheat intercrop was determined as 197-wheat seeds/m².

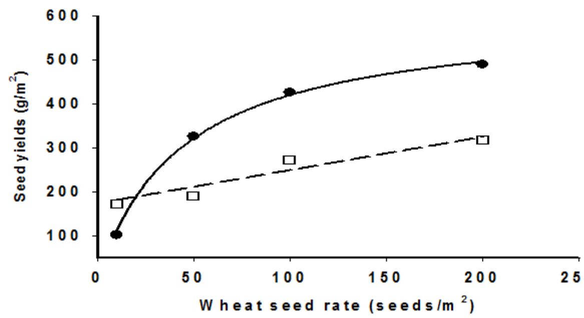

Fig. 2. Effect of wheat seed rate (wsr) on the seed yields for winter wheat (cv. Mallaca) sole crop ● (solid curve) and the total intercrop seed yield □ (broken line) for Experiment 1. The fitted equations are described in the text. Bean sole crop seed yield = 208 g/m² at 40 bean seeds/m².

For Experiment 1, the bean sole crop SY was 208 g/m² at 40-bean seeds/m². Intercropping reduced (but not significantly) bean SY by as much as 72 g/m². This corresponds to 35 % decline in yield (Table 4). However, wsr did not had significant effect ($P = 0.271$) on bean SY (SED 34.1, DF 12). Mean bean SY averaged across wsr was 157 g/m² (i.e. for both the sole crop and intercrops; Fig. 1).

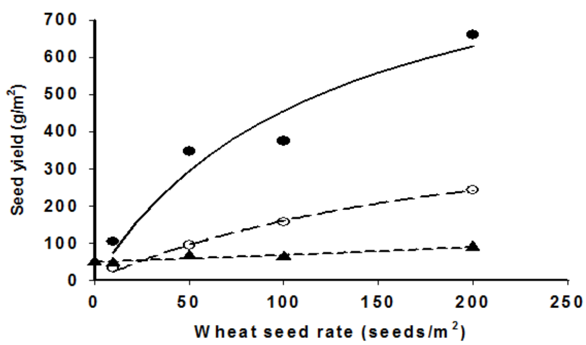

Fig. 3. Effect of wheat seed rate (wsr) on winter wheat (cv. Mallaca) sole crop ● (solid curve), wheat intercrop ○ (broken curve) and winter faba bean (cv Clipper) ▲ (broken line) seed yields for Experiment 2. The fitted equations are described in the text.

In Experiment 1, as was the case with the wheat SY, the total intercrop SY increased with increase in wsr ($P < 0.001$ for quadratic wsr) but the asymptote was not reached (Fig. 2). The effect of bean treatment was also significant ($P = 0.010$), as well as the interactive effect of wsr and bean treatment for quadratic x intercropping ($P < 0.001$) and cubic x intercropping ($P = 0.003$). Averaged across wsr, for the mean effects of intercropping, WSC SY were significantly greater than intercrop SY. Mean SY were 268. 4 g/m^2 and 232. 4 g/m^2 for 0 and 40 bean seeds/m^2 respectively (SED 12. 26, DF 15). Similarly, as shown in Fig. 2 the TIC SY increases linearly with increase in wsr and was quantified as Y = 172.9 + 0.76 wsr ($r^2 = 0.92$). Fig. 2 also indicates that the WSC SY was significantly greater than the TIC SY across wsr, except at 10-wheat seeds/m^2 where the TIC SY was greater. The maximum TIC SY of 317.7g/m^2 was obtained at 200-wheat seeds/m^2. At this intercrop combination, wheat contributed more SY than the bean, suggesting that wheat was more competitive than the bean. However, there was no significant difference between the maximum TIC SY with the 272.9 g/m^2 SY obtained at 100 wheat seeds/m^2. Note that the maximum WSC SY (489.5 g/m^2 at 200 wheat seeds/m^2) and the maximum TIC SY (317.7g/m^2) were significantly greater than the 208 g/m^2 BSC SY, for the interactive effects of wsr and bean treatment.

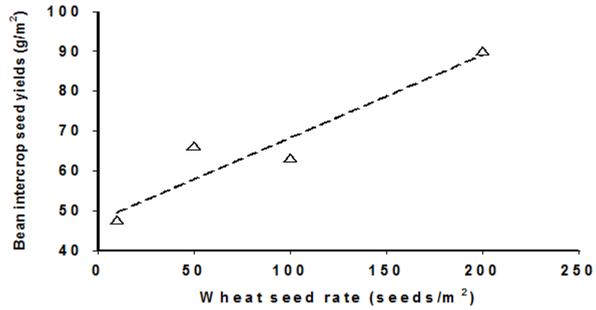

Fig. 4. Effect of wheat seed rate on winter faba bean (cv Clipper) Δ (broken line) seed yields for Experiment 2. The fitted equation is described in the text.

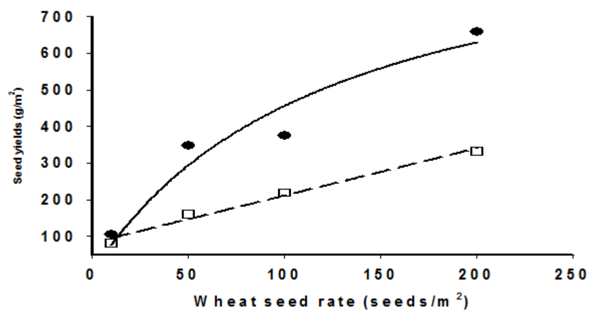

Fig. 5. Effect of wheat seed rate (wsr) on the seed yields for winter wheat (cv. Mallaca) sole crop ● (solid curve) and the total intercrop seed yield □ (broken line) for Experiment 2. The fitted equations are described in the text.

Seed yields for experiment 2 (organically managed, 2005-2006)

In Experiment 2, wheat SY increased with increase in sr ($P < 0.001$ for linear wsr). Averaged across wsr, the mean effect of bean treatment was significant ($P < 0.001$). An interactive effect for linear wsr and bean treatment was found ($P < 0.001$). Averaged across wsr, mean wheat SYs were 372 g/m^2 and 132 g/m^2 for 0 and 40 bean seeds/m^2 respectively (SED 23. 1, DF 12; Table 5). Equation 1 quantified the response of WSC SY to wsr (Fig. 3), and further details were given elsewhere (Yahuza, 2012b). The predicted asymptote of the WSC SY was 1016 g/m^2 with an optimal sr (based on equation 2) of 194-wheat seeds/m^2. However, the observed maximum WSC SY of 660 g/m² obtained at 200-wheat seeds/m² was lower.

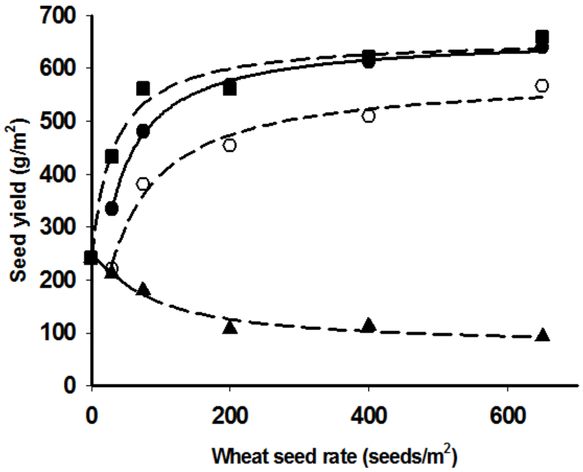

Fig. 6. Effect of wheat seed rate (wsr) on spring wheat (cv. Paragon) sole crop ● (solid curve), wheat intercrop ○ (broken curve), spring faba bean (cv Hobbit) ▲ (broken curve) and the total (i.e. including plots with 0 wsr) ■ (broken curve) seed yield for Experiment 3. The fitted equations and parameter values are given in the text.

Similar trend as demonstrated in Experiment 1, was found in Experiment 2, From 50 wheat seeds/m² onwards WSC significantly produced more SY than the intercrop as wsr increased (Fig. 3). Equation 1 quantified the response of the WIC SY to wsr (Fig. 3), and details were provided earlier (Yahuza, 2012b). Intercropping decreased the predicted asymptotic yield for the wheat to 489 g/m² but increased the optimum sr (based on equation 2) needed slightly to 196 wheat seeds/m². However, the observed maximum WIC SY of 243 g/m² was obtained at 200-wheat seeds/m². Note that there was no significant difference between the 157 g/m² WIC SY obtained at 100-wheat seeds/m² with the maximum value observed. However, intercropping reduced wheat SY by as much as 417 g/m² at 200-wheat seeds/m². This was equivalent to wheat SY decline of about 63 % (Table 5).

Table 3. OWSSY, FWSSY, OWISY, FWISY, OWSYR, FWSYR, OWSYR % and FWSYR %) for Experiment 1.

Wheat seed rate (seeds/m²)	OWSSY (g/m²)	FWSSY (g/m²)	OWISY (g/m²)	FWISY (g/m²)	OWSYR (g/m²)	FWSYR (g/m²)	OWSYR (%)	FWSYR (%)
10	102	112	22	15	80	97	78	87
50	326	321	55	65	271	257	83	80
100	425	420	120	113	305	307	71	73
200	490	495	179	181	311	315	63	64

For each of the wheat sole crop and intercrops, equation 1 was used to quantify the data.

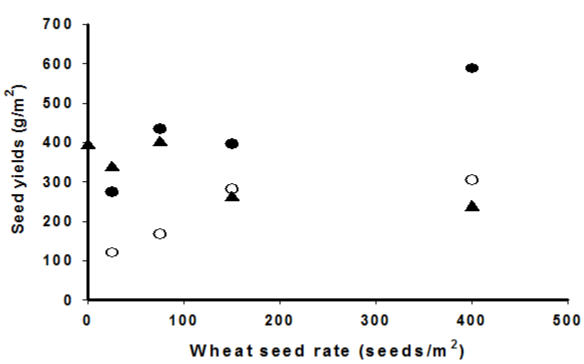

Fig. 7. Effect of wheat seed rate on winter wheat (cv. Mallaca) sole crop ●, wheat intercrop ○, and winter faba bean (cv Clipper) ▲ seed yields for Experiment 4.

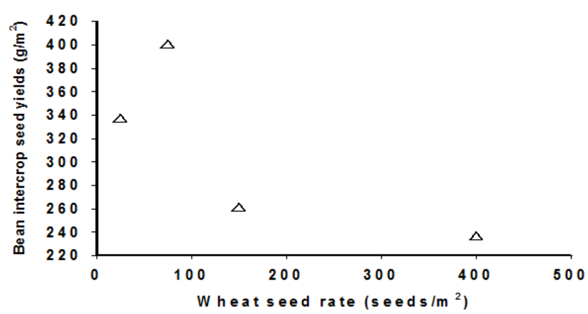

Fig. 8. Effect of wheat seed rate on winter faba bean (cv Clipper) Δ seed yields for Experiment 4.

The BSC did not out-yield the BIC substantially and yield increases (P = 0.035) as wsr increased (Fig. 3). Bean sole crop SY was 49 g/m^2 at 40-bean seeds/m^2. Compared to the SY obtained at 10-wheat seeds/m^2, yield was significantly greater at 200-wheat seeds/m^2. The maximum BIC SY of 89.8 g/m^2 was obtained at 200-wheat seeds m^2 (SED 19.49, DF 12). Further analysis showed that bean intercrop SY increases with increase in wsr and was quantified as Y = 47.4 + 0.208 wsr (Fig. 4), r^2 = 0.89. Due to attack of the bean by chocolate spot disease (*Botrytis fabae*; data not presented), the BIC out-yielded the BSC as can be seen by the negative values in Table 6. Thus, intercropping facilitated more bean SY by as much as 41 g/m^2. This was equivalent to 84 % increase in yield (Table 6).

Table 4. OBSSY, OBISY, OBSYR and OBSYR % for Experiment 1.

Wheat seed rate (seeds/m^2)	OBSSY (g/m^2)	OBISY (g/m^2)	OBSYR (g/m^2)	OBSYR (%)
10	208	151	57	27
50		136	72	35
100		153	55	26
200		139	69	33

Note that bean seed yield did not differ significantly. See Figures 1 and 2 for mean value across wsr.

In Experiment 2 the TIC SY increase with increase in wsr (P = 0.031 for quadratic wsr).The effect of bean treatment was also highly significant (P < 0.001) and the interactive effects with wsr deviated from linearity (P = 0.031 for cubic x bean treatment). Averaged across wsr, WSC significantly out-yielded the total intercrop. Mean SYs were 297.2 g/m^2 and 168.9 g/m^2 for 0 and 40 bean seeds /m^2 respectively (SED 18.42, DF 15). For the interactive effects, the WSC significantly out-yielded the TIC from 50-wheat seeds/m^2 or more (Fig. 5). The maximum TIC SY of 332 g/m^2 was obtained at 200-wheat seeds/m^2. This was significantly greater than SY obtained at the lower wsr. As was the case in Experiment 1, at this intercrop combination, wheat contributed greater SY than the bean, suggesting that wheat was more competitive than the bean. Fig. 5 showed that the total intercrop SY increases linearly with increase in wsr and was quantified as Y = 81.8 + 1.29 wsr, (r^2 = 0.98).

Table 5. OWSSY, FWSSY, OWISY, FWISY, OWSYR, FWSYR, OWSYR %) FWSYR% for Experiment 2.

Wheat seed rate (seeds/m^2)	OWSY (g/m^2)	FWSY (g/m^2)	OWISY (g/m^2)	FWISY (g/m^2)	OWSYR (g/m^2)	FWSYR (g/m^2)	OWSYR (%)	FWSYR (%)
10	104	77	34	23	70	54	67	70
50	347	294	95	96	252	198	73	67
100	375	456	157	160	218	295	58	65
200	660	630	243	241	417	388	63	62

For both the wheat sole crop and intercrops equation 1 described the data satisfactorily.

Table 6. OBSSY, FBSSY, OBISY, FBISY, OBSYR, FBSYR, OBSYR % and FBSYR% for Experiment 2.

Wheat seed rate	OBSSY (g/m^2)	FBSSY (g/m^2)	OBISY (g/m^2)	FBISY (g/m^2)	OBSYR (g/m^2)	FBSYR (g/m^2)	OBSYR (%)	FBSYR (%)

(seeds/m²)								
10	49	49	47	49	2	-1	3	-1
50			66	58	-17	-9	-35	-18
100			63	68	-14	-19	-29	-40
200			90	89	-41	-40	-84	-82

The negatives values seen indicate that the bean intercrop out-yielded the bean sole crop.

Seed yields for experiment 3 (spring-sown conventionally managed, 2006)

In Experiment 3, wheat SY increased with sr ($P < 0.001$ for quadratic wsr). Averaged across wsr, for the mean effect of intercropping, wheat SY was significantly reduced ($P < 0.001$). Mean SYs were 526.7 g/m² and 425.6 g/m² for 0 and 40 bean seeds/m² respectively (SED 13.01, DF 15). For the interaction of wsr and bean treatment, the observed maximum WSC SY was 639 g/m² at 650-wheat seeds/m². Note that there was no significant difference between the maximum SY obtained with yields obtained at 400 and 200-wheat seeds/m² each. Equation 1 quantified the response of WSC SY well (Fig. 6), and details were given in Yahuza (2012b). For the WSC, the predicted asymptotic yield was determined as 660 g/m² with an optimal wsr (based on equation 2) of 526-wheat seeds/m². This indicates that equation 1 applied had satisfactorily described wheat SY for this experiment, which was spring-sown. The total intercrops (plus bean sole crop), wheat intercrop, and bean intercrop SY responses were quantified simultaneously using equations 3, 1 and 4 respectively (Fig. 6).

For Experiment 3, equation 3 describes total yields in response to wsr well.

$$Y = y_o + \left(\frac{wsr}{a_{wt} + b_{wt} wsr} \right) \quad 3$$

Whilst bean yield was quantified using equation 4

$$Y = \left(y_o + \left(\frac{wsr}{aw_t + bw_t wsr} \right) \right) - \left(\frac{wsr}{aw_i + bw_i wsr} \right)$$

4

In equations 3 and 4, Y = yields (g/m²), y_o refers to bean sole crop yield (g/m²). a_w and b_w are constants such that $1/a_w$ represents yield per plant in a competition free environment, $y_o + (1/b_w)$ represents the predicted asymptotic (maximum) yield and wsr refers to wheat sowing rate (seeds/m²). The subscript t and i are used to distinguish parameter that refers to the total intercrop (t) from that referring to wheat intercrop (i).

Table 7. Parameter values and standard errors (s.e) for the simultaneous fits of equations 3, 1 and 4 to the total intercrop (plus bean sole crop), wheat intercrop and bean intercrop seed yields for the spring sown experiment (Experiment 3).

Parameter	estimate	s.e.
y_o	240.8	14.4
a_{wt}	0.0776	0.0138
b_{wt}	0.002405	0.000111
a_{wi}	0.08009	0.00785
b_{wi}	.0017124	0000459

Where y_o = bean sole crop seed yield (g/m²), the additional subscripts t and i defines the parameters that refers to the total intercrop and wheat intercrop respectively (see the text for details).

Further details regarding the simultaneous fits of these equations to quantify SY for experiment 3 were provided in Yahuza (2012b). However, for clarity parameter estimates are repeated here (Table 7). The predicted WIC SY was determined as 584 g/m². The observed maximum WIC SY of 566.10 g/m² was obtained at 650-wheat seeds/m² (Fig. 6). This indicates that the equations applied had satisfactorily described the data. Wheat SY decline due to intercropping was lesser in this experiment compared to the previous experiments. For instance, at 650-wheat seeds/m², intercropping reduced wheat SY by only 73 g/m². This was equivalent to 11 % reduction in WIC SY compared to the WSC (Table 8).

Bean SY decreases as wsr increased (Fig. 6). The bean SY response to wsr was curvilinear ($P < 0.001$ quadratic wsr). The BSC SY of 241g/m² was obtained at 40-bean seeds/m². Compared to the BSC, intercropping reduced yield from 75-wheat seeds/m² or more. The maximum BIC SY of 211.60 g/m² was obtained at 30-wheat seeds/m². This was significantly greater than bean SY obtained at higher wsr (SED 17.13, DF 15). Note that the maximum BIC SY did not differ significantly with SY obtained at 75-wheat seeds/m². The BIC SY was quantified initially as $Y = 211.6 - 0.49\ wsr + 0.0005\ wsr^2$, $r^2 = 0.87$. However, further analyses indicate that equation 4 quantified BIC SY responses better (Fig. 6). The parameter values are presented in Table 7. Intercropping reduced bean SY by as much as 148 g/m². This was equivalent to 62 % (Table 9).

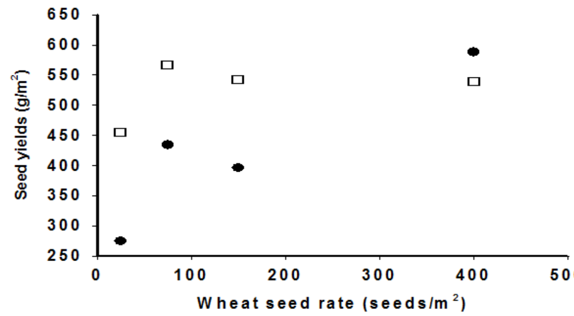

Fig. 9. Effect of wheat seed rate (wsr) on the seed yields for winter wheat (cv. Mallaca) sole crop ● and the total intercrop seed yield □ for Experiment 4.

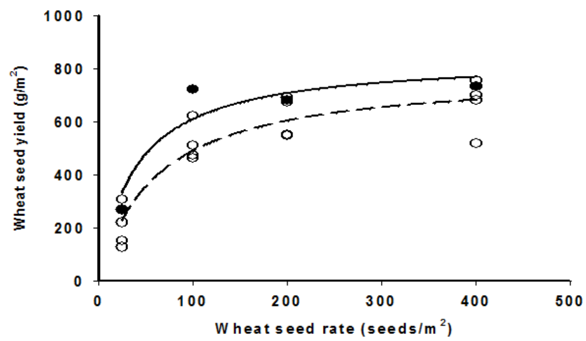

Fig. 10. Effect of wide ranges of wheat seed rate (seeds/m²) on winter wheat (cv. Mallaca) sole crop ● (solid curve) and wheat intercrop ○ (broken curve) seed yield for Experiment 5. Equation 1 quantified the data for each of wheat sole crop and intercrop, and the parameter values for the wheat sole crop are presented in the text while that for the intercrop are given in Table 12.

Table 8. OSY, FSY, OWSSY, FWSSY, OSYR, FSYR, OSYR% and FSYR % for Experiment 3.

Wheat seed rate (seeds/m²)	OSY (g/m²)	FSY (g/m²)	Remarks	OWSSY (g/m²)	FWSSY (g/m²)	OSYR (g/m²)	FSYR (g/m²)	OSYR (%)	FSYR (%)
0	241	241	BSSY						
30	432	441	TISY						
75	561	532	TISY						
200	560	599	TISY						
400	622	626	TISY						
650	659	637	TISY						
30	221	228	WISY	334	335	113	106	34	31
75	380	360	WISY	481	475	100	116	21	24
200	453	473	WISY	568	576	115	103	20	18

400	508	523	WISY	613	615	104	93	17	15
650	566	545	WISY	639	631	72.6	87	11	14
0	241	241	BSSY						
30	212	213	BISY			29.4	27.8	12	12
75	181	172	BISY			60.5	68.9	25	29
200	107	126	BISY			134.2	115.3	56	48
400	114	103	BISY			127.5	138.1	53	57
650	93	92	BISY			148.1	148.7	61	62

BSSY= Bean sole crop seed yields, TISY = Total intercrop seed yields, WISY = Wheat intercrop seed yields and BISY = Bean intercrop seed yields. See the text for fitted equations.

In Experiment 3, the TIC SY increases as wsr increased ($P < 0.001$ for quadratic wsr). The effect of intercropping was significant ($P < 0.001$) and this interacted significantly with the wsr ($P < 0.001$ for quadratic wsr x bean treatment). Averaged across wsr, for the mean effect of bean treatment SYs were 439 g/m^2 and 512.4 g/m^2 for 0 and 40-bean seeds/m^2 respectively (SED 11.22, DF 18). For the interaction of wsr and bean treatment, the TIC out-yielded the WSC significantly at 30 and 75- wheat seeds/m^2 each. Although the TIC SY was also greater than BSC, at 200-wheat seeds/m^2 or more, there was no significant difference between the TIC SY and WSC SY (Fig. 6). However, the maximum TIC SY of 659 g/m^2 was obtained at 650-wheat seeds/m^2. However, this did not differ significantly from the yields obtained at 400 (622 g/m^2) and 75 (560.6 g/m^2) wheat seeds/m^2. Equation 3 described the total SY (plus bean sole crop) and was done simultaneously with the fitting of wheat intercrop SY (see the parameter values in Table 7). The predicted total asymptotic SY was determined as 657 g/m^2 and was defined as $y_o + 1/b_{wt}$. This simplifies to $1/b_{wt}$ if bean sole crop (y_o) was not quantified as discussed previously (Yahuza, 2012b). As was the case in the earlier experiments, wheat contributed greater SY than the bean, suggesting that wheat was more competitive than the bean.

Table 9. OBSSY, FBSSY, OBISY, FBISY, OBSYR, FBSYR, OBSYR % and FBSYR for Experiment 3 .

Wheat seed rate (seeds/m^2)	OBSSY (g/m^2)	FBSSY (g/m^2)	OBISY (g/m^2)	FBISY (g/m^2) based on quadratic function	FBISY (g/m^2) based on equation 4	OBSYR (g/m^2)	FBSYR (g/m^2) based on quadratic function	FBSYR (g/m^2) based on equation 4	OBSYR (%)	FBSYR (%)based on quadratic function	FBSYR (%) based on equation 4
30	241	241	212	197	213	29	44	28	12	18	12
75			181	178	172	61	63	69	29	26	29
200			107	133	126	134	108	115	48	45	48
400			114	94	103	128	147	138	57	61	57
650			93	98	92	148	143	149	62	59	62

Seed yields for experiment 4 (conventionally managed, 2006-2007)

In Experiment 4 averaged across the 3 BSD as wsr increased so did wheat SY ($P < 0.001$). The effects of bean treatment was significant ($P < 0.001$), but there was no significant interactive effect between wsr and intercropping (P > 0.05). Averaged across the bean and BSD, wheat SYs were 158, 234, 311 and 375 g/m² for 25, 75, 150 and 400 wheat seeds/m² respectively (SED 48. 8, DF 30). Averaged across wsr, for the mean effects of bean treatments, wheat SYs were 423 g/m² and 218 g/m² for 0 and 40-bean seeds/m² respectively (SED 39. 8, DF 30). For the interaction of wsr and intercropping, the maximum WSC SY of 588 g/m² was obtained at 400-wheat seeds/m² (Fig. 7). Note that this did not differ significantly from the SY obtained at 75 and 150-wheat seeds/m² (SED 97.5, DF 30). Compared to the maximum WSC SY, intercropping reduced wheat SY significantly at 75 and 400 wheat seeds/m² (Fig. 7; SED 79.6, DF 30). Averaged across bean treatment, the maximum WIC SY was 304 g/m² obtained at 400-wheat seeds/m² (Fig. 7). Note that there was no significant difference between the maximum WIC SY and the SY obtained at 150 and 75-wheat seeds/m² (SED 56.3, DF 30). Given the inconsistent pattern, no equation was used to quantify the WSC and intercrop SYs responses to wsr (Fig. 7). Nevertheless, as was the case in the previous experiments, intercropping reduced wheat SY by as much as 284 g/m² at 400-wheat seeds/m². This was equivalent to 48 % reduction in SY (Table 10).

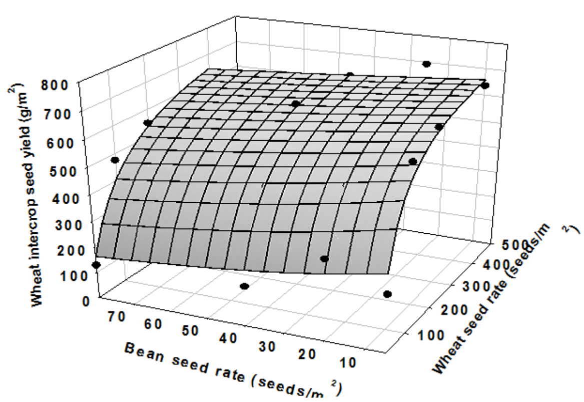

Fig. 11. Effect of wide ranges of wheat and bean seed rates (seeds/m2) on winter wheat (cv Mallaca) intercrop seed yield for Experiment 5. The data was quantified using equation 5 and the parameter values are presented in Table 12. The filled circles are the observed values (results).

Averaged across the BSD, bean SY declined (P = 0.020) with increase in wsr (P = 0.005 linear wsr effects). Bean sole crop SY was 392 g/m² at 30-bean seeds/m² (Fig. 8). Intercropping reduced bean SY at 150 and 400 wheat seeds/m² (Fig. 9; SED 56.6, DF 28). The maximum BIC SY of 400 g/m² was obtained at 75-wheat seeds m². However, the bean intercrop SY was not quantified due to lack of definite pattern (Fig. 8). As for the wheat, intercropping reduced bean SY by as much as 156 g/m². This was equivalent to 40 % decline in SY (Table 11).

Table 10. OWSSY, OWISY, OWSYR and OWSYR % for Experiment 4.

Wheat seed rate (seeds/m²)	OWSY (g/m²)	OWISY (g/m²)	OWSYR (g/m²)	OWSYR (%)
25	274	120	154	56
75	434	167	267	62
150	396	282	114	29
400	588	304	284	48

Note than each mean is an average across 3 BSD.

Table 11. OBSSY, OBISY, OBSYR and OBSYR % for Experiment 4.

Wheat seed rate (seeds/m²)	OBSSY (g/m²)	OBISY (g/m²)	OBSYR (g/m²)	OBSYR (%)
25	392	336	56	14
75		400	-8	-2
150		260	132	34
400		236	156	40

Note than each mean is an average across 3 BSD.

Averaged across the BSD, the response of the TIC SY to wsr deviated from linearity (P = 0.011 for the cubic wsr). The effect of intercropping was highly significant (P < 0.001) and there was interactive effect between wsr and bean treatment (P = 0.003 for linear wsr x bean effects). Averaged across wsr, mean SY were 338 g/m² and 499 g/m² for 0 and 40 bean seeds /m² respectively (SED 37.4, DF 38). Averaged across the

BSD, for the interaction of wsr and intercropping, intercrops yields increases compared to the WSC as wsr increased, except at 400 wheat seeds/m² where the WSC SY was slightly greater (but not significant) (Fig. 9; SED 83.6, DF 38). The maximum TIC SY of 567 g/m² was obtained at 75-wheat seeds/m². Note that there was no significant difference between the TIC SY as wsr increased (Fig. 9; SED 59.1, DF 38; Mean = 526 g/m²). Unlike the earlier experiments, in this experiment, bean contributed more SY than the wheat. This suggests that bean was more competitive than the wheat in the intercrop with respect to SY. However, unlike the other experiments, in this experiment, the SY were estimated from smaller area and were hand harvested.

Seed yields for experiment 5 (conventionally managed, 2007-2008)

In Experiment 5, wheat SY responded positively to increase in wsr ($P < 0.001$ for quadratic wsr). Bean sr had significant effects on wheat SY ($P = 0.004$ for bsr effects). However, no interaction was detected between bsr with the wsr for the response of wheat SY ($P > 0.05$). Averaged across bsr, mean wheat SY were 216, 559, 630 and 678 g/m² for 25, 100, 200 and 400-wheat seeds/m² respectively (SED 40. 9, DF 37). Note that there was no significant difference between SY obtained at 400-wheat seeds/m² from that at 200-wheat seeds/m². Similarly, averaged across wsr mean wheat SY were 603, 555, 532, 497 and 418 g/m² for 0, 5, 20, 40 and 80-bean seeds/m² respectively (SED 45.7, DF 37). Compared to the yields at 0 bean seeds/m², intercropping reduced SY significantly when bsr was increased up to 40 bean seeds/m² or more. The maximum mean wheat intercrop SY of 555 g/m² was obtained at 5-bean seeds/m². However, this did not differ significantly from yields obtained at 20 and 40-bean seeds/m².

For the response of wheat SY to the interactive effect of wsr and bsr, equation 1 quantified the response of WSC SY (Fig. 10). The coefficient of determination was 81.1%. The parameter values for the fit for the WSC are a_w (estimate 0.0447 s.e 0.021) and b_w (estimate 0.001188 s.e 0.000158). The predicted asymptotic yield for WSC was determined as 841 g/m². However, the observed maximum WSC SY was 734 g/m² obtained at 400-wheat seeds/m². Based on equation 2, the optimal wsr for the WSC was determined as 358-wheat seeds/m². Similarly, for the WIC, SY increase with increase in wsr up to a maximum level before it plateaud (Fig. 10 and 11). Bean sr had lesser impact on the wheat SY (Fig. 11). In general wheat SY increased with increase in wsr, therefore yields were greater at the higher sr compared to the lower ones (Fig. 10). Although the WSC out-yielded the WIC, exceptions exist (SED 91.4, DF 37). For instance, at 400-wheat seeds/m² whilst WSC SY was 734 g/m², WIC SY was slightly greater reaching up to 755 g/m² at 400-wheat seeds/m²/ 20-bean seeds/m² combinations.

Table 12. Estimated parameter values and standard errors (in bracket) for the various equations fitted to the wheat intercrop seed yield to show that equation 5 described the data better than other equations for Experiment 5.

Fitted equation (s)	Parameters estimates and standard errors (in bracket)			Coefficient of determination (%)
1	a_w	b_w		
	0.0759 (0.0161)	0.0012727 (0.0000977)		83.6
5	a_w	b_w	c_w	
	0.0490 (0.0139)	0.0012521 (0.0000775)	0.000920 (0.000356)	89.2

6	a_w	b_w	c_w	d_w	
	0.0590 (0.0179)	0.001167 (0.000113)	0.000515 (0.000539)	0.00000309 (0.00000317)	89.3

See the text for details on each of the equations and the meaning of the parameters.

Initially, equation 1 quantified the response of the WIC SY (Fig. 10). The parameter values for the fits to the WIC SY are presented in Table 12. The predicted asymptotic yield for the WIC SY based on equation 1 was given as 786 g/m². However, the inter-specific asymptotic equation (equation 5) proposed by Wright (1981) explained more variation in yield than equation 1 (that is based on intra-specific competition) whilst equation 6 (a modification of equation 5) proposed by Dolman (1985) gave a poorer fit to the data.

$$Y = wsr \big/ \left(a_w + b_w wsr + c_{wb} bsr\right) \qquad 5$$

Where wsr and bsr refers to wheat and bean srs respectively, c_{wb} is a parameter to describe the effect of increasing bsr on wheat and a_w and b_w are as defined previously in equations 1.

$$Y = wsr \big/ \left(a_b + b_w wsr + c_{wb} bsr + d_{wb} wsr\ bsr\right) \qquad 6$$

Where d_{wb}wsrbsr is a parameters to describe the effects of separate effect of bsr and wsr respectively at each density of the other component in the intercrop on yield. All other constants are as defined in equations 1 and /or 5.

Fig. 11 illustrates the asymptotic increase in wheat SY as the wheat and bean sr increased. Using equation 5 the predicted asymptotic yield for WIC was reduced to 460 g/m² suggesting that using equation 1 was an over simplification of the competition within the intercrop. Based on equation 2, the predicted WIC optimal sr was 371 wheat seeds/m². However, the modified version of equation 2, (equation 7 proposed here) was used to determine the optimal wsr as 225-wheat seeds/m².

Equation 2 was modified as equation 7 to determine 99% of the predicted yield (optimum yield) at the maximum density (wsr), since Experiment 5 was based on RSD.

$$wsr_{crit} = \left(a_w 0.99 yMean_{\max}\right) \big/ \left(c - b_w 0.99 yMean_{\max}\right) \qquad 7$$

Table 13. OWSSY, FWSSY, OWISY, FWISY, OWSYR, FWSYR , OWSYR % and FWSYR% for Experiment 5.

Wheat seed rate (seeds/m²)	Bean seed rate (seeds/m²)	OWSSY (g/m²)	FWSSY (g/m²)	OWISY (g/m²)	FWISY (g/m²)	OWSYR (g/m²)	FWSYR (g/m²)	OWSYR (%)	FWSYR (%)
25	5	270	336	221	295	49	41	18	12
100	5	723	611	624	559	99	52	14	9
200	5	682	709	674	658	8	51	1	7
400	5	734	770	701	721	33	48	5	6
25	20	270	336	309	253	-39	83	-14	25
100	20	723	612	511	519	212	92	29	15
200	20	682	709	552	629	130	79	19	11
400	20	734	770	755	704	-21	66	-3	9

25	40	270	336	153	214	117	123	43	36
100	40	723	611	464	474	259	138	36	23
200	40	682	709	692	595	-10	114	-1	16
400	40	734	770	681	682	53	88	7	11
25	80	270	336	129	162	141	173	52	51
100	80	723	611	475	404	248	208	34	34
200	80	682	709	550	536	132	172	19	24
400	80	734	770	520	642	214	128	29	17

Fitted equations are based on equation 1 and 5 for the wheat sole crop and intercrop respectively. See the text for details.

Table 14. OBSSY, OBISY, FBISY, OBSYR, FBSYR, OBSYR % and FBSYR for Experiment 5.

. Wheat seed rate (seeds/m²)	OBSSY (g/m²)	OBISY (g/m²)	FBISY (g/m²)	OBSYR (g/m²)	FBSYR (g/m²)	OBSYR (%)	FBSYR (%)
25	142	174	162	-32	-20	-23	-14
100		141	132	1	10	1	7
200		94	103	48	39	34	27
400		85	83	57	59	40	41

The negatives values seen indicate that the bean intercrop out-yielded the bean sole crop. See the text for details.

Where c is a unit dependent constant (c = 1 when yield and density are expressed on the same area basis), a_w and b_w are as defined previously in equations 1 and 2. The parameter $yMean_{max}$ (for an experiment with an asymptotic response to wsr) is the mean of the predicted yield at the maximum wsr; wsr crit is population at 0.99ymax

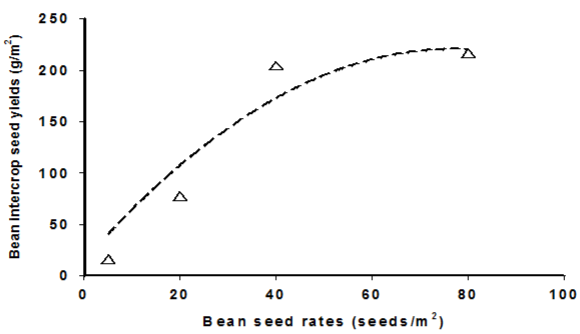

Fig. 12. Effect of wide ranges of bean seed rate (seeds/m²) on winter bean (cv Clipper) sole crop ▲ (solid curve) and intercrop Δ (broken curve) seed yield for Experiment 5.

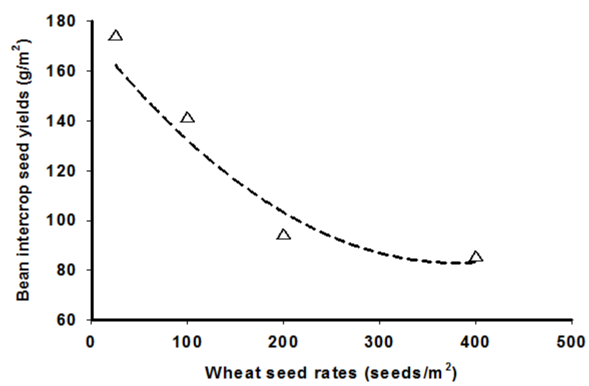

Fig. 13. Effect of wide ranges of wheat seed rate (seeds/m²) on winter bean (cv. Clipper) intercrop Δ (broken curve) seed yield for Experiment 5.

Compared to the previous winter experiments, particularly Experiments 1 and 2 wheat SY was not reduced much in this experiment. Nevertheless, intercropping reduced wheat SY by as much as 248 g/m². This was equivalent to 34 % reduction in yields (Table 13).

In Experiment 5, wsr did not have significant effect on bean SY (P > 0.05). Mean bean SY for all plots was 127 g/m². Bean SY increases with increase in bsr (P = 0.041 for quadratic bsr). No significant interactive effect was detected between wsr and bsr on bean SY response (P > 0.05). The maximum bean SY of 215 g/m² was obtained at 80-bean seeds/m². However, this did not differ significantly from the 203 g/m² SY obtained at 40-bean seeds/m². Generally, bean SY increased with increase in bsr (Fig. 12). Hence was quantified as $Y = 15 + 5.34\ bsr - 0.035\ bsr^2$ (Fig. 12), $r^2 = 0.91$. However, BIC SY response to increase in wsr was also quantified as $Y = 174 - 0.48\ wsr + 0.0006\ wsr^2$ (Fig. 13), $r^2 = 0.94$. As was the case with the previous experiments, intercropping reduced bean SY by up to 57 g/m² at 400-wheat seeds/m² (Table 14). This was equivalent to 40 % reduction in yields (Table 14).

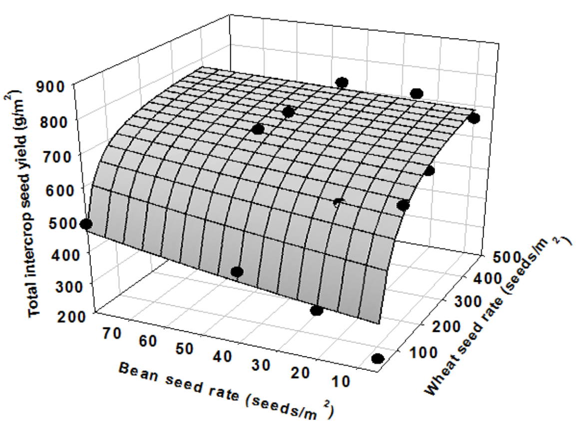

Fig. 14. Effect of wide ranges of wheat and bean seed rates (seeds/m²) on total intercrop seed yield for Experiment 5. Equation 5 was applied to quantify the data and the parameter values are presented in Table 15. The filled circles are the observed data (results).

In Experiment 5, the TIC SY responded positively to increase in wsr ($P < 0.001$ for quadratic wsr; Fig. 14). The effect of bsr on the TIC SY also deviated from linearity (P = 0.047 for quadratic bsr). Although the interactive effect between wsr and bsr did not reveal significant result (P > 0.05), when the response was separated into the various polynomials, linear wsr effect x linear bsr effect was significant (P = 0.026). Averaged across wsr, intercropping significantly improved SY compared to WSC at 40-bean seeds/m² as bsr increased. Mean SY were 482 g/m², 459 g/m², 502 g/m², 601 g/m² and 549 g/m² for 0, 5, 20, 40 and 80 bean seeds/m² respectively (SED 44.0, DF 47). Note that there was no significant difference between the maximum TIC SY from the TIC SY obtained at 80-bean seeds/m². Similarly, averaged across bsr, intercropping significantly improved SY compared to BSC across wsr. Mean SY were 114 g/m², 356 g/m², 672 g/m², 704 g/m² and 746 g/m² for 0, 25, 100, 200 and 400 wheat seeds/m² respectively. However, there was no significant difference between the maximum SY at 400-wheat seeds/m² and SY obtained at 100 and 200 wheat seeds/m² as wsr increased.

Compared to the maximum WSC SY, there was no significant difference between the WSC SY and the TIC SY as wheat and bean sr increased, except at 25-wheat seeds/m² with beans combinations. However, the maximum SY for the WSC was significantly greater than the BSC SY as bsr increased. The maximum TIC SY of 795 g/m² was obtained at 100-wheat seeds/m²/ 40-bean seeds/m² combinations. At this intercrop combination, wheat contributed more SY than the bean, and was more competitive than the bean. Although this was significantly greater than the bean SY as bsr increased, this did not differ from the WSC SY and other intercrop combinations except at 25-wheat seeds/m² mostly.

It was assumed that all plants (i.e. seeds sown per plots) are counted as wheat equivalent. Thus, the TIC SY was quantified using equation 1 with the wsr as the main explanatory variable (Table 15). Using similar approach with bean as the main explanatory variable did not work. This indicates that with respect to the SY, wheat was clearly more competitive than the bean. With wsr as the main explanatory variable, the predicted asymptotic yield for the TIC was determined as 810 g/m² with an optimal wsr (based on equation 2) of 345-wheat seeds/m². However, equation 5 quantified the TIC SY better and was accepted (Fig. 14; Table 15). The predicted asymptotic SY was reduced to 677 g/m² but the optimal wsr (based on equation 7) was increased to 435-wheat seeds/m². Using equation 6 did not improve the fits and was rejected (Table 15). Generally, the TIC SY responded positively to increase in wsr and bsr effects were less important. Fig. 14 show the asymptotic increase in the TIC SY to indicate similarities with the responses of WIC SY.

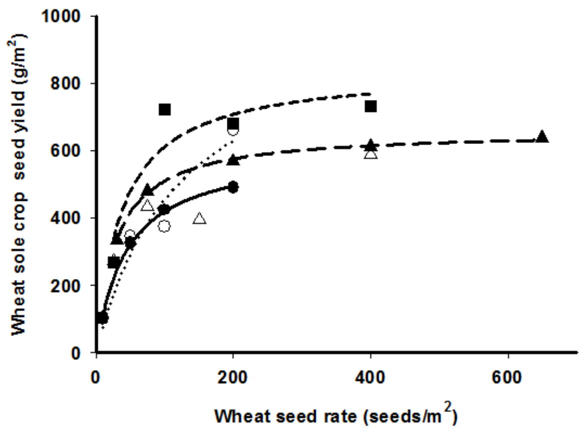

Fig. 15. Wheat sole crop seed yields (g/m²) for Experiments 1 ● (solid curve), 2 ○ (dotted curve), 3 ▲ (long-dash curve), 4 Δ, and 5 ■ (short-dash curve) to indicate that Experiment 5 out-yielded others substantially with the lowest maximum yield obtained in Experiment 1.

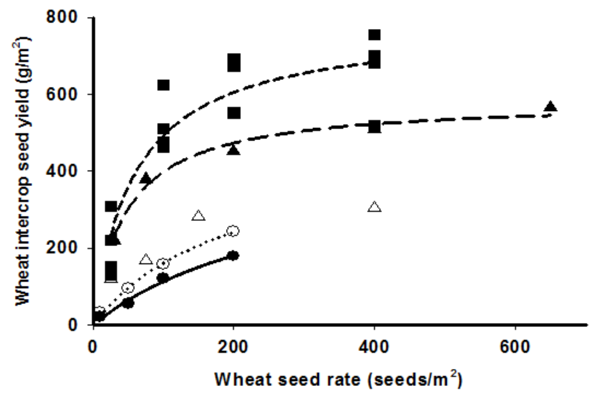

Fig. 16. Wheat intercrop seed yields (g/m²) for Experiments 1 ● (solid curve), 2 ○ (dotted curve), 3 ▲ (long-dash curve), 4 Δ, and 5 ■ (short-dash curve) to indicate that Experiment 5 out-yielded others substantially with the lowest maximum yield obtained in Experiment 1.

Table 15. Estimated parameter values and standard errors (in bracket) for the various equations fitted to the total intercrop seed yield for Experiment 5, assuming all plants are counted in wheat equivalent to show that equation 5 fitted the response better than others.

Fitted equation	Parameters estimates and standard errors (in bracket)				Coefficient of determination (%)
	a_w	b_w	c_w	d_w	
1	0.03344 (0.00632)	0.0012351 (0.0000562)			80.6
5	0.04171 (0.00900)	0.0012399 (0.0000526)	-0.000237 (0.000142)		82.9
6	0.0472 (0.0109)	0.0011665 (0.0000876)	-0.000365 (0.000185)	0.00000188 (0.00000181)	83.1

See the text for details on each of the equations and the meaning of the parameters.

Comparisons of seed yields across the experiments
Based on the results for the WSC, WIC and TIC greater yields were obtained in Experiment 5 compare to the other experiments whilst BIC SYs were greater in Experiment 4 than others were (Fig. 15-18). For the wheat SYs, as indicated in Fig. 16, it was interesting to note that Experiment 3 (spring-sown) clearly out-yielded the autumn-sown ones even at 200-wheat seeds/m^2 (maximum sr sown in Experiments 1 and 2) and 400-wheat seeds/m^2 (maximum sr sown in Experiment 4). Similarly, comparison based on the predicted values as analysed using the intra-specific competition suggest that the predicted asymptotic SY of 786 g/m^2 found in Experiment 5 was clearly greater than the predicted maximum SYs obtained in the other experiments. However, based on inter-specific competition, the predicted asymptotic maximum WIC SY of 460 g/m^2 obtained in Experiment 5 (Fig. 11) even though it compares well with the predicted maximum SYs in Experiments 1 and 2 was lower than the predicted asymptotic SY obtained in Experiment 3, which was spring-sown (Fig. 6). However, it was interesting to note that even based on inter-specific competition analyses the 677 g/m^2 predicted TIC SY obtained in Experiment 5 (Fig. 14) was slightly greater than the predicted maximum TIC SY obtained in Experiment 3 (Fig. 6), and was substantially greater than the maximum TIC SY obtained in Experiments 1 (Fig. 2), 2 (Fig. 5) and 4 (Fig. 9).

For the bean intercrop, as indicated in Fig. 17, though patterns were not obtained in Experiments 4 for example, in most cases across the experiments greater BIC SY were obtained at the lower wsr. Unlike wheat SYs, the maximum BIC SY was obtained in Experiment 4 with Experiment 5 also producing appreciable SY (Fig. 17). By contrast, the lowest BIC SY was obtained in Experiment 2, largely because of the disease problems (Fig. 17). However, for Experiment 2, the positive response to wsr seen was largely due to a reduction in the severity of the infection in the intercrop as wsr increased (Fig. 4 and 17). Thus, unlike the wheat intercrop SYs, greater BIC SYs were obtained in Experiment 1 compared to Experiment 2 (Fig. 17). However, as can be seen in Fig. 17, it was interesting to note that the maximum BIC SYs obtained in Experiment 3 (spring-sown) was substantially greater than maximum SYs obtained in Experiments 1 and 2, though Experiments 4 and 5 produced greater SYs than the spring-sown experiment (Fig. 17). Similarly, as shown in Fig. 18, the TIC SY was substantially greater in Experiment 5 compared to the other experiments. With respect to the TIC SY, even at 200-wheat seeds/m^2 (the maximum sr sown in Experiments 1 and 2), the experiments were ranked Experiment 5> Experiment 3> Experiment 4> Experiments 1 and 2 (Fig. 18). By contrast, as is shown in Fig. 18, the lowest yields were obtained in Experiments 1 and 2.

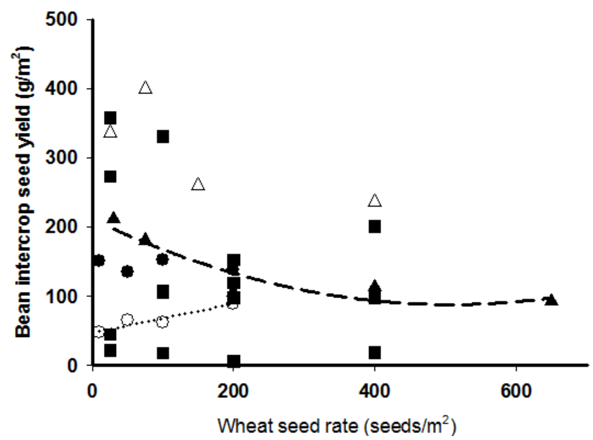

Fig. 17. Bean intercrop seed yields (g/m^2) for Experiments 1 ●, 2 ○ (dotted line), 3 ▲ (long-dash curve), 4 Δ, and 5 ■ to indicate that Experiment 4 out-yielded others substantially with the lowest maximum yield obtained in Experiment 2.

As regards conventional versus organic system in the first cropping year, for both the WSC and WIC and whether it was based on maximum SYs from the results or predicted asymptotic SYs, Experiment 2 (organically-managed) clearly out-yielded Experiment 1 (conventionally-managed). Based on the results, the maximum WSC SY of 660 g/m^2 at 200-wheat seeds/m^2 obtained under the organic system here was substantially greater than the maximum 490 g/m² SY obtained at the same sr under the conventionally-managed experiment (Fig. 1 and 15) . More interesting was the predicted asymptotic WSC SY of 1016 g/m² under the organic experiment, which was clearly greater than that obtained under the conventionally-managed experiment.

Although the observed wheat SYs under the organic experiment were clearly greater than yields obtained under the conventional experiment, the reverse was the case as regards bean SY (Fig. 17). Thus, bean SY was greater under conventional system than under organic system for both the sole and intercrop. Averaged across wsr, for the mean effects of intercropping, the TIC SY was significantly greater in the conventional experiment than in the organic one. However, for the interactive effects of wsr and intercropping, the maximum TIC SY was similar between the conventional experiment and the organic one. Indeed, except at the lower sr where the conventional experiment produced greater SYs than the organic experiment, at the maximum sr of 200-wheat seeds/m² none of the two experiments substantially out-yielded each other (Fig. 18).

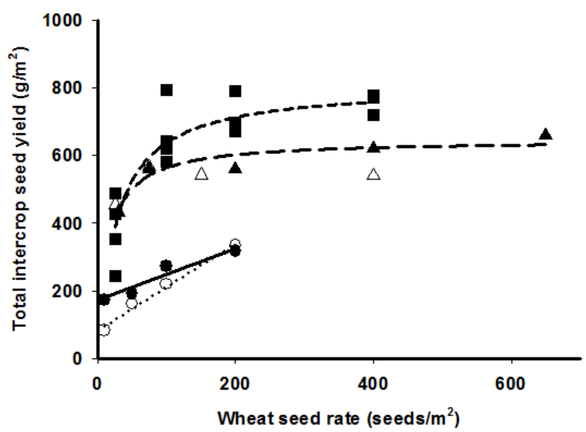

Fig. 18. Total intercrop seed yields (g/m²) for Experiments 1 ● (Solid line), 2 ○ (dotted line), 3 ▲ (long-dash curve), 4 Δ, and 5 ■ (short-dash curve) to indicate that Experiment 5 out-yielded others substantially with the lowest maximum yields obtained in Experiments 1 and 2.

Greater wheat, bean and total intercrop maximum SY based on results or predicted values were obtained in Experiment 3 (spring-sown) compare to Experiment 1 (winter-sown). For Experiment 3, the maximum WIC SY based on results and predicted asymptotic yield were 566 g/m² and 584 g/m² respectively (Fig. 6) which were substantially greater than yields obtained under the winter-sown experiment (Fig. 1). However, bean SYs were similar between the two experiments (Fig. 17). Averaged across wsr, for the mean effects of intercropping, the TIC SY was significantly greater in the spring-sown experiment than in the winter-sown one. Similarly, for the interactive effects of wsr and intercropping, the maximum TIC SY was significantly greater for the spring-sown intercrop than the winter-sown one (Fig. 18).

It was clear that for the majority of the experiments carried out both wheat and bean yields were reduced due to intercropping (Tables 3- 6, 8- 11, 13 and 14). Based on results and fitted data, for the wheat greater than 60 % SY decline were observed in both Experiments 1 and 2 (Tables 3 and 2). Similarly, for the bean in Experiment 3 up to 62% decline in SY due to intercropping was found (Table 8). The only exception was in Experiment 2 where intercropping facilitated greater bean intercrops SY compare to the bean sole crop (Table 6).

Discussion

Application of yield-density equations in wheat/bean intercropping system

One of the main objectives of the present research was to quantify seed yield response to sr using competition approach. A major advantage of this approach at analysing data for the sole crop or intercrops is that it allows for extrapolation of data beyond actual results (Craufurd, 1996; Park *et al.,* 2002; Neumann *et al.,* 2009). For instance, in my Experiments 1 and 2 whilst the actual WSC SYs were 490 g/m² and 660 g/m² respectively, the predicted asymptotic yields ($1/b_w$) were determined as 604 g/m² and 1016 g/m² respectively (Fig. 1-3 and 5). Nevertheless, the predicted asymptotic SYs for each of these experiments are within the ranges of WSC SYs that were obtained under actual field conditions in the UK previously (Khah *et al.,* 1989; Ellis *et al.,* 1999; Gooding *et al.,* 2002). Similar trends were also found as regards the observed WIC SYs in comparison with the predicted values. For instance in Experiment 5 whilst observed maximum WIC SY of 755 g/m² was obtained at 400-wheat seeds/m²/ 20-bean seeds/m² combinations, quantifying the data using equation 5 suggests that the asymptotic yield was 460 g/m² (Fig. 11). This clearly indicates that the presence of bean in the intercrop reduced wheat SYs. It was interesting that in Experiments 3 (Fig. 6) and 5 (Fig. 14) the TIC SY response followed similar asymptotic pattern as the wheat, thus clearly illustrating that wheat was the better competitor of the two component crops (Helenius and Jokinen, 1994; Neumann *et al.,* 2009). In Experiment 5, for instance whilst the maximum observed TIC SY was 795 g/m² at 100-wheat seeds/m²/ 40-bean seeds/m² combinations, the predicted asymptotic yield based on equation 1 was 810 g/m². However, it was sensible to expect the presence of bean in the intercrop would have a substantial effect on the TIC SY. Thus, analyses based on equation 5 decreased the predicted asymptotic yield down to 677 g/m² (Fig. 14). Had the results been analysed using the ANOVA procedure alone such extrapolations will not have been possible (Ellis *et al.,* 1999; Yahuza, 2011b). In agreement with the results obtained here, several authors have applied the asymptotic equations to quantify yields in several crop species (Khah *et al.,* 1989; Craufurd, 1996; Shirtliffe and Johnston, 2002; Mligo and Craufurd, 2007). Nevertheless, quantifying yields using asymptotic equations are mostly applicable in situations where water and nutrients are not the major limiting growth resource and the crops are free of pest and disease problems (Counce, 1987; Ellis *et al.,* 1999). Thus, here as regards the experiments in which responses were asymptotic it can be speculated that radiation was the main resource that was being competed for, since water is not a major problem in the UK (Gooding *et al.,* 2002), and the conventional experiments were supplied with N fertilizer.

For a simple additive design, in general yield-density equations are not well explored. As discussed elsewhere (Yahuza, 2012b), the fact that in my investigations I have not only applied equations derived from the literature in quantifying yields (Willey and Heath, 1969; Bleasdale, 1984; Shirtliffe and Johnston, 2002), but succeeded in modifying some of the equations, illustrates the novelty of the present research. For instance in Experiment 3, I have modified the simple asymptotic YDE in order to quantify the total intercrop (plus bean sole crop yield) since bean was the minor component in the intercrop using equation 3. For this experiment, given that WIC SY responses was also asymptotic, it was sensible to expect BIC SY response to be a difference between the asymptotic responses of the total intercrop (plus bean sole crop yield) and the WIC SY based on equation 4 (Fig. 6). Whilst, for the sole crops and intercrop based on RSD, appreciable work appear to have been done as it relates to YDEs (Helenius and Jokinen, 1994; Craufurd, 1996; Park *et al.,* 2002), no one as proposed simple YDE for quantifying a simple additive intercrop as was carried out here. Determining sr combinations is difficult under intercropping because of the need to reduce inter-specific competition for growth resources (Neumann *et al.,* 2009). In addition, management practices as regards fertilizer application, weed management and crop protection may differ for the sole crop and intercrops (Bulson *et al.,* 1997; Azam-Ali and Squire, 2002; Yahuza, 2011a). In any case, maximum yield for any plant in a crop may be achieved at that p of plants at which competition with the plant is minimal (Khah *et al.,* 1989; Ellis *et al.,* 1999). Often the interest is in yield of a crop rather than yield of a plant in a crop (Gooding *et al.,* 2002). In general provided growth conditions are favourable, yield of a crop increases linearly as density increases as more plants are occupying space that would have been left vacant and/or occupied by weeds (Willey and Heath, 1969; Bleasdale, 1984). In such cases yield can be simply quantified using a linear function (Counce, 1987). However, such relationship often deviates from linearity, and quantifying yields using quadratic function has no meaningful biological interpretations and is less efficient in describing yields satisfactorily (Khah *et al.,* 1989; Mligo and Craufurd, 2007). Thus, in situations where yields responded quadratically to increase in density, applying either an asymptotic and/or a parabolic equation is biologically more appropriate (Bleasdale, 1984; Counce, 1987; Ellis *et al.,* 1999; Craufurd, 2000). Here in addition to applying meaningful reciprocal equations to quantify SYs, new ones were proposed as was detailed previously (Yahuza, 2012b).

In general, where an asymptotic equation holds, the biological validity of the equation is based on the assumption that the mean yield per unit area increases towards ($1/b_w$) which is the asymptotic yield (maximum yield attainable) as the density is increased (Bleasdale, 1984; Helenius and Jokinen, 1994; Mligo and Craufurd, 2007). Given that the asymptote of yield per area is a measure of the potential of a given environment, it follows that b_w is a meaningful factor that defines environmental potential (Willey and Heath, 1969; Craufurd, 1996). Conversely, as the p is decreased mean yield per plant increases towards ($1/a_w$) which is the yield of an isolated plant or a plant in a competition-free environment (Helenius and Jokinen, 1994; Mligo and Craufurd, 2007). This suggests that the constant 'a_w' defines the genetic potential of the crop (Willey and Heath, 1969; Craufurd, 1996; 2000). Moreover, it had also been suggested that a_w/b_w is the 'relative' responsiveness to density (Gooding *et al.*, 2001). These authors argued that the ratio will be greater for crop species with lower plasticity to decrease in p (low $1/a_w$), but good at capturing and partitioning resources to the seed where density is high (high $1/b_w$). Clearly, as regards my investigations it was clear that wheat had greater competitive ability than the bean as regards the partition of resources to the seed given the asymptotic responses followed in most of the experiments. Indeed where SY followed an asymptotic pattern, the harvest index (the ratio between the overall biomass to the SY) is not substantially affected by p (Craufurd, 2000; Gooding *et al.*, 2002). In any case, in certain circumstance, such as poor establishment, pest and disease problems, manual harvesting etc (as was the case in my Experiment 4; Fig. 7-9) there would be the need to use p instead of sr in quantifying the data when yields are analysed using competition approaches (Counce, 1987; Ellis *et al.,* 1999).

The fact that the total intercrop SY followed similar asymptotic response, as was the case with wheat SY to increase in wsr in Experiments 3 (Fig. 6) and 5 (Fig. 14) further demonstrates the relevance of using competition approach in analysing density trials as was carried out here. A major peculiarity of intercrops is that plants might compete for growth resources with neighbours of both the same and at least one different crop species (Wright, 1981; Fukai and Trenbath, 1993; Park *et al.,* 2002). Thus, in intercropping investigations, the term intra-specific competition is used to describe the competition between plants of the same crop species (Dolman, 1985; Helenius and Jokinen, 1994). As regards the present investigation, the competition between a wheat plant with another wheat plant or competition between bean plant with another bean plant in the crop or intercrop can be referred to as intra-specific competition. On the other hand, the term inter-specific competition is used to describe the competition between plants of different crop species in an intercrop (Azam-Ali and Squire, 2002; Neuman *et al.,* 2009). For the experiments reported here, competition between a plant of wheat and a plant of bean in the intercrop can be referred to as inter-specific competition. However, it is widely accepted that when inter-specific competition for a given limiting factor is less than inter-specific competition among plants for that same factor there is a potential for high total production in the intercrop (Azam-Ali and Squire, 2002; Park *et al.,* 2002; Neuman *et al.,* 2009). Fukai and Trenbath (1993) ascribed the term dominant to refer to the most competitive component whilst the term dominated refers to the suppressed component. As regards YDEs, it is interesting to note that for intercropping, modified versions of the biologically meaningful asymptotic and parabolic equations were developed (Wright, 1981; Helenius and Jokinen, 1994). The modified equations were meant to account for the peculiarities of intercropping where both intra-specific and inter-specific competition exists (Dolman, 1985; Park *et al.,* 2002). Thus, in Experiment 5 the inter-specific asymptotic equation was applied. It will interest the reader to know that this equation has not previously been used to quantify SY in wheat/bean intercropping system as was demonstrated here.

Wright (1981) can perhaps be credited as the one who first approached yield-density studies in intercropping with some novelty working with intercropped Italian rye grass (*Lolium multiflorum*)/ red clover (*Trifolium pratense*), and his work was reviewed recently (Yahuza, 2011b). Nevertheless, for a given intercrop X and Y, the extra term $c_{xy}p_y$ in Wright's equation (equation 5) implies that an increase in density of a second component in the crop has similar effects on the weight per plant though this depends on the value of a_y (related to the genetic potential of crop type Y) compared with a_x (related to the genetic potential of crop type X). As discussed elsewhere (Yahuza, 2011b) where the density of the second component is 0 in Wright' equations, the equations simplifies to sole crop of X, so that the parameters b_x and a_x are identical to b and a in the sole crop version. Thus, yields of the sole crop of X and Y tend towards $1/b_x$ and $1/b_y$ at high densities; while their yields as intercrop components tend towards $1/(b_x - c_{xy})$ and $1/(b_y - c_{yx})$ (Wright, 1981; Yahuza, 2011b) provided that neither p_x nor p_y is very small (Yahuza, 2011b). Although Baumann *et al.* (2001) and Park *et al.* (2002) applied the equation in celery (*Apium graveolens*)/leek (*Allium porrum*) intercropping system and fodder maize (*Zea mays*)/Dwarf French bean (*Phaseolus vulgaris*) respectively, no wheat/bean intercropping experiment was previously analysed using the inter-specific asymptotic equations as was carried out here. In Experiment 5, it was obvious wheat was more competitive than the bean probably because of the bird damage to the beans (data not presented), which had influenced negatively on the actual densities of beans. Thus, it was not surprising that the inter-specific equation did not work well in respect of the beans SY. Dolman (1985) working on intercropped carrot (*Daucus carota*) and onions (*Allium cepa*) and using a similar design as Wright, argued that it is necessary that an interactive term $d_{xy}p_xp_y$ and $d_{yx}p_yp_x$ is introduced to equation 5 such that the density of each component in the intercrop can have a different effect at different densities of the other component using equation 6 (Yahuza, 2011b). Although, Dolman succeeded in applying equation 6 to describe yields of onion/carrot intercrop both of whom are of vegetative yields, to date the equations have not been applied to describe intercrops involving crops of reproductive yields. Given that the present investigation was carried out at the same location as Dolmans' it was thought evaluating the validity of the equation 6 using crops of reproductive yields such as wheat/bean intercrop would be worthy. This was based on the premise that empirical models have greater validity in the areas they were developed (Azam-Ali and Squire, 2002). In my investigations, equation 6 was limited in quantifying yields in Experiment 5 where the sr of the two components crops were both varied (Tables 12 and 15), probably because of factors discussed previously. However, taking into consideration the fact that it was only Experiment 5 that was designed using RSD as was Dolman's, further works are needed not only at the same location but elsewhere to determine the validity of these modified inter-specific asymptotic YDEs.

Counce (1987) contended that that where a simple intra-specific asymptotic equation holds, then a critical or optimum density exists that can be determined as the p necessary to obtain 99% of the predicted yield (optimum yield) at the maximum p of an experiment based on equation 2. Here, equation 2 was applied where the responses were asymptotic but was limited in determining optimum sr meaningfully. A further modification of Counce's equation to apply to Experiment 5 (equation 7) which was based on RSD also appear to be limited in its determination of optimum sr. For instance in Experiment 1 whilst the optimum wsr for the WSC and intercrop were determined as 189 wheat seeds/m² and 197 wheat seeds/m² respectively, it was clear from the results that for this experiment in respect of the WIC, asymptote was not reached despite the fact that the results were well quantified using equation 1. Of more interest was the application of the equation to determine optimum WIC sr in Experiment 5. For this experiment, using equation 2 and based on the results analysed using the inter-specific asymptotic equation, suggest that for the WIC, optimum sr was determined as 371 wheat seeds/m². This clearly indicates the limitations of the equation in determining optimum sr even in situations where the responses were asymptotic. Moreover, in the UK under field conditions for the sole crops, recommended sr for winter wheat is about 200-250 seeds/m² (Gooding *et al.*, 2001; 2002), and sr ought be lower under intercropping to allow for both intra-specific and inter-specific competition effects (Bulson *et al.,* 1997; Haymes and Lee, 1999). Nevertheless, in practice, Counce's equation has not been applied widely in density trials. However, recently Mligo and Craufurd (2007) applied equation 2 successfully but with slight modifications. Craufurd (2000) had earlier applied the same equation 2 in an additive intercropping situation. However, here a modification of equation 2 to determine optimum sr for intercropping based on the RSD as was the case in my Experiment 5, was proposed. Using the modified equation (equation 7) and based on the analyses using the inter-specific asymptotic equations indicate that the optimum wsr was 225 wheat seeds/m². Despite the fact that it was only Experiment 5 that was based on the RSD, it was clear that equation 7 proposed here has more meaningful application than the simple equation Counce (1987) proposed when similar designs as was my Experiment 5 are used. Thus, given the fact that these investigations was based on a 3-year field trials even though in the second year no meaningful asymptotic responses were found, further works are needed to validate the use of Counce's equation and also the modification proposed here.

Table 1. Weather data during the cropping season for Experiment 5 at the experimental site Sonning, Berkshire, UK.

Year	Month	Mean air monthly temperature (°C)	Mean monthly solar radiation (MJ/m²/day)	Mean monthly rainfall (mm)
2007	September	14.5	6.4	35.1
2007	October	11.2	3.7	68.8
2007	November	7.7	2.5	45.6
2007	December	5.4	2.7	86.4
2008	January	6.4	6.0	19.6
2008	February	5.4	7.2	82.6
2008	March	6.5	10.5	59.0
2008	April	8.1	12.1	66.4
2008	May	13.7	17.2	49.4
2008	June	14.9	17.4	78.0
2008	July	16.6	11.8	74.6
2008	August	16.8	9.2	47.8
2008	September	13.6	6.0	54.4
2008	October	9.1	2.4	67.6
2008	November	7.1	2.2	32.4

See Yahuza (2012a) and Yahuza (2012c) for the weather data during the cropping seasons for Experiments 1, 2 and 3, and 4 respectively. The long-term mean air monthly temperature, long-term mean solar radiation and the long-term mean monthly rainfall for the experimental site were presented earlier (Yahuza 2012a; c).

Comparisons of seed yields across the experiments/cropping years

The main thrusts of this research were not investigations on wheat sole crop; a reference sole crop is needed in order to assess intercrop SY productivity (Fukai and Trenbath, 1993; Azam-Ali and Squire, 2002). That the wheat and TIC SYs were greater in Experiment 5 and to some extent; Experiment 4 can be ascribed mainly to favourable growing conditions as indicated by greater rainfall compared to the earlier experiments (Table 1; Yahuza, 2012a; c). The cropping years 2006-2007 (Experiments 4; Yahuza, 2012c) and 2007-2008 (Experiment 5; Table 1) were wetter than the 2005-2006 cropping year (Yahuza, 2012a) when Experiments 1, 2 and 3 were established. Indeed, the rainfalls during the growing periods for Experiment 4 (Yahuza, 2012c) and 5 (Table 1) were greater than the long-term average for the site (Yahuza, 2012a; c). In addition, the damage to the beans by birds in Experiment 5 meant that wheat was growing with lesser competition in the intercrop. It was, therefore, not surprising to note that even based on inter-specific competition analyses (Helenius and Jokinen, 1994; Park *et al.,* 2002), as regards the predicted TIC SY Experiment 5 (Fig. 14) out-yielded others substantially (Fig. 2, 5, 6 and 9). Moreover, the out-yielding of Experiments 1 and 2 by Experiment 3 even though they were established in the same cropping year was not surprising. It was obvious that the greater yields obtained in that experiment compare to the winter-sown ones was a reduction in inter-specific competition for resources between wheat plants and bean plants in the intercrop due to different varieties involved (Helenius and Jokinen, 1994). For instance, as regards plants heights in Experiment 3, the spring wheat (Paragon) and bean (Hobbit) varieties were less dominant over each other compared to the dominance of the winter bean (Clipper) over winter wheat (Mallaca) as was noticed in Experiments 1 and 2 (data not presented).

Averaged across wsr, for the mean effects of intercropping, the maximum wheat sole crop SYs found in this research compares well with previously reported yields of up to 648g/m² at the same location (Hongo, 1995). However, Gooding *et al.* (2002) demonstrated that winter WSC SYs of up to 920 g/m² could be obtained at the same location. Therefore, the maximum WSC SYs obtained here was lower. The disparity between the WSC obtained in my study and theirs can be explained by the low N fertilizer, which was applied to the crops here. Here, given that both the intercrops and sole crops in each experiment were agronomically treated similarly, the sole crops were not well fertilized with N whereas in their study or other studies where such higher SYs were obtained in the UK previously (Whaley *et al.,* 2000; Foulkes *et al.,* 2007), the sole crops were not starved of N fertilizer. Wheat crop is responsive to N fertilizer (Gooding and Davies, 1997; Ellis *et al.,* 1999; Fisher, 2007). In this research, high N fertilization was avoided because legumes have the ability to fix N by themselves with the aid of symbiotic bacteria, rhizobia (Bulson, 1991; Pristeri *et al.,* 2006; Anon, 2010). Excessive N fertilization may interfere with the legumes ability to fix N symbiotically and may subject the crop to grow vegetatively (Yahuza, 2011a). Adding more N to the system would allow the wheat to produce more tillers some of which may persist until maturity and there may not be a need to increase the sr compared to the levels sown here (Whaley *et al.,* 2000). Obviously, the low N applied to the crop in the experiments reported here meant that competition for N between the plants in the crop or intercrop might be high (Gooding *et al.,* 2007). This would lead to reduction in maximal productivity per plant (Counce, 1987; Ellis *et al.,* 1999). In such intense competitive situations, not only do the numbers of plants that survive to maturity reduce, but also the ability of the surviving plants to partition assimilates to the seeds decreases (Fisher, 2007; Reynolds *et al.,* 2007). Despite, the lower WSC SYs obtained in this study, compared to the previous study or UK national average of about 800 g/m^2, the study indicate that for winter wheat, sr of about 200 seeds/m^2 or lower might be optimal under UK managed conditions. This is in agreement with previous findings in the UK (Whaley *et al.,* 2000; Gooding *et al.,* 2002). Similarly, averaged across wsr the maximum wheat intercrop SY of up to 555 g/m^2 for the mean effects of intercropping found here compares well with previous studies. For the interactive effects of wsr and intercropping, maximum SY found in Experiment 5 here were slightly greater than the 530 g/m^2 obtained previously at the same location (Hongo, 1995). Nevertheless, here, for most of the experiments it was shown that about 100-wheat seeds/m^2 or lower may be appropriate to be sown to get appreciable WIC SYs.

The bean sole crop maximum SY of up to 392 g/m^2 found in this research compares well with the 348 g/m^2 found elsewhere (Helenius and Jokinen, 1994), but lower than 502 g/m^2 found previously at the same location (Hongo, 1995). In addition, elsewhere, Adisarwanto and Knight (1997) obtained SY of up to 670 g/m^2. This indicates that the maximum BSC SY obtained here was substantially lower. However, the maximum bean intercrop SY was greater than 338 g/m^2 and 138.3 g/m^2 obtained by Hongo (1995) and Helenius and Jokinen (1994) respectively. The fact that greater maximum BIC SY was obtained in Experiment 4 and to some extent Experiment 5 (Fig. 17) was as explained previously in respect of the weather effects. However, for Experiment 2, the positive response to wsr seen was largely due to a reduction in the severity of the disease infection on bean plants in the intercrop as wsr increased (Fig. 4 and 17). Indeed, unlike wheat intercrop SYs, greater BIC SYs were obtained in Experiment 1 compared to Experiment 2 (Fig. 17). Moreover, the fact that the maximum BIC SYs obtained in Experiment 3 (spring-sown) was substantially greater than maximum yields obtained in Experiments 1 and 2, (Fig. 17), further suggests a reduction in inter-specific competition for growth resources in the spring-sown experiment compare to the winter-sown ones largely due to the contrast of varieties involved. In general, the low bean SY obtained here cannot be explained by the low N applied to the experiments because bean a legume is less responsive to N (Ghanbari-Bonjar and Lee, 2002; Yahuza, 2011a). As explained previously, bean has the capacity to synthesize N and may leave the soil available N for the other component crop in the intercrop (Gooding *et al.,* 2007). However, in general bean is typically known to have substantial season-to-season or year-to-year variation even within the same location, and even within the same cultivar (Adisarwanto and Knight, 1997; Hames and Lee, 1999). Such variations could be attributed to several factors particularly weather variations, soil types, pest and disease problems and varieties involved (Anon, 2010; Khan *et al.,* 2010; Stoddard *et al.,* 2010).

Averaged across wsr, for the mean effects of intercropping, it was demonstrated that up to 601 g/m^2 total intercrop SY was obtained. It was obvious that for the mean effects of intercropping the TIC SY were substantially greater than wheat sole crop SY in three of the experiments. This is in agreement with previous reports in the literature. For instance, Hongo (1995) previously demonstrated that the TIC SY was greater than yields for each of the sole crops in wheat/bean intercropping system at the same location. However, it was demonstrated that for the interactive effects of wsr and intercropping, the maximum total intercrop SY was not consistently greater than the maximum WSC SY was across the experiments. That the TIC SY was greater in Experiment 5 than others following similar pattern as wheat was largely due to weather effects and other factors explained earlier. In any case, the maximum TIC SY was consistently greater than maximum SY of the bean across the experiments. This clearly indicates that in most cases wheat in the intercrop contributed more SY to the total intercrop than the beans. Thus, it was clear that for the majority of the experiments wheat was more competitive than the bean.

Comparisons of seed yields for the conventionally-managed experiment with the organically-managed experiment in the first cropping year

In the first cropping year as regards conventional versus organic system, that greater yields were obtained in Experiment 2 (organically-managed; Fig. 3 and 15) than Experiment 1 (conventionally-managed; Fig. 1 and 15) was in contrast to the wider literature (Bulson, 1991; Stolze and Lampkin, 2009). It was obvious that the maximum WSC SY of 660 g/m² obtained under the organic system here (Fig. 3 and 15), was closer to the mean winter wheat SY of 800 g/m² under conventional system in the UK (Whaley *et al.,* 2000; Gooding *et al.,* 2002). The typical yield of organic winter wheat under sole cropping in the UK is within the range of 350 g/m² to 536 g/m² (Bulson *et al.,* 1997; Huxham *et al.,* 2005). Here it was shown that for the WSC under organic management greater yields could be obtained. More interesting was the predicted asymptotic WSC SY of 1016 g/m² under the organic experiment, which was clearly greater than the mean winter wheat SY of about 800 g/m² under even conventional system in the UK (Gooding *et al.,* 2002; Nix, 2009). The greater wheat SY for the organic than the conventional can be ascribed to two factors mainly. First, soil analyses showed that available N was greater under organic management than the conventional system (Table 2). However, N supplies in the organic system often do not match with N demands by the crop from sowing through to maturity (Gooding *et al.,* 2007). This is because the system relies mainly on non-synthetic sources of N such as crop rotation, green manuring and intercropping to meet the N demand of the crops (Huxham *et al.,* 2005; Stolze and Lampkin, 2009). Hence, the high N availability at the early growing season should not have had substantial impact on SY compared to the conventional experiment that was fertilized with N fertilizer. This is based on the premise that SY depends largely on current assimilate production and translocation to the reproductive parts (Foulkes *et al.,* 2007; Reynolds *et al.,* 2005; 2007).

In addition, even though it is not widely accepted that N is transferred from a legume component in an intercrop to a non-legume component, it is widely believed that there is a possibility of a residual benefits through decomposition and mineralization of legume straw etc (Ghanbari-Bonjar and Lee, 2002; Yahuza, 2011a). It is well established that the first cereals following a legume crop in a rotation might benefit more from residual N than the subsequent crops under organic management (Huxham *et al.,* 2005). Here, the organic experiment was the first crop established after legume crop in a rotation. This might explain the high available soil N in the organic area compared to the conventional area found from the soil analyses (Table 2). Secondly, it could be that the failure of the beans due to disease problem in the organic experiment could have facilitated wheat to compensate by an increase in yield through less inter-specific competition (Fukai and Trenbath, 1993; Yahuza, 2011a). Indeed, it was observed that most of the diseased bean plants were defoliated, and some of the defoliated foliage was decomposing whilst wheat plants were still at the reproductive stage. It may be possible that wheat plants during seed filling were able to derive N from the decomposed and mineralized foliage of the diseased bean plants in the intercrop. It should be reiterated that one of the major problems of organic production system is the high susceptibility of the crops to pest and diseases as the use of synthetic chemicals are not allowed (Stolze and Lampkin, 2009).

In most cases, the conventionally-managed crops have greater yield potentials than the organically-managed ones (Bulson, 1991; Bulson *et al.,* 1997; Huxham *et al.,* 2005). In my study, though only one organically managed intercrop experiment was involved, an indication that wheat yields may be greater under organically managed conditions was illustrated (Fig. 15 and 16). Wheat is known to be responsive to N fertilization (Ellis *et al.,* 1999), which is prohibited under organic management conditions (Stolze and Lampkin, 2009). Concerning wheat SY, the out-yielding of the conventional experiment by the organic one might be attributed to the low N applied in the conventional experiment compared to the recommended dose for the WSC. However, it would be argued that with respect to N fertilization, the principles involved in managing a conventional WSC are different from those for managing a conventional wheat/bean intercropping system, for example. Here though soil analyses were done only once, in the field wheat in the organic experiment appeared to be devoid of symptoms indicating deficiency of N. Indeed, even at the reproductive stages visually wheat in the organic area were looking more greenish (indicating good supply of N) than their conventional counterparts which were sown same day were. Thus, it is sensible to expect wheat in the organic area to out-yield the conventional one (Figu. 15 and 16). The only limitation of the present investigation was that only one organically-managed crop was included. This suggests that further investigations are necessary to confirm results of my work, before conclusions can be drawn.

Table 2. Some chemical properties of the soil at the University farm, Sonning, Berkshire, UK during the cropping years.

Experiment (Cropping year)	pH	P (mg/I)	K (mg/I)	Mg (mg/I)	Available N @ 0-90 cm depth (kg N/ha)	Sulphate (mg/I)
1 (2005-2006)	7.1	45	138	50	28.9	68.1
2 (2005-2006)	6.3	35	119	48	66.7	66.7
3 (2006)	6.8	34	109	55	45.2	65.1
4 (2006-2007)	7.1	35	79	67	9.7	33.9
5 (2007-2008)	6.6				33.6	24.3

Unlike the observed wheat yields, results indicate that greater bean SY were obtained under my conventional experiment (Experiment 1) than the organic experiment (Experiment 2) (Fig. 17). Bulson *et al.* (1997) reported bean sole crop SY of up to 370 g/m² under organic management system previously in the UK. Thus, the bean SY obtained for both the sole crop and intercrop here under both conventional and organic systems were low. This could be due to the fact that bean in the organic experiments were diseased, even though intercropping decreased the severity of the infection as was indicated in the greater SY of the intercrop than the sole crop for the organic experiment (Fig. 3 and 4). This meant that yields would be greater under the conventionally-managed experiment. Indeed, bean sole crop SY were greater than the bean intercrop SY under the conventional system (but not statistically significant; Fig. 1 and 17), which was a reverse of the situation in the organic experiment (Fig. 17). That bean SY was greater for the intercrops and increases with increase in wsr clearly demonstrate the capacity of intercropping in reducing pest and disease problems (Khan *et al.,* 2010; Yahuza, 2011a).

It was demonstrated that for the mean effects of intercropping, the TIC SY was substantially greater in the conventional experiment (Experiment 1) than in the organic one (Experiment 2), suggesting that the conventionally managed experiment was more productive. Nevertheless, it was obvious that the observed TIC SY were similar between the two systems. It was apparent that for the conventional experiment, the lower WIC SY was compensated by comparatively greater bean SY (Fukai and Trenbath, 1993; Yahuza, 2011a), which was a reverse of the situation in the organic experiment. Thus, it was shown that similar TIC SY is achievable under both conventional and organic system even though the proportion of contribution by wheat and bean components differs between the two systems. However, the fact that irrespective of whether comparisons was based on maximum yields from results or predicted values, for each of the two system WSC clearly out-yielded the TIC suggest that there may not be benefit for growing wheat/bean intercrop if improvement in SY was the main objective (Fukai and Trenbath, 1993; Azam-Ali and Squire, 2002). It should be pointed out that whilst in these investigations, organic experiment was investigated in only the first cropping year, conventional experiments were carried out over a period of 3 years, thus a limitation to any conclusion that can be made here. Note that here, comparisons between the organic and conventional experiments were between Experiments 1 (referred to as conventional) and 2 (referred to as organic), since they have similar designs, drilled on the same day and received similar agronomic treatment as was permitted under organic system (for the organic experiment).

Comparisons of seed yields for the winter-sown experiment with the spring-sown experiment in the first cropping year

That greater yields were obtained in the in Experiment 3 (spring-sown; Fig. 6) compare to Experiment 1 (winter-sown; Fig. 1) was in contrast to the wider literature (Gooding and Davies, 1997; Gooding *et al.,* 2002; Pristeri *et al.,* 2006). This can be ascribed mainly to lesser inter-specific competition between wheat and bean in the intercrop for the spring experiment (Park *et al.,* 2002; Neumann *et al.,* 2009) due to the different varieties involved as explained earlier. The literature shows that typically yields are usually greater under winter-sown conditions than under the spring-sown conditions (Ellis *et al.*, 1999). To contrast the capacity of the winter-sown crops to tiller as a way of compensating for low p, the sr of spring-sown crops are usually greater (Gooding and Davies, 1997; Nix, 2009). Therefore, the comparatively higher sr sown in the spring experiment compared to the winter experiment here was justified. Under sole cropping conditions, winter wheat yields of up to 800 g/m² or more have been reported in the UK (Whaley *et al.,* 2000; Gooding *et al.,* 2002). For the WSC, Ellis *et al.* (1999) reported maximum wheat SY of 523 g/m² and 257 g/m² for winter-sown and spring-sown crops respectively previously. Although the maximum winter wheat SY obtained in this investigation compares well with yields reported by Ellis *et al.* (1999), they were lower than the 920 g/m² SY found more recently at the same location (Gooding *et al.*, 2002). Similarly, under sole cropping conditions, it had been demonstrated that spring wheat SY of up to 500 g/m² can be obtained at the same location (Khah *et al.,* 1989). Therefore, though the ranges of WSC SY found here compares well with the literature, previous studies have not achieved the maximum spring WSC SY of up to 638.7 g/m² found here (Fig. 6 and 15). This means that none of the component crops appeared to be dominant on the other. Indeed, as explained earlier, for the spring experiments wheat and bean plant heights were similar in contrast to the autumn–sown experiments. In the UK, winter wheat is the most widely grown arable crop (Nix, 2010; Yahuza, 2011a). Here, it was demonstrated that greater SYs are achievable under spring-sown conditions too. The growers' preference for the winter-sown wheat is largely due to both higher yields and quality attributes associated with bread making compared to the spring-sown one (Gooding and Davies, 1997; Nix, 2009). Although here only one spring experiment was involved, an indication that greater yields may be obtained under spring-sown conditions was demonstrated .

As for the wheat, concerning the bean SY it was demonstrated that the spring-sown experiment (Experiment 3) out-yielded the winter-sown one (Experiment 1) slightly (not significantly; Fig. 17), suggesting that the former was more productive than the latter. Haymes and Lee (1999) obtained spring bean SY of up to 400 g/m². This compares well with the maximum bean SY (across the experiments) but greater than the spring bean maximum SY. The fact that the TIC SY was substantially greater in the spring-sown experiment than in the winter-sown ones (Fig. 18), was due to lesser inter-specific competition between wheat plants and bean plants in the intercrop for the former compare to the latter due to factors explained previously. As explained concerning the wheat, this finding is inconsistent with the wider literature, where winter-sown crop had been shown to produce more SYs than the spring-sown crop (Gooding and Davies, 1997). Thus, it is obvious this finding has positive implication for the prospective grower of wheat/bean intercrop, since the spring-sown crops have shorter duration than the autumn-sown ones (Gooding *et al.,* 2002; Pristeri *et al.,* 2006). However, more work is required to ascertain the findings of this research as regards the out-yielding of the winter-sown crop by the spring-sown crop, since here only one spring-sown crop was investigated.

Estimates of seed yield decline/facilitations due to intercropping

It was obvious that that for the majority of the experiments carried out both wheat and bean yields were reduced due to intercropping (Tables 3- 6, 8- 11, 13 and 14). With such high yield decline because of intercropping it is sensible to expect the recommended sr for intercropping each of the two component sole crops to be lower than the recommended values for their sole crops (Bulson, 1991; Bulson et *al.,* 1997; Haymes and Lee, 1999). It was interesting to note that for the majority of the experiments carried out maximum TIC SY obtained at the maximum sr did not out-yields that obtained at 100 and/or 75 wheat seeds/m² . Moreover, for each of the two-component crops yield decline were less severe at 100 and/or 75 wheat seeds/m². This reiterates that the recommended sr for intercropping the two components crops is substantially lower than the recommended values for each of the two component sole crops in agreement with the literature (Bulson et *al.,* 1997; Haymes and Lee, 1999). Based on these results for the wheat, it can be asserted that 100-wheat seeds/m² or lower should be sown under intercropping conditions. For the bean, except Experiment 5 where wide bsr were sown, most of the experiments had only 40-bean seeds/m² sr, so conclusion for wider adoption cannot be drawn here. However, in respect of the experiments carried out here and given the fact that bean was the minor component, for greater intercrop productivity and to minimize yield, 100-wheat seeds/m² or lower can be intercrop with 40 and/or 30-bean seeds/m².

The literature indicates that wheat quality attributes related to the bread making qualities are often associated with the protein content of the seed, which in turn is related to the N concentration of the seed (Bulson *et al.,* 1997; Gooding and Davies, 1997). Here though intercropping reduced wheat SYs in most of the experiments it could have been associated with greater concentration of N in the seed for the intercrop wheat compared to the sole crops (Gooding *et al.,* 2007). Here, quality attributes were not investigated, but previous investigations suggest that WIC SY reduction is often compensated by greater N concentration in the seed (Bulson, 1991; Bulson *et al.,* 1997; Gooding *et al.,* 2007). This implies that intercropping wheat with bean has the potential to improve the quality of wheat. It should be pointed out that the quality attributes of wheat are not determined by N concentration only (Gooding and Davies, 1997). However, other quality attributes such as moisture contents, presence of impurities such as stones, weed seeds etc can be easily taken care in the laboratory (Gooding and Davies, 1997), but the N concentration of the seed even though related to the moisture content cannot be easily manipulated in the laboratory. Moreover, the fact that averaged across wsr, intercrops were able to suppress weeds better than the sole crops in most of the experiments reported here suggests that impurities such as weed seeds may be lower for the intercrop compare to the sole crops (data not presented).

Physiological and agronomic implications of the study

For the wheat, the little differences seen between seed yields at lower sr and the ones with higher sr in some of the experiments here can be attributed to the plastic nature of the wheat crop (Whaley *et al.,* 2000; Gooding *et al.,* 2002). From the standpoint of crop physiology, SY may be source and/or sink driven (Fischer, 2007; Reynolds *et al.,* 2007). In other words, the crop needs to produce sufficient receptors for assimilates produced by the canopy through the process of photosynthesis (Foulkes *et al.,* 2007; Reynolds *et al.,* 2005). For the wheat, one way of guaranteeing adequate provision for the storage of assimilates produced is by producing tillers that may survive to bear ears (Whaley *et al.,* 2000). It might be argued that whilst wheat at the lower sr may be mainly source limited, because of lower canopy coverage despite greater tillering capacity, it may not be clear whether wheat yields at higher sr are source or sink limited. It may be possible that at higher sr, the main limitation would be the sink rather than the source. This is because though at higher sr total canopy coverage may be obtained, this may be associated with lower sink capacity for the assimilates produced to be partitioned to the reproductive parts. More plants per unit area invariably mean lesser ability to produce tillers that might bear ears and/or reduction in the sizes of the fertile ears (Whaley *et al.,* 2000; Azam-Ali and Squire, 2002; Gooding *et al.,* 2002). Thus, similar yields to plots with lower sr may be possible, and this may be reflected in lesser differences between plots with higher sr and the ones with lower ones as was found in some experiments here (e.g. Experiment 4). The benefits of wheat/bean intercrop as regards source-sink relations compared to the sole crops is that the even at lower sr, source may pose a limited problems to yield, since total canopy coverage may be obtained earlier. However, due to intense competition within the intercrop particularly at the higher sr, it is likely that some sink limitation may be unavoidable.

It should be emphasised that in the present research for the conventional experiments, higher wheat SY would have been obtained had a higher N rate been applied in the experiments reported here. Nix (2009) stated that the recommended N rate for application to wheat in the UK is 210 kg/ha. The higher N applied in other experiments might explain the disparity between the yields obtained in those experiments compare with the maximum wheat SY seen here. For instance, see the study of Foulkes *et al.* (2007) and compare the yields they obtained with the present investigations in relation to applied N. Here it was only in Experiment 5 that up to 120 kg N/ha was applied. Thus, the higher wheat SY found in that experiment even at 100-wheat seeds/m^2 compared to the other experiments was not surprising (Fig. 15 and 16). It should be reiterated that the lower N rates applied to the WSC here was to allow for valid comparisons with the intercrop treatments (Fukai and Trenbath, 1993; Azam-Ali and Squire, 2002; Yahuza, 2011a).

My research demonstrated that 100-wheat seeds/m^2 might be sufficient to intercrop with bean at 40-bean seeds/m^2 or lower under a range of conditions. Whilst in the UK, recommended sr for winter wheat is about 200-250 seeds/m^2 (Gooding *et al.,* 2002), here it was shown that for the majority of the experiments carried out lower sr may be sufficient under intercropping. In agreement with this results, previous studies have also indicated that sr were different for the sole crops and the intercrops (Hongo, 1995; Haymes and Lee, 1999). However, under organic system yields obtained at 200-wheat seeds/m^2 differed substantially from others. Thus, under organic systems, increasing wsr up to 200-wheat seeds/m^2 may be justified. Nevertheless, given that here beans in the organic experiment were diseased suggests that more work is required to clarify whether recommended sr may differ as was indicated in this study.

Conclusions

The present research had succeeded in quantifying the seed yields for wheat/bean intercropping system using yield-density equations derived from the literature and others proposed here. For the majority of the experiments wheat yields, whether sole cropped or intercropped responded asymptotically to wsr. On the other hand, bean yield declined as wsr increased in most cases, whilst total intercrop yield response was asymptotic in at least two of the experiment, following similar pattern as the wheat. This study showed that though averaged across wsr, for the mean effects of intercropping TIC SY was substantially greater in three experiments; TIC did not produce significantly greater yields than the WSC as wsr increased. Therefore, it was concluded that agronomic tools such as different sowing date, compatible varieties and sowing depth be employed in addition to sr to minimise competition. Nevertheless, this study indicate that 100 wheat seeds/m^2 or lower may be appropriate to intercrop with faba bean at 40 bean seeds/m^2 or lower for the majority of the experiments carried out in order to reduce competition. This indicates that recommended sr for intercropping wheat with bean in the UK, is substantially lower than the 200-250 wheat seeds/m^2 recommended for the sole crops. Consequently, it was clear that except wheat and bean component crops are sown at sr substantially lower than their sole crops recommended sr, substantial yield reductions due to intercropping cannot be avoided.

Moreover, in the first cropping year, it was demonstrated that the maximum WSC and WIC SYs were substantially greater under the organically-managed experiment than the conventionally-managed one. Thus, this finding is at variance with the literature, except that here the organic experiment was not repeated. Similarly, in the first cropping year, it was shown that whilst spring-sown wheat, whether sole cropped or intercropped performed better than winter-sown one, the yields of spring and the winter beans were similar. Despite the fact that only one spring-sown experiment was involved in my research, this result had indicated positive potentials for growing spring-sown wheat/bean intercrop instead of the winter-sown one.

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