



## Biomass yields, radiation interception and radiation use efficiency as influenced by seed rate in a cereal/legume intercropping system

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### Abstract

For a cereal/legume intercrop, yield improvement under well-watered conditions depends on greater interception and use of photosynthetically active radiation (PAR) by the intercrop. However, in wheat/faba bean (bean) intercropping system, the effects of sowing rate (sr) on productivity is not well investigated. Findings from five field experiments indicate that mostly the wheat biomass yields (BY) responses to sr were asymptotic. A maximum wheat sole crop BY of up to 1428 g/m<sup>2</sup> was found in one of the experiments. Except in one experiment where bean sole crop produced BY of up to 1037 g/m<sup>2</sup>: bean produced lower biomass than the wheat sole crop. The total intercrop produced greater BY than the wheat sole crop in two of the experiments. Across the experiments, the maximum intercepted PAR was 711 MJ/m<sup>2</sup> and 641 MJ/m<sup>2</sup> for the wheat sole crop and bean sole crop respectively. In some experiments intercropping improved the PAR interception. Mostly, the maximum wheat sole crop RUE was lower than 3 g/MJ PAR: occasionally intercropping improved the estimates significantly. Intercropping was more efficient than sole cropping as indicated by the total intercrop crop performance ratio (CPR) values for the BY, which were greater than unity with a maximum value of up to 1.63 obtained in one of the experiments. Positive CPR values for intercepted PAR and/or RUE were found at the intercrop that produced greater biomass. This research indicates that wheat/bean intercropping system is beneficial because whilst wheat might use transmitted radiation to produce, bean might use direct irradiance to produce.

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## Introduction

The influence of biomass yields (BY) as a major determinant of seed yield is well-documented (Biscoe and Gallagher, 1978; Giunta *et al.*, 2009; Confalone, 2010). Typically provided the crop is well nourished and not deficient of water the BY response to increase in plant population density (p) is asymptotic (Willey and Heath, 1969; Dolman, 1985; Park *et al.*, 2002). For the wheat sole crop, for example, it had been documented that the BY response to seed rate (sr) or p is asymptotic, following similar pattern as the seed yields (Gooding *et al.*, 2002; Yahuza, 2011a). Therefore, an understanding of biomass yield-density relations is necessary since it is one of the main determinants of seed yields (Fisher, 2007; Neumann *et al.*, 2009). Whilst the harvest index (HI) is also a determinant of seed yield, there are several evidences to indicate that it is less variable compare to the BY (Foulkes *et al.*, 2007). Worldwide cereal/legume intercropping system had received greater attention due to the evidences that it affords greater productivity than sole cropping (Marshall and Willey, 1983; Helenius and Jokinen, 1994; Azam-Ali and Squire, 2002). Nevertheless, for wheat (*Triticum aestivum* L.)/faba bean (*Vicia faba* L.; bean) intercropping system, biomass yield-density relations is not well understood despite earlier work carried out on this intercrop combination (Bulson *et al.*, 1997; Haymes and Lee, 1999). Thus, further works is needed in order to understand biomass yield-density relations for this intercrop combination, particularly under different contrasting growing conditions.

Solar radiation is a flux of electromagnetic energy, which must be intercepted and utilized instantaneously, as it cannot be stored for later use (Azam-Ali and Squire, 2002). These authors contended that its importance lies in its vital role in photosynthesis, evaporation and transpiration. The biomass accumulated by a crop largely depends on the amount of photosynthetically active radiation (PAR) intercepted and the efficiency of the use of the intercepted radiation, provided water and nutrients are not limiting (Marshall and Willey, 1983; Awal *et*

*al.*, 2006; Confalone *et al.*, 2010). Thus, as equally important as the amount of radiation intercepted by the crop, is the radiation use efficiency (RUE), defined as the efficiency, with which the crop uses the intercepted radiation (Azam-Ali and Squire, 2002; Zhang *et al.*, 2008 ; Yahuza, 2011b). In general, any agronomic management practice that allows the crop to remain healthy and intercept more radiation is necessary in order to improve productivity (Biscoe and Gallagher, 1978; Vandermeer, 1989; Carretero *et al.*, 2010). This is because provided water is not in short supply, the amount of BY produced by any given crops depends on the amount of radiation intercepted which itself is largely determined by the size of the leaf area and its distribution with time (Biscoe and Gallagher, 1978). For the wheat sole crop, there has been an evidence to indicate that the accumulated PAR normally follows similar asymptotic pattern as the BY in response to sr (Gooding *et al.*, 2002; Yahuza, 2011a). Intercropping is also another way to improve the PAR interception by the crop (Awal *et al.*, 2006; Zhang *et al.*, 2007; 2008; Jahansooz *et al.*, 2007). However, only a few studies on wheat/bean intercropping system had presented data on light capture previously (Hongo, 1995; Haymes and Lee, 1999). Hence, further investigations aimed at understanding light capture by this intercrop compared to their component sole crops is necessary in order to explain variation in BY between the sole crops and intercrops.

It is widely agreed that no intercropping research is complete without comparing the performance of the intercrops to that of their component sole crops using at least one index (Vandermeer, 1989; Azam-Ali and Squire, 2002). In general, the land equivalent ratio (LER) is the most widely adopted index, perhaps because of the agronomic implication of any value found when the index is used (Willey, 1985; Yahuza, 2011c). Harris *et al.* (1987) proposed the concept of crop performance ratio (CPR) to assess the performance of intercrops compare to the component sole crops due to limitations of the LER. Consequently, unlike the LER, the literature indicate

that the CPR is the appropriate index for calculating the biological advantage of intercrop compare to the component sole crops, because the index calculates the efficiency with which resources such as radiation are used to produce dry matter (Harris *et al.*, 1987; Azam Ali *et al.*, 1990). However, similar to the LER, a value of CPR greater than 1 indicates an intercrop advantage and a CPR less than 1 an intercrop disadvantage (Azam-Ali and Squire, 2002). Based on evaluations using the LER, the practical benefits of wheat /bean intercropping system were demonstrated in the United Kingdom (UK) previously (Hongo, 1995; Haymes and Lee, 1999), but none of these investigations made use of CPR, which has different interpretation (Azam-Ali and Squire, 2002). Thus, given its interpretation, it is important that the CPR is used here since radiation interception and use is one of the main thrust of this research, and the LER is clearly limited in this case (Harris *et al.*, 1987; Azam-Ali and Squire, 2002).

The objectives of this paper are as follows 1. To quantify the biomass yields response to sr, and make comparisons across the experiments. 2. To establish accumulated PAR-density relationship aimed at explaining variation in BYs. 3. To determine the effects of sr on the radiation use efficiency in order to explain variation in BYs. 4. To evaluate intercrop performance based on crop performance ratio.

## Materials and methods

### Study area

The experiments reported in this paper were carried out at the University of Reading's Crop Research Unit, Sonning, Berkshire, UK (0° 56' W, 51° 27' N). Long-term mean monthly rainfall (47 years mean), solar radiation and temperature (37 year mean) for the site ranges from 40.1-67.3 mm, 2-17.5 MJ/m<sup>2</sup>/day and 5.1-17.3 °C respectively (Yahuza, 2012). 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, soil samples were taken at the end of February each cropping year at random locations in the field 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 1).

### Experimental designs, treatments and crop management

Experiment 1 (autumn-sown conventional experiment, 2005-2006) was a complete factorial combination of five wheat seed rates (wsr) (0, 10, 50,100,200 seeds/m<sup>2</sup>) with or without 40 seeds/m<sup>2</sup> of bean randomized in four blocks with wsr as the main plot factor and bean treatment as the split-plot factor. However, in addition the design was complicated by a further factor, sulphur (S). The S treatment main plots had an area 10m x 20m. The S treatment were with and without 40 kg SO<sub>4</sub> /ha. The wsr plot had an area 10m x 4m. The experimental design of 40 plots was based on the additive intercropping design. Each bean treatment subplot had an area of 10m x 2m or 0.002 hectare (ha). The experiment followed 3 years of leys of unfertilized perennial rye grass (*Lolium perenne*). The experimental site was ploughed and harrowed on 5 and 6 September 2005, respectively. The wheat cultivar (Mallaca) and bean cultivar (Clipper) were both drilled on the 17 October 2005. For the intercrop, there were equidistant alternate rows between wheat and bean. Plot layout for the intercrop comprised 8 rows of wheat and 8 separate rows of bean for the intercrop plots (i.e. not mixed together within a row), whereas the sole crop had only 8 rows. For the S treatment, Nitram (ammonium nitrate granules, (34.5%N)) was applied to blocks 1 and 3 at 264 kg/ha, equivalent to 91 kg N/ha at 169 days after sowing (DAS), at GS 30 (Zadoks *et al.*, 1974). This was carried out by spraying the fertilizer onto the crops. Similarly, Nitram was applied to blocks 2 and 4 at 178 kg/ha in addition to double top (ammonium sulphate) at 116 kg/ha, which was equivalent in total to 92 kg N/ha and 35 kg SO<sub>4</sub>/ha.

Glyphosate (*N*-(phosphonomethyl)glycine) was sprayed on 2 August 2005 before establishment.

Note that in this experiment no herbicide was sprayed after establishment. Hence, with respect to herbicide application, this experiment might be referred to as low input intercrop. However, in this research this experiment is regarded as a conventional experiment. Fungicide was applied on 5 April 2006 at GS 31 as Folicur (tebuconazole) at 1 litre/ha, Clortosip (chlorothalonil) at 2 litres/ha, Cleancrop (fenpropimorph) at 1 litre/ha all in 260 litres /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.

Experiment 2 (autumn-sown organic experiment 2005-2006), was similar to Experiment 1 in design, except that this experiment was managed organically. However, the site and indeed the farm is not a certified organic farm. The field was left under a perennial rye grass and red clover (*Trifolium pratense*) ley for 3 years. This was to help replenish soil fertility and protect the crops from pest and disease build up. Hence, as depicted in Table 1, the experimental site accumulated substantial N for use by the following crop (i.e. the present first arable crop). The experimental site was ploughed and harrowed on 5 and 6 September 2005, respectively. The wheat cultivar (Mallaca) and bean cultivar (Clipper) were both drilled on 17 October 2005. For the S treatment, on Wednesday 19 April 2006, Thiovit Jet, which is 80% S was applied to block 2 and 4 by spraying directly onto the crop. This was applied at a rate of 20 kg/ha, which was equivalent to 16 kg S/ha. It was equivalent to 40 kg SO<sub>4</sub>/ha.

Experiment 3 consist of spring wheat (cv. Paragon) sr (0, 30, 75, 200, 400 and 650) seeds/m<sup>2</sup> with or without 40 seeds/m<sup>2</sup> 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. For the intercrop, there were equidistant alternate rows between wheat and bean. Plot layout for this experiment comprised 8 rows of wheat and 8 separate rows of bean for the intercrop plots (i.e. not mixed together within a row), whereas the sole crop

had only 8 rows. The experiment had 48 plots each with an area of 10m x 2m and was drilled on 2 March 2006. The crops were sprayed with 3.3 litres BASF 'Claymore' (pendimethalin) per ha in 200 litres of water on 11 March 2006 (pre-emergence of the bean). Fungicide was applied on Wednesday 7 June 2006 as tebuconazole at 1 litre per ha, chlorothalonil at 2 litres per ha and fenpropimorph at 1 litre per ha all in 260 litres of water/ha. At 84 DAS, 177 kg/ha of Nitram fertilizer was applied. This was equivalent to 60 kg N/ha.

Experiment 4 consist of five wheat (cv Mallaca) sr (0, 25, 75, 150, 400 seeds/m<sup>2</sup>) with or without 30 seeds/m<sup>2</sup> bean (cv Clipper) treatment as affected by three bean sowing dates (BSD; Yahuza, 2012). The experiment was laid-out in a randomized complete block design replicated in 3 blocks. Note that the bean sowing date factor was nested within the bean treatment (Yahuza, 2012). The experiment consisted of 60 plots each with an area of 2m x 15m. For the intercrop, there were equidistant alternate rows between wheat and bean. Plot layout for this experiment comprised 8 rows of wheat and 8 separate rows of beans for the intercrop plots (i.e. not mixed together within a row), whereas the sole crop had only 8 rows. The first sowing (SSWB) was carried out on 30 October 2006. The second bean was drilled on 22 November 2006 (SB23DAW). The last bean sowing was Wednesday 6 December 2006 (SB37DAW). For weed control, on 3 November 2006 pendimethalin was sprayed on pure wheat plots and SSWB intercrop at a rate of 3.3 l/ha in 200 litres of water (pre-emergence of the bean). Similarly, pendimethalin was applied to SB23DAW intercrop on Wednesday 29 November 2006 at a rate of 3.3 l/ha in 200 litres of water (pre-emergence of the beans). In addition, SB37DAW were sprayed with pendimethalin on 8 December 2006 at a rate of 3.3 l/ha in 200 litres of water (pre-emergence of the bean). At growth stage 31 fungicide were sprayed as chlorothalonil at 2 l/ha, tebuconazole at 1 l/ha and fenpropimorph at 1 l/ha all in 240 l of water. Similarly, at GS 31, 250 kg/ha of Nitram fertilizer was applied. This was equivalent to 86 kg N/ha.

Experiment 5 was based on a conventional response surface (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/m<sup>2</sup>) and five bean (cv. Clipper) sr (0, 5, 20, 40, 80 bean seeds/ m<sup>2</sup>) randomized in 3 blocks 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 pendimethalin at a rate of 3.3 litres per ha in 200 litres of water. On 8 April 2008, tebuconazole was applied at 1 litre per ha, fenpropimorph at 1 litre per ha and chlorothalonil at 2 litres per ha all in 210 litres per ha of water. Similarly, at GS 30, 348 kg/ha of Nitram was applied per hectare. This was equivalent to 120 kg N per ha.

#### Radiation measurements and calculations

The PAR intercepted by the crop was assessed at approximately 15-day intervals at five random locations in each plot. Measurements were carried out with a 1-m-long bar ceptometer containing 80 sensors (Delta-T-Decagons sunflecks S. F-80 Delta-T Devices Ltd, Cambridge, UK), above the canopy and below it. The assessment was usually carried out between the hours of 11.00-14.00 hours on clear days. The procedures described by several authors (Gooding *et al.*, 2002; Yahuza, 2011b) to calculate the total amount of PAR intercepted per day and then over the life of the crop was followed. Based on the procedures described by these authors, the fractional PAR interception per day were determined. The proportion of intercepted PAR by the canopy, usually called radiation interception efficiency (RIE) (Carretero *et al.*, 2010) was calculated as the ratio between the difference of incident PAR (i.e. PAR above the canopy) and transmitted PAR (i.e. PAR below the canopy) to the incident PAR (PAR above the canopy) as given in equation 1.

$$RIE = \left( \frac{(I_o - t)}{I_o} \right) \quad 1$$

Where I<sub>o</sub> and t refers to PAR above (incident PAR) and below (transmitted PAR) the canopy respectively.

Thereafter, following the methods of Kindred and Gooding (2005), logistic curve was fitted to the mean values of the RIE x thermal time (tt) (i.e. accumulated temperature from sowing until maturity) for each plot to derive fractional PAR intercepted per day (PAR<sub>f</sub>) using equation 2

$$PAR_f = \frac{c}{1 + e^{(-bx(tt-m))}} \quad 2$$

Where c = maximum PAR intercepted, m = tt at 50 % of the maximum PAR interception and b = logistic rate scalar for light interception.

The thermal time was calculated from the weather data obtained from the automotive equipment at the site. This was accomplished by summing the daily mean air temperature above a threshold (base temperature) 0° C from sowing until maturity (Giunta *et al.*, 2009). Subsequently, these values were multiplied with the daily incident (global) radiation recorded at the automated weather station situated nearby (but within the experimental site) to calculate the total amount of PAR intercepted per day and then over the life of the crop (Kindred and Gooding, 2005). This is also called the accumulated, cumulative or total intercepted PAR. Following, Giunta *et al.* (2009) conversion of the daily total radiation receipt to PAR was assumed as 0.5. Subsequently, equations including hyperbolic yield-density equations were applied to quantify the effects of sr on the accumulated PAR, where applicable (Gooding *et al.*, 2002).

Following the procedure described by several authors (Gooding *et al.*, 2002; Jahansooz *et al.*, 2007; Yahuza, 2011b), the radiation use efficiency (RUE) (g/MJ) was calculated by dividing the final above-ground biomass (g/m<sup>2</sup>) by the accumulated PAR (MJ/m<sup>2</sup>). Note that in this paper except if

otherwise stated, the RUE refers to the efficiency of conversion of accumulated PAR from sowing until maturity.

#### *Final biomass yields determination*

The above-ground biomass for both wheat and bean were collected from destructive samples taken from 1m x 0.5m area with a quadrat at maturity. Four rows were included for sole crop plot and eight for the intercrops and the plants were cut at the soil surface. Samples were separated into the components, weighed, placed in dishes labelled and packed in ovens and dried at a temperature of 85°C for 48 hours. After drying, the samples were weighed. To get a precise estimate of final BY, the procedure described by Gooding *et al.* (2002) was followed. In Experiments 1 and 2, the assessment was carried out 293 DAS. On the other hand, in Experiment 3, the final BY was determined at 152 DAS. Similarly, in Experiments 4 and 5 the final BY was assessed 287 and 270 DAS respectively. Total intercrop final BY was calculated simply by adding wheat intercrop and bean intercrop BYs.

#### *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<sup>2</sup> 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 (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 were analysed using the General ANOVA with the treatment structure given as pol (wsr; 3) x (bean/BSD). This means that the BSD

factor was nested within the bean treatment. The block structure was the replications. However, as stated earlier in this paper means presented are averages across the three BSD. 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 the replications.

Regressions mainly using hyperbolic yield-density equations (Willey and Heath, 1969; Bleasdale, 1984; Yahuza, 2011a) were performed across wsr particularly for the 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<sup>2</sup> was compared with equation 3 to determine whether it fitted better when the response to wsr deviated significantly from linearity.

$$Y = \frac{wsr}{a_w + b_w} \quad 3$$

In equation 3, Y = yield (g/m<sup>2</sup>), a<sub>w</sub> and b<sub>w</sub> 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<sup>2</sup>).

Typically, where equation 3 holds, the responses of the reciprocals of yield per plant to density is linear (Bleasdale, 1984) as described by equation 4,

$$1/w = a_w + b_w wsr \quad 4$$

In equation 4, w = yield per plant, a<sub>w</sub> and b<sub>w</sub> are constants as defined in equation 3.

However, besides applying more complicated equations other than equation 3 to quantify the BYs, other simpler or more complicated ones were applied. In addition, for Experiment 5, the inter-specific yield-density equations (Dolman, 1985; Park *et al.*, 2002) were applied to quantify the wheat and total intercrop BYs.

*Estimating intercrop performance*

Intercrop performance was estimated based on evaluations using crop performance ratio. For the biomass and accumulated PAR, CPR was calculated according to the procedures described by Harris *et al.* (1987) and Yahuza (2011c). The proportion-sown area was 50% (0.5) wheat and 50% (0.5) bean for each of the experiments. This was because for the intercrops, a row of wheat was followed by a row of bean. Therefore, the yield per unit area of wheat in the intercrop  $WY_i$  was divided by the proportion  $P_{iw}$ , of wheat in the intercrop to give the yield per unit area sown to wheat. This quantity was then expressed as a fraction of wheat in the sole plot,  $WY_s$  to give CPR. Similar calculations were also done for the bean, thus allowing the total intercrop CPR (TCPR) to be calculated. Hence, wheat CPR, bean CPR and total intercrop CPR were calculated using equations 5, 6 and 7 respectively.

$$CPR_{wheat} = \frac{WY_i}{P_{iw} WY_s} \quad 5$$

$$CPR_{bean} = \frac{BY_i}{P_{ib} BY_s} \quad 6$$

$$TCPR_{wheat+bean} = \frac{WY_i + BY_i}{P_{iw} WY_s + P_{ib} BY_s} \quad 7$$

In equations 5-7,  $WY_i$  and  $WY_s$  are wheat yields per unit area ( $g/m^2$ ) in the intercrop and sole crop respectively, and  $P_{iw}$  is the proportional sown area of wheat in the intercrop (which was 0.5). Similarly,  $BY_i$  and  $BY_s$  are bean yields per unit area ( $g/m^2$ ) in the intercrop and sole crop respectively, and  $P_{ib}$  is the proportional sown area of bean in the intercrop (which was 0.5).

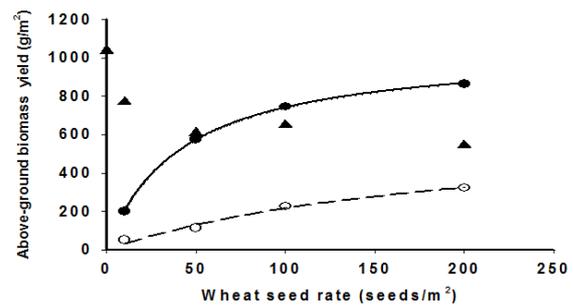
With respect to the calculation of CPR for the RUE, given that this variable is not necessarily affected by density, the CPR for the RUE was calculated simply by dividing by the sole crop that gave the maximum RUE (Harris *et al.*, 1987).

**Results**

*Responses of the biomass yields to seed rate*

Responses of the biomass yields to seed rate in Experiment 1:

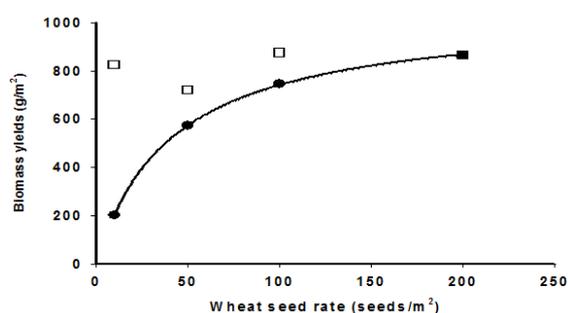
In Experiment 1, wheat BY increased with increase in wsr ( $P < 0.001$  for quadratic wsr). Wheat BY were substantially reduced ( $P < 0.001$  for bean treatment) by intercropping. Averaged across wsr, for the mean effects of intercropping wheat BY were  $596 g/m^2$  and  $179 g/m^2$  for 0 and 40-bean seeds/ $m^2$  respectively (SED 42.9, DF 12). The interactive effect of wsr and intercropping was significant ( $P = 0.050$  for quadratic wsr x bean treatment). For the interactive effects, wheat sole crop produced significantly more BY than the wheat intercrop at 100 and 200-wheat seeds/ $m^2$  (Figure 1). The maximum wheat sole crop BY of  $864 g/m^2$  was obtained at 200-wheat seeds/ $m^2$  (Figure 1; SED 71.1, DF 19.06). For the intercrop, the maximum BY of  $323 g/m^2$  was obtained at 200-wheat seeds/ $m^2$  (Fig. 1).



**Fig. 1.** Effect of wsr on biomass yields ( $g/m^2$ ) for winter wheat (cv. Mallaca) sole crop ● (solid curve), wheat intercrop ○ (broken curve) and winter faba bean (cv Clipper) ▲ in Experiment 1. The parameter values for the equation 3 applied to the wheat sole crop BY are  $a_w$  (estimate 0.06595 s.e 0.00883) and  $b_w$  (estimate 0.001584 s.e 0.000188). Similarly, the parameter values for equation 3 fits to the wheat intercrop BY are  $a_w$  (estimate 0.3045 s.e 0.0616)  $b_w$  (estimate 0.001556 s.e 0.000418).

Equation 3 quantified the responses of wheat sole crop BY as wsr increased satisfactorily (Figure 1). The coefficient of determination for the equation applied was 95.2 %. The predicted asymptotic yield for the wheat sole crop BY was determined as  $631 g/m^2$ . However, the maximum wheat sole crop BY

from the result was greater than the predicted value (Fig. 1). Similarly, equation 3 quantified the responses of wheat intercrop BY satisfactorily (Fig. 1). The coefficient of determination for the equation 3 applied was 97.0%. The predicted asymptotic yield for the wheat intercrop was determined as 643g/m<sup>2</sup>. This value was slightly greater than the predicted value for the sole crop. This suggests that intra-specific competition between wheat plants was greater than the inter-specific competition with the bean plants in the intercrop. In other words, a plant of wheat was more competitive with itself than with the bean. However, the maximum wheat intercrop BY from the results was substantially lower than the predicted value (Fig. 1).

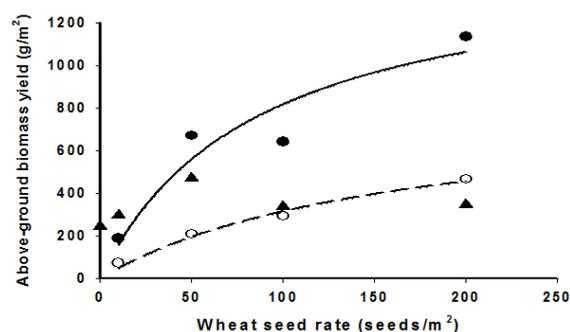


**Fig. 2.** Effect of wsr on the biomass yields (g/m<sup>2</sup>) for winter wheat (cv. Mallaca) sole crop● (solid curve) and the total intercrop □ in Experiment 1.

Wheat seed rate had significant effect on bean BY ( $P = 0.044$  for linear wsr). Bean sole crop produced greater biomass (1037 g/m<sup>2</sup>) compared to the intercrops (Figure 1). Compared to the sole bean, intercropping significantly reduced the BY at 50 and 200 wheat seeds/m<sup>2</sup> (SED 185.3, DF 12). The maximum bean intercrop yield of 772 g/m<sup>2</sup> was obtained at 10-wheat seeds/m<sup>2</sup> (Figure 1). Within the intercrop, BY did not differ significantly. Mean bean BY for all plots (including sole crop) = 722 g/m<sup>2</sup>.

Wheat seed rate had a significant effect on the total intercrop BY ( $P < 0.001$  for the linear wsr effect). The effect of bean treatment was also significant ( $P < 0.001$ ) and there was significant interactive effect detected with the wsr ( $P = 0.044$  for cubic wsr x bean effect). Averaged across wsr, for the mean effects of intercropping BY were 866 g/m<sup>2</sup> and 477 g/m<sup>2</sup> for 40

and 0-bean seeds/m<sup>2</sup> respectively (SED 57.2, DF 15). For the interactive effects of wsr and bean treatment, the maximum total intercrop BY of 877 g/m<sup>2</sup> was obtained at 100-wheat seeds/m<sup>2</sup> (Figure 2). However, except at 10-wheat seeds/m<sup>2</sup> where the total intercrop BY was significantly greater than that for the wheat sole crop, yields were similar between the total intercrop and the wheat sole crop as wsr increased (Figure 2; SED 127, DF 26.75). Also within the total intercrop, there was no significant difference between BYs as wsr increased. Hence, the total intercrop BY was not quantified (Figure 2). The bean sole crop BY (1037g/m<sup>2</sup>) was greater than that obtained by the total intercrop across wsr. At the lower sr bean contributed more BY to the total than did the wheat. On the other hand, at the higher wsr, the two component crops contributed substantially to the total BY.



**Fig. 3.** Effect of wheat seed rate on biomass yields (g/m<sup>2</sup>) for winter wheat (cv. Mallaca) sole crop● (solid curve), wheat intercrop ○ (broken curve) and winter faba bean (cv Clipper) ▲ in Experiment 2 (managed organically). The parameter values for the equations 3 applied to the wheat sole crop BY are  $a_w$  (estimate 0.0563 s.e 0.0281) and  $b_w$  (estimate 0.000660 s.e 0.000230). Similarly, the parameter values for equation 3 fit to the wheat intercrop BY are  $a_w$  (estimate 0.1960 s.e 0.0359) and  $b_w$  (estimate 0.001218 s.e 0.000252).

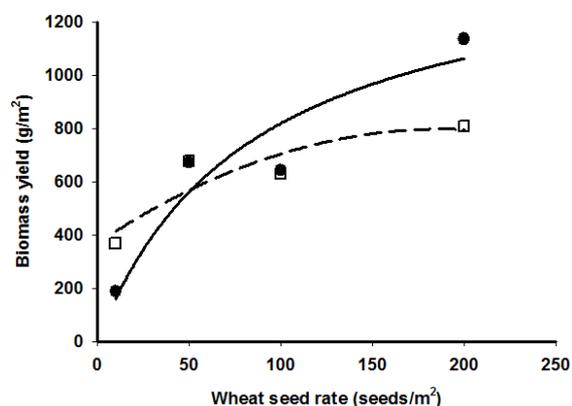
Responses of the biomass yields to seed rate in Experiment 2:

In Experiment 2, wheat BY increase as wsr increased ( $P = 0.022$  for cubic wsr). Intercropping substantially reduced the wheat BY ( $P < 0.001$  for bean treatment). There was a significant interactive effect detected ( $P = 0.003$  for linear wsr x bean

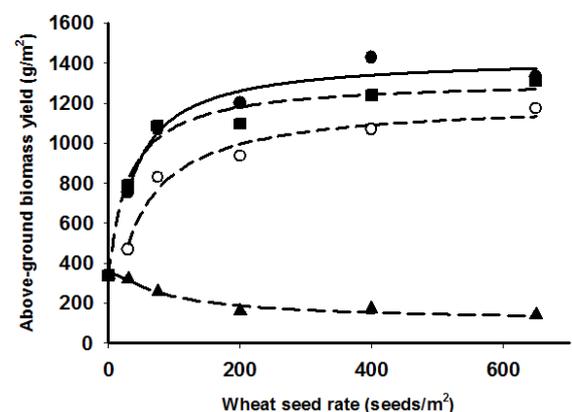
treatment). Averaged across wsr, for the mean effects of intercropping, wheat BY were 659 g/m<sup>2</sup> and 258 g/m<sup>2</sup> for 0 and 40 bean seeds/m<sup>2</sup> respectively (SED 47.2, DF 12). For the interactive effects, wheat BY was significantly greater for the sole crop at 50-wheat seeds/m<sup>2</sup> or more (Figure 3; SED 91.1, DF 20.89). The maximum wheat sole crop BY of 1136 g/m<sup>2</sup> was obtained at 200-wheat seeds/m<sup>2</sup> (Figure 3). The maximum BY for the wheat intercrop was 464 g/m<sup>2</sup> (Figure 3). Equation 3 quantified the response of wheat sole crop BY satisfactorily (Figure 3). The coefficient of determination for the equation applied was 83.5%. The predicted asymptotic BY for the wheat sole crop was 1515 g/m<sup>2</sup>. However, the maximum wheat sole crop BY of 1136 g/m<sup>2</sup> from the results was obtained at 200-wheat seeds/m<sup>2</sup> (Figure 3). Similarly, equation 3 fitted the response of the wheat intercrop BY to wsr satisfactorily (Figure 3). The coefficient of determination for the equation applied was 97.5%. Intercropping decreased the predicted asymptotic BY for the wheat down to 821 g/m<sup>2</sup>. Since this value was lower than the predicted value for the sole crop, it suggests that intra-specific competition between wheat plants was lower than the inter-specific competition with the bean plants in the intercrop. In other words, a plant of wheat was less competitive with itself than with the bean. This was not surprising in this experiment given the fact that the infection of beans with chocolate spot disease (*Botrytis fabae*; data not presented) meant that wheat was growing with lesser competition in the intercrop (in conditions similar to that for the sole crops). Nevertheless, the maximum wheat intercrop BY of 464 g/m<sup>2</sup> from the results, which was obtained at 200-wheat seeds/m<sup>2</sup> (Figure 3), was substantially lower than the predicted asymptotic yield.

The bean intercrops produced greater BY compared to the 242 g/m<sup>2</sup> of the sole crop (Figure 3). Maximum intercrop biomass of 471g/m<sup>2</sup> was obtained at 50-wheat seeds/m<sup>2</sup>. ANOVA indicate that the effect of wsr on bean BY was not significant ( $P > 0.05$ ; SED 108.9, DF 12). Accordingly, no regression line was fitted (Figure 3). Average bean

BY for all plots (i.e. both sole crops and intercrops) was 339 g/m<sup>2</sup>.

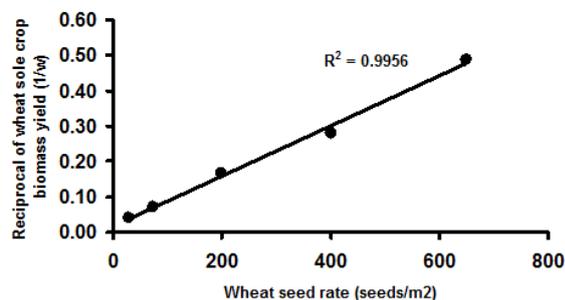


**Fig. 4.** Effect of wheat seed rate on the biomass yields (g/m<sup>2</sup>) for winter wheat (cv. Mallaca) sole crop ● (solid curve) and the total intercrop biomass yield □ (broken curve) in Experiment 2 (organically managed). For the total intercrop the parameter estimates for the equation 3 applied are  $a_w$  (estimate 0.01474 s.e 0.00571) and  $b_w$  (estimate 0.001251 s.e 0.000109).

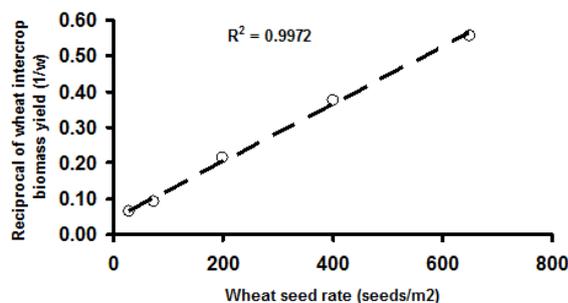


**Fig. 5.** Effect of wheat seed rate on biomass yields (g/m<sup>2</sup>) for spring wheat (cv. Paragon) sole crop ● (solid curve), wheat intercrop ○ (broken curve), spring faba bean (cv. Hobbit) ▲ (broken curve) and the total (i.e. including plots with zero wheat seed rate) ■ (broken curve) for Experiment 3. The parameter values for the equation 3 applied to the wheat sole crop BY are  $a_w$  (estimate 0.01885 s.e 0.00329) and  $b_w$  (estimate 0.0006990 s.e 0.0000258). Similarly, the parameter values for the simultaneous fits of equations 8, 3 and 9 to the total intercrop (plus bean sole crop), wheat intercrop and bean intercrop biomass yields are  $y_0$  (estimate 337.2 s.e. 31.7)  $a_{wt}$  (estimate 0.0327 s.e. 0.00541)  $b_{wt}$

(estimate 0.001023 s.e. 0.0000441 )  $a_{wi}$  (estimate 0.03553 s.e. 0.00373 ) and  $b_{wi}$  (estimate 0.000828 s.e. 0.0000229)



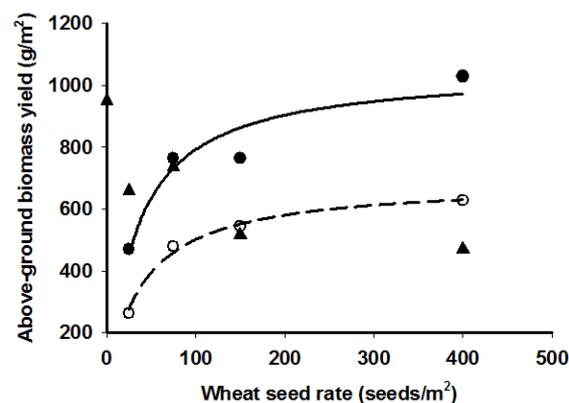
**Fig. 6.** Effect of wheat seed rate on the reciprocal of wheat sole crop biomass yield per plant • (solid line) for Experiment 3 (spring-sown). See the text for fitted equation and parameter values.



**Fig. 7.** Effect of wheat seed rate on the reciprocal of wheat intercrop biomass yield per plant ○ (broken line), for Experiment 3 (spring-sown). See the text for fitted equation and parameter values.

The total intercrop BY increased with increase in wsr ( $P = 0.004$  for quadratic wsr,  $P < 0.001$  for the cubic wsr effect). Bean treatment had no significant effect on the total intercrop BY ( $P > 0.05$ ), but there was a significant interactive effect detected between wsr and the bean ( $P = 0.006$  for linear wsr x bean effect). Averaged across wsr, for the mean effects of bean treatments BY were  $527 \text{ g/m}^2$  and  $545 \text{ g/m}^2$  for 0 and 40 bean seeds/ $\text{m}^2$  respectively (SED 60.9, DF 15). For the interactive effects, the maximum total intercrop BY of  $808 \text{ g/m}^2$  was obtained at 200 wheat seeds/ $\text{m}^2$ , but at that sr wheat sole crop BY was significantly greater (Figure 4; SED 118, DF 25.7). However, unlike in Experiment 1, from 50-wheat seeds/ $\text{m}^2$  or more both the wheat sole crop and the total intercrop produce greater BY than the bean sole crop. Thus, wheat contributed more BY than the bean in the intercrop (Figure 4). The total

intercrop BY was quantified using equation 3 (Figure 4). The coefficient of determination for the equation applied was 83.8 %. For this experiment both the wheat sole and intercrop, responses were also quantified using equation 3. Thus, in this experiment wheat appear to be the more competitive component in the intercrop as is indicated in Figure 4.



**Fig. 8.** Effect of wheat seed rate on biomass yields ( $\text{g/m}^2$ ) for winter wheat (cv. Mallaca) sole crop • (solid curve), wheat intercrop ○ (broken curve) and winter faba bean (cv Clipper) ▲ in Experiment 4. The parameter values for the equations 3 applied to the wheat sole crop BY are  $a_w$  (estimate 0.03136 s.e 0.00976) and  $b_w$  (estimate 0.0009508 s.e 0.0000894). Similarly, the parameter values for the fits of equation 3 to the wheat intercrop BY are  $a_w$  (estimate 0.05438 s.e 0.00524) and  $b_w$  (estimate 0.001452 s.e 0.0000451).

*Responses of the biomass yields to seed rate in Experiment 3:*

In Experiment 3, wheat BY increased with increase in wsr ( $P < 0.001$  for quadratic wsr). The effect of intercropping was significant ( $P < 0.001$ ) but wsr did not interact significantly with bean treatment ( $P > 0.05$  for wsr x bean treatment effects). Averaged across wsr, for the mean effect of intercropping, wheat sole crop produced significantly greater BY than the intercrop. The BY were  $1156 \text{ g/m}^2$  and  $896 \text{ g/m}^2$  for the wheat sole crops and intercrops respectively (SED 38.5, DF 15). For the interactive effects of wsr and intercropping, equation 3 quantified the response of wheat sole crop BY well (Figure 5; SED 97.4, DF 24.33). The coefficient of determination for the equation applied was 93.7%.

**Table 1.** Some chemical properties of the soil at the University farm, Sonning, Berkshire, UK during the cropping years.

Experiment (Cropping year)	pH	P (mg/l)	K (mg/l)	Mg (mg/l)	Available N @ 0-90 cm depth (kg N/ha)	Sulphate (mg/l)
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

**Table 2.** Estimated parameter values for the various equations fitted to the wheat intercrop BY for Experiment 5.

Fitted equation	Parameters estimates and standard errors (in bracket)				Coefficient of determination (%)
3	$a_w$ 0.03639 (0.00704)	$b_w$ 0.0008108 (0.0000487)			83.5
10	$a_w$ 0.02613 (0.00714)	$b_w$ 0.0008009 (0.0000427)	$c_w$ 0.00035 (0.000173)		87.1
11	$a_w$ 0.03191 (0.00885)	$b_w$ 0.0007413 (0.0000618)	$c_w$ 0.000132 (0.000238)	$d_w$ 0.00000202 (0.00000163)	87.9

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

**Table 3.** Estimated parameter values for the equations fitted to the total intercrop BY for Experiment 5, assuming all plants are counted in wheat equivalent.

Fitted equation	Parameters estimates and standard errors (in bracket)			Coefficient of determination (%)
3	$a_w$ 0.01607 (0.00336)	$b_w$ 0.0007694 (0.000034)	$c_w$	74.1
11	$a_w$ 0.02203 (0.00463)	$b_w$ 0.0007708 (0.0000295)	$c_w$ -0.0001607 (0.0000706)	80.4

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

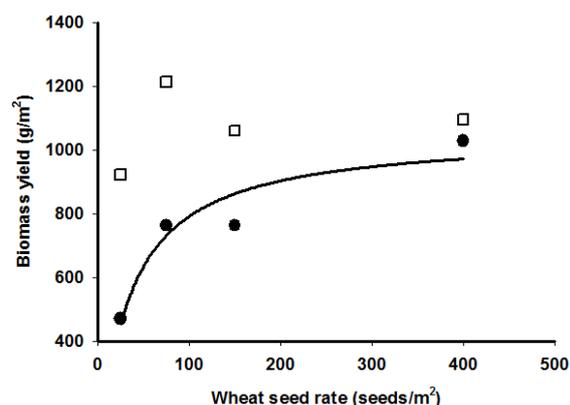
**Table 4.** Effects of wheat seed rate on wheat sole crop and total intercrop radiation use efficiency for Experiment 1.

Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop RUE (g/MJ)	Total intercrop RUE (g/MJ)
10	0.56	1.78
50	1.38	1.46
100	1.60	1.82
200	2.04	1.69
SED wsr x bean	0.27	
DF	26.7	

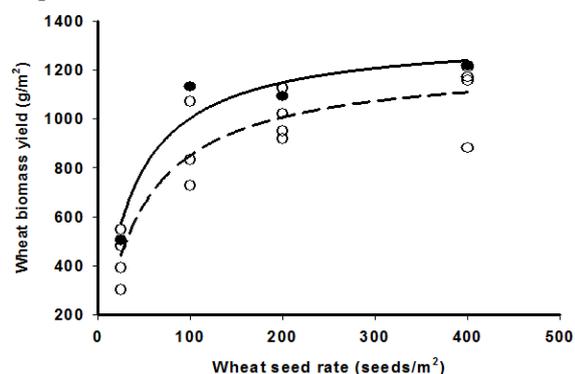
Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop RUE (g/MJ)	Total intercrop RUE (g/MJ)
0	0.00	1.29
30	3.04	2.69
75	3.95	3.56
200	4.03	3.52
400	4.58	3.84
650	4.38	4.00
SED wsr x bean	0.32	
DF	31.92	

**Table 5.** Effects of wheat seed rate on wheat sole crop and total intercrop radiation use efficiency for Experiment 2.

The predicted asymptotic yield for the wheat sole crop BY was determined as 1431 g/m<sup>2</sup>. The maximum wheat sole crop BY of 1428 g/m<sup>2</sup> from the results obtained at 400 seeds/m<sup>2</sup> (Figure 5) compares well with the predicted asymptotic yield. This indicates that equation 3 applied had satisfactorily described the data.



**Fig. 9.** Effect of wheat seed rate on the biomass yields (g/m<sup>2</sup>) for winter wheat (cv. Mallaca) sole crop ● (solid curve) and the total intercrop □ in Experiment 4.



**Fig. 10.** Effect of wheat seed rate (seeds/m<sup>2</sup>) on biomass yields (g/m<sup>2</sup>) for winter wheat (cv Mallaca) sole crop ● (solid curve) and wheat intercrop ○ (broken curve) in Experiment 5. The parameter values for the equations 3 applied to the wheat sole crop BY are  $a_w$  (estimate 0.02527 s.e 0.00848) and  $b_w$  (estimate 0.0007442 s.e 0.0000673). The parameter values for the equation 3 applied to the wheat intercrop BY is given in Table 2.

Similarly, wheat intercrops BY increase with increase in wsr (Figure 5). Hence, the total intercrops, wheat intercrop, and bean BYs responses were quantified simultaneously using equations 8, 3 and 9 respectively (Figure 5). The coefficient of

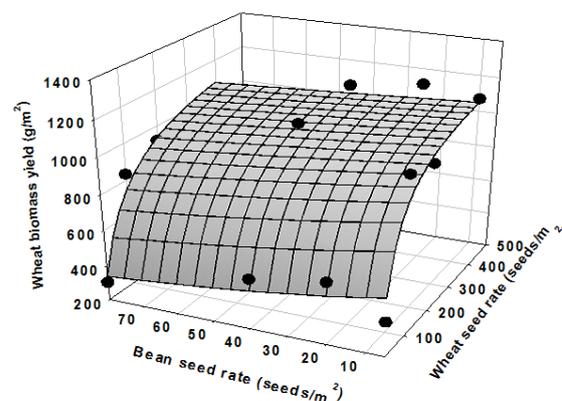
determination for the simultaneous fits using these equations was 98%. The predicted wheat intercrop BY was determined as 1207 g/m<sup>2</sup>. However, the maximum wheat intercrop BY of 1173 g/m<sup>2</sup> from the results obtained at 650-wheat seeds/m<sup>2</sup> was slightly lower.

$$Y = y_o + \left( \frac{wsr}{a_{wt} + b_{wt} wsr} \right) \quad 8$$

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

9

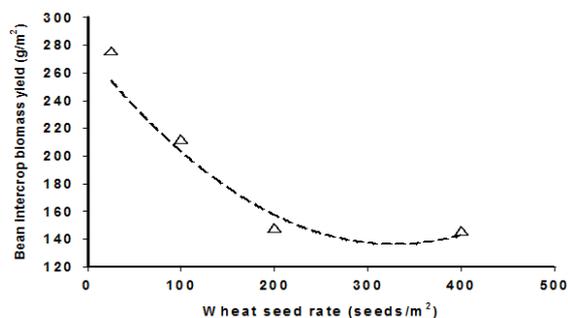
In equations 8 and 9, Y = yields (g/m<sup>2</sup>),  $y_o$  refers to bean sole crop yield (g/m<sup>2</sup>).  $a_w$  and  $b_w$  are constants such that  $1/a_w$  represents yield per plant in a competition free environment,  $y_o + (1/b_w)$  represents the predicted asymptotic (maximum) yield and wsr refers to wheat sowing rate (seeds/m<sup>2</sup>). The subscript t and i are used to distinguish parameter that refers to the total intercrop (t) from that referring to wheat intercrop (i).



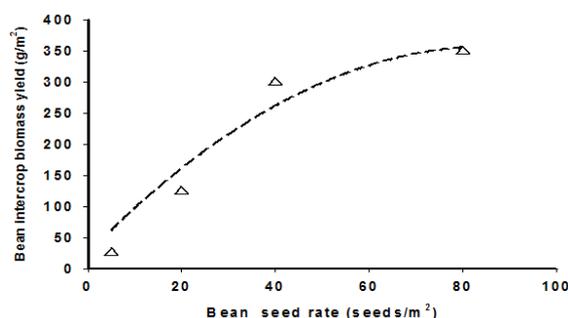
**Fig. 11.** Effect of of wheat and bean seed rates (seeds/m<sup>2</sup>) on biomass yield (g/m<sup>2</sup>) for winter wheat (cv. Mallaca) intercrop in Experiment 5. Equation 10 described the data and the parameter values are presented in Table 2. The filled circles are the observed data (result).

Wheat seed rate had significant effect on bean BY ( $P < 0.001$  for wsr). The bean sole crop produced greater BY (337.3 g/m<sup>2</sup>) compare to the intercrops in most cases (SED 25. 85, DF 15). The maximum bean intercrop BY of 320.4 g/m<sup>2</sup> was obtained at 30-wheat seeds/m<sup>2</sup>. From 75 wheat seeds/m<sup>2</sup> or more

intercropping significantly reduced bean BY as wsr increased (Figure 5). Equation 9 described the bean BY response to wsr well (Figure 5).



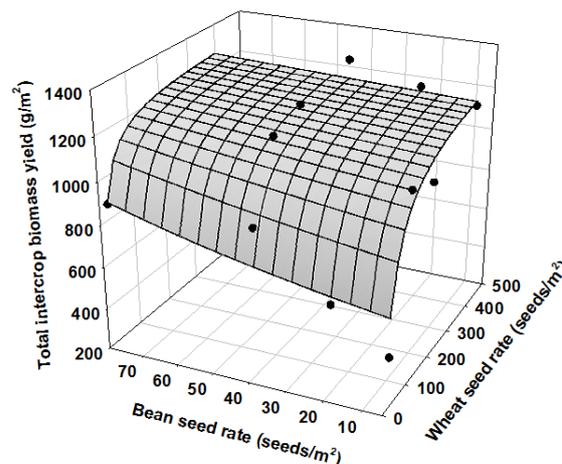
**Fig. 12.** Effect of wheat seed rate on winter faba bean (cv. Clipper) intercrop  $\Delta$  (broken curve) biomass yield ( $\text{g/m}^2$ ) in Experiment 5. The fitted equation and parameter values are given in the text.



**Fig. 13.** Effect of bean seed rate on winter faba bean (cv. Clipper) intercrop  $\Delta$  (broken curve) biomass yield ( $\text{g/m}^2$ ) in Experiment 5. The fitted equation and parameter values are given in the text.

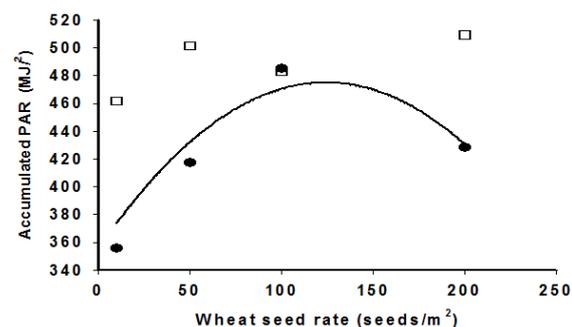
The total intercrop BY increased with increase in wsr ( $P < 0.001$  for each of quadratic and cubic wsr effects). The effect of the bean on the total intercrop BY was not significant ( $P > 0.05$ ), but there was a significant response to the interactive effect of wsr and bean detected ( $P = 0.001$  for quadratic wsr  $\times$  bean effect). Averaged across wsr, for the mean effects of intercropping, BY were  $963 \text{ g/m}^2$  and  $977 \text{ g/m}^2$  for 0 and 40 bean seeds/ $\text{m}^2$  respectively (SED 30.9, DF 18). For the interactive effects of wsr and intercropping, the intercrop biomasses produced were greater than that for the bean sole crop across all wsr (Figure 5; SED 90.5, DF 28.58). However, at 400-wheat seeds/ $\text{m}^2$  wheat sole crop produced more BY than the total intercrop (Figure 5). The maximum total intercrop BY was obtained at 650-wheat seeds/ $\text{m}^2$  (Figure 5). It was earlier shown that the

total intercrop (plus bean sole crop), wheat intercrop and the bean BYs responses to wsr were quantified using equation 8, 3 and 9 respectively (Figure 5).



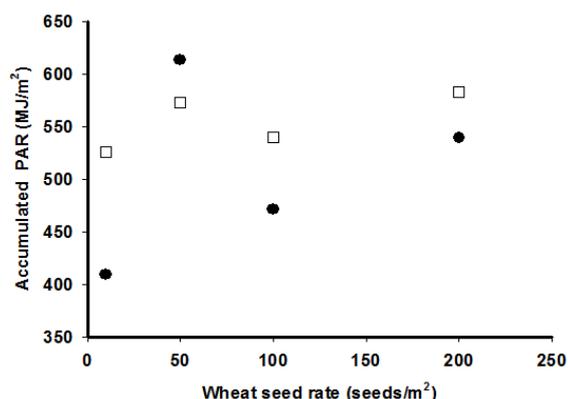
**Fig. 14.** Effect of wheat and bean seed rates on the biomass yield ( $\text{g/m}^2$ ) for total intercrop in Experiment 5. Equation 10 described the data satisfactorily and parameter values are given in Table

3.

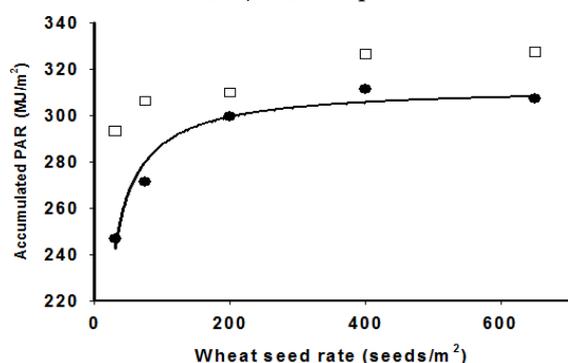


**Fig. 15.** Effect of wheat seed rate on winter wheat (cv. Mallaca) sole crop  $\bullet$  (solid curve) and the total intercrop  $\square$  accumulated PAR ( $\text{MJ/m}^2$ ) in Experiment 1. The fitted equation and parameter values are given in the text.

Further analyses indicate that the responses of the reciprocals of wheat sole crop and wheat intercrop BY per plant to wsr were linear (Figures 6 and 7), supporting the fitting of asymptotic equations to the yields per area (Figure 5). Note that the parameter values for fitting the linear reciprocal equations for both the sole crop and intercrop is given by equation 4 (see the parameters for the fits using equation 3 for estimates of  $a_w$  and  $b_w$ ).



**Fig. 16.** Effect of wheat seed rate on winter wheat (cv. Mallaca) sole crop● and the total intercrop □ accumulated PAR (MJ/m<sup>2</sup>) in Experiment 2.

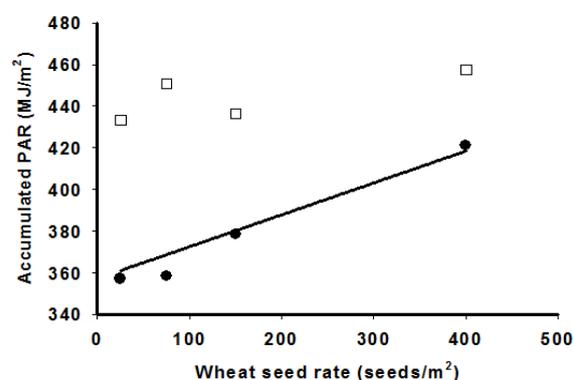


**Fig. 17.** Effect of wheat seed rate on accumulated PAR (MJ/m<sup>2</sup>) for winter wheat (cv.) sole crop● (solid curve) and the total intercrop □ for Experiment 3. The parameter values for the equation 3 applied to the accumulated PAR are  $a_w$  (estimate 0.02754 s.e 0.00374) and  $b_w$  (estimate 0.0032025 s.e 0.0000454).

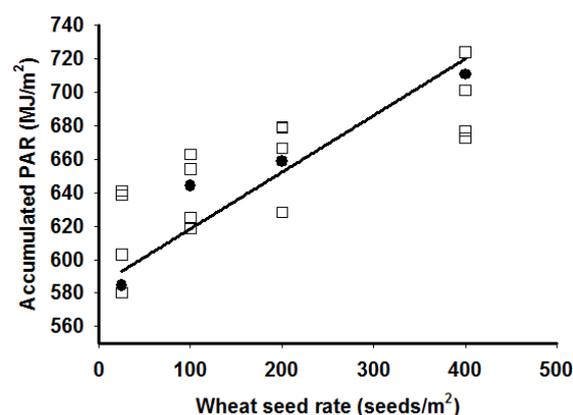
Responses of the biomass yields to seed rate in Experiment 4:

In Experiment 4, wheat BY increased with increase in wsr ( $P = 0.011$  for quadratic wsr). The effect of intercropping was significant ( $P < 0.001$  for bean treatment). There was no significant interaction between wsr and bean treatment ( $P > 0.05$ ). Averaged across wsr, for the mean effects of intercropping BY were 756 g/m<sup>2</sup> and 478 g/m<sup>2</sup> for 0 and 30 bean seeds/m<sup>2</sup> respectively (SED 54. 8, DF 30). The wheat sole crop BY was quantified well using equation 3. The coefficient of determination for the equation applied was 86.3%. The predicted asymptotic yield was determined as 1052 g/m<sup>2</sup>. This compares well with the maximum wheat sole crop

BY of 1028 g/m<sup>2</sup> from the results obtained at 400-wheat seeds/m<sup>2</sup> (Figure 8; SED 134. 2, DF 30). Similarly, wheat intercrop BY was quantified well using equation 3 (Figure 8; SED 77.5, DF 30). The coefficient of determination for the equation applied was 98.8%. The predicted asymptotic yield was determined as 689 g/m<sup>2</sup>. The maximum wheat intercrop BY of 627 g/m<sup>2</sup> from the results obtained at 400-wheat seeds/m<sup>2</sup> was lower. This suggests that the data could have been well quantified using a simple linear function. However, given the variation in BY as detected by ANOVA (for the main effects of wsr), the quantification using equation 3 was upheld.



**Fig. 18.** Effect of wheat seed rate on accumulated PAR (MJ/m<sup>2</sup>) for winter wheat (cv. Mallaca) sole crop● (solid line) and the total intercrop □ in Experiment 4. The fitted equations and parameter values are given in the text.



**Fig. 19.** Effect of wsr on accumulated PAR (MJ/m<sup>2</sup>) for winter wheat (cv. Mallaca) sole crop● (solid line) and the total intercrop □ in Experiment 5. The fitted equation and parameter values are given in the text.

In Experiment 4 bean biomass yield response to wsr was inconsistent ( $P = 0.014$  for quadratic wsr effect). The sole crop bean BY was  $948 \text{ g/m}^2$ . Intercropping significantly decreased bean BY across wsr (Figure 8; SED,  $90.4$ , DF 28). For the intercrop, the maximum bean BY of  $734 \text{ g/m}^2$  was obtained at 75-wheat seeds/ $\text{m}^2$  (Figure 8).

**Table 7.** Effects of wsr on wheat sole crop and total intercrop radiation use efficiency for Experiment 4.

Wheat seed rate (seeds/ $\text{m}^2$ )	Wheat sole crop RUE (g/MJ)	Total intercrop RUE (g/MJ)
0	0.00	2.37
25	1.32	2.17
75	2.11	2.75
150	2.08	2.47
400	2.45	2.42
SED wsr x bean	0.30	
DF	38	

In Experiment 4, the total intercrop responded significantly to increase in wsr ( $P = 0.001$  for quadratic wsr,  $P = 0.002$  for cubic wsr effect). The effect of bean treatment was also highly significant ( $P < 0.001$ ) and there was a significant interactive effect detected with the wsr ( $P = 0.047$  for quadratic wsr x bean effect). Averaged across wsr, for the mean effect of intercropping BY were  $1047 \text{ g/m}^2$  and  $604 \text{ g/m}^2$  for 30 and 0 bean respectively (SED  $52.4$ , DF 38). For the interactive effects of wsr and bean treatment, the total intercrop produced more BY than the wheat sole crop in most cases, except at 400 wheat seeds/ $\text{m}^2$  where yields did not differ significantly (Figure 9; SED  $117.1$ , DF 38). The maximum total intercrop BY of  $1213 \text{ g/m}^2$  was obtained at 75-wheat seed/ $\text{m}^2$  (SED  $82.8$ , DF 38). However, since no consistent pattern was found, the total intercrop BY was not quantified (Figure 9).

Responses of the biomass yields to seed rate in Experiment 5:

In Experiment 5, wheat BY increased as wsr increased ( $P < 0.001$  for quadratic wsr). The effect of bsr on wheat BY was significant ( $P = 0.048$ ), with the linear effects showing a strong significance ( $P = 0.003$ ). However, there was no significant interactive

effect detected between wsr and bsr ( $P = 0.667$ ). Averaged across wsr, for the mean effects of bsr wheat BY were  $987 \text{ g/m}^2$ ,  $915 \text{ g/m}^2$ ,  $885 \text{ g/m}^2$ ,  $885 \text{ g/m}^2$  and  $735 \text{ g/m}^2$  for 0, 5, 20, 40 and 80 bean seeds/ $\text{m}^2$  respectively (SED  $78.7$ , DF 37). Compared to the maximum yield at 0-bean seeds/ $\text{m}^2$ , yield was significantly reduced at 80-bean seeds/ $\text{m}^2$ . Similarly, averaged across bsr, for the mean effects of wsr wheat BY were  $446 \text{ g/m}^2$ ,  $928 \text{ g/m}^2$ ,  $1022 \text{ g/m}^2$  and  $1127 \text{ g/m}^2$  for 25, 100, 200 and 400 wheat seeds/ $\text{m}^2$  respectively (SED  $70.4$ , DF 37). The maximum wheat sole crop BY was obtained at 400-wheat seeds/ $\text{m}^2$ .

For the interactive effects of wsr and bsr, equation 3 quantified the response of wheat sole crop BY well. The coefficient of determination for the equation applied was 88.6%. The predicted asymptotic yield for the wheat sole crop BY was determined as  $1344 \text{ g/m}^2$ . However, the maximum wheat sole crop BY of  $1217 \text{ g/m}^2$  from the results obtained at 400-wheat seeds/ $\text{m}^2$  (Figure 10), was lower. Hence, as was the case in Experiments 1 and 2, wheat BY could have been quantified using a simple linear function but the application of equation 3 was found to be more appropriate given the curvilinear effects of BY response to wsr as was indicated by ANOVA outputs (for the main effects of wsr).

For the interactive effects of wsr and intercropping, wheat intercrop BY increased with increase in wsr but bsr decreased the yields (Figure 10 and 11). Equation 3 quantified the response of wheat intercrop BY well (Figure 10). The parameter values for the fits for the wheat intercrop BY are given in Table 2. Based on equation 3 the predicted asymptotic yield for the wheat intercrop BY was determined as  $1233 \text{ g/m}^2$ . The maximum wheat intercrop BY of  $1211 \text{ g/m}^2$  from the results obtained at 400 wheat seeds/ $\text{m}^2$ /20 bean seeds/ $\text{m}^2$  combinations was slightly lower. However, given the curvilinear response to wsr averaged across bean treatment ( $P < 0.001$  for quadratic wsr), further analysis showed that equation 10 improved the fit and was accepted instead (Figure 11). Table 2 show

the parameter values for the fits using the various equations. Based on equation 10, the predicted asymptotic yield for the wheat intercrop was reduced to 869 g/m<sup>2</sup>, suggesting that effect of bean on wheat yields was important. Although equation 11 fitted the data,  $c_w$  and  $d_w$  were not significant, hence this equation was rejected (Table 2).

$$Y = \frac{wsr}{(a_w + b_w wsr + c_{wb} bsr)} \quad 10$$

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 equation 3.

$$Y = \frac{wsr}{(a_b + b_w wsr + c_{wb} bsr + d_{wb} wsr bsr)} \quad 11$$

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 equation 3 and/or 10.

In Experiment 5, bean BY did not respond significantly to  $wsr$  ( $P > 0.05$ ). Bean BY averaged across all plots was 199 g/m<sup>2</sup>. The effect of  $bsr$  on bean BY response was linear ( $P < 0.001$ ). However, there was no significant interaction detected between  $wsr$  and  $bsr$  effects ( $P > 0.05$ ). However, further analysis showed that bean intercrop BY declined quadratically with increase in  $wsr$  and was quantified as  $Y = 275 - 0.85 wsr + 0.0013 wsr^2$  (Figure 12),  $r^2 = 0.95$ . Averaged across  $bsr$ , the maximum bean BY of 349 g/m<sup>2</sup> was obtained at 80-bean seeds/m<sup>2</sup>. The maximum bean BY was significantly greater than yields obtained at 5 and 20 bean seeds/m<sup>2</sup>. Further analysis showed that bean intercrop BY increase quadratically with increase in  $bsr$  and was quantified as  $Y = 25 + 7.7 bsr - 0.045 bsr^2$  (Figure 13),  $r^2 = 0.93$ .

The total intercrop BY increased with increase in  $wsr$  ( $P < 0.001$  for both the quadratic and cubic  $wsr$  effect). The effect of bean treatment on the total intercrop BY also deviated from linearity ( $P = 0.036$

for quadratic  $bsr$  effect). There was significant linear  $wsr \times$  linear  $bsr$  effect detected ( $P = 0.036$ ). Averaged across  $bsr$ , total intercrop BY were 175 g/m<sup>2</sup>, 667 g/m<sup>2</sup>, 1097 g/m<sup>2</sup>, 1139 g/m<sup>2</sup> and 1243 g/m<sup>2</sup> for 0, 25, 100, 200 and 400 wheat seeds/m<sup>2</sup> respectively (SED 70.1, DF 47). Similarly, averaged across  $wsr$ , total intercrop BYs were 789 g/m<sup>2</sup>, 756 g/m<sup>2</sup>, 832 g/m<sup>2</sup>, 1007 g/m<sup>2</sup> and 936 g/m<sup>2</sup> for 0, 5, 20, 40 and 80 bean seeds/m<sup>2</sup> respectively (SED 70.1, DF 47).

For the interactive effects of  $wsr$  and  $bsr$ , as indicated in Figure 14, the maximum total intercrop BY of 1324g/m<sup>2</sup> was obtained at 400 wheat seeds/m<sup>2</sup>/40 bean seeds/m<sup>2</sup> combinations (SED 156.8, DF 47). The maximum total intercrop BY was significantly greater than that obtained by the bean sole crop across  $bsr$ . For the interactive effects of  $wsr$  and  $bsr$ , bean sole crop BYs were 16 g/m<sup>2</sup>, 141 g/m<sup>2</sup>, 315 g/m<sup>2</sup> and 404 g/m<sup>2</sup> for 5, 20, 40 and 80 bean seeds/m<sup>2</sup> respectively. However, this did not differ significantly from the wheat sole crop BY except at 25-wheat seeds/m<sup>2</sup>. For the interactive effects of  $wsr$  and  $bsr$ , wheat sole crop BY were 506 g/m<sup>2</sup>, 1131 g/m<sup>2</sup>, 1092 g/m<sup>2</sup> and 400 g/m<sup>2</sup> for 25, 100, 200 and 400 wheat seeds/m<sup>2</sup> respectively. Thus, for the interactive effects of  $wsr$  and  $bsr$ , wheat sole crop produced BYs similar to that achieved by the total intercrop, even though the yields were slightly greater under the latter (Figure 14). In this experiment, the total intercrop BY response could be quantified using equation 3 (Table 3), equation 10 quantified the response better (Figure 14). The parameter values for the equation 10 applied to quantify the total intercrop BY is given in Table 3.

#### *Effects of seed rate on radiation interception and its use*

Effects of seed rate on radiation interception and its use in Experiment 1:

In Experiment 1 the accumulated PAR response to increase in  $wsr$  deviated from linearity ( $P = 0.035$  for quadratic  $wsr$ ). The effect of intercropping was also significant ( $P < 0.001$ ) and there was significant interactive effect detected with the  $wsr$  ( $P = 0.007$  for quadratic  $\times$  bean effect). Averaged across  $wsr$ , for the

mean effects of intercropping, the 490.6 MJ/m<sup>2</sup> accumulated PAR by the total intercrop was significantly greater than the 401.3 MJ/m<sup>2</sup> accumulated by the wheat sole crop (SED 14.32, DF 15). This indicates that averaged across wsr,

accumulated PAR was a major determinant of variation in BY between the sole crop and intercrops for the mean effects of intercropping.

**Table 8.** Effects of seed rates on wheat sole crop and total intercrop radiation use efficiency for Experiment 5.

Wheat seed rate (seeds/m <sup>2</sup> )	Bean seed rate (seeds/m <sup>2</sup> )	Total intercrop RUE (g/MJ)	Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop RUE (g/MJ)	Bean seed rate (seeds/m <sup>2</sup> )	Bean sole crop RUE (g/MJ)
25	5	0.74	25	0.85	5	0.03
100	5	1.77	100	1.75	20	0.24
200	5	1.64	200	1.65	40	0.52
400	5	1.70	400	1.72	80	0.60
25	20	1.07				
100	20	1.62				
200	20	1.71				
400	20	1.84				
25	40	1.40				
100	40	1.88				
200	40	1.90				
400	40	1.98				
25	80	1.35				
100	80	1.52				
200	80	1.71				
400	80	1.70				
SED wsr x bsr	0.23					
DF	47					

**Table 9.** The biomass yields (BY) crop performance ratio (CPR) for the wheat, bean and the total intercrop in Experiment 1.

Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop BY (g/m <sup>2</sup> )	Wheat intercrop BY (g/m <sup>2</sup> )	Wheat partial CPR	Bean sole crop BY (g/m <sup>2</sup> )	Bean intercrop BY (g/m <sup>2</sup> )	Bean partial CPR	Total intercrop CPR
10	201	53	0.12	1037	772	1.49	0.87
50	574	114	0.26		609	1.17	0.76
100	747	227	0.53		650	1.25	0.92
200	864	323	0.75		544	1.05	0.91

**Table 10.** The biomass yields (BY) crop performance ratio (CPR) for the wheat, bean and the total intercrop in Experiment 2.

Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop BY (g/m <sup>2</sup> )	Wheat intercrop BY (g/m <sup>2</sup> )	Wheat partial CPR	Bean sole crop BY (g/m <sup>2</sup> )	Bean intercrop BY (g/m <sup>2</sup> )	Bean partial CPR	Total intercrop CPR
10	188	72	0.13	242	296	2.45	0.53
50	671	206	0.36		471	3.89	0.98
100	642	291	0.51		339	2.80	0.91
200	1136	464	0.82		345	2.85	1.17

**Table 11.** The biomass yields (BY) crop performance ratio (CPR) for the wheat, bean and the total intercrop in Experiment 3.

Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop BY (g/m <sup>2</sup> )	Wheat intercrop BY (g/m <sup>2</sup> )	Wheat partial CPR	Bean sole crop BY (g/m <sup>2</sup> )	Bean intercrop BY (g/m <sup>2</sup> )	Bean partial CPR	Total intercrop CPR
30	753	469	0.66	337	320	1.90	0.89
75	1066	830	1.16		257	1.52	1.23
200	1201	937	1.31		159	0.94	1.24
400	1428	1070	1.50		171	1.02	1.41
650	1332	1173	1.64		138	0.82	1.49

**Table 12.** The biomass yields (BY) crop performance ratio (CPR) for the wheat, bean and the total intercrop in Experiment 4.

Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop BY (g/m <sup>2</sup> )	Wheat intercrop BY (g/m <sup>2</sup> )	Wheat partial CPR	Bean sole crop BY (g/m <sup>2</sup> )	Bean intercrop BY (g/m <sup>2</sup> )	Bean partial CPR	Total intercrop CPR
25	469	263	0.51	947.67	657.33	1.39	0.93
75	763	479	0.93		734.00	1.55	1.23
150	763	544	1.06		516.33	1.09	1.07
400	1028	627	1.22		469.00	0.99	1.11

**Table 13.** The biomass yields (BY) crop performance ratio (CPR) for the wheat, bean and the total intercrop in Experiment 5.

Wheat seed rate (seeds/m <sup>2</sup> )	Bean seed rate (seeds/m <sup>2</sup> )	Wheat sole crop BY (g/m <sup>2</sup> )	Wheat intercrop BY (g/m <sup>2</sup> )	Wheat partial CPR	Bean sole crop BY (g/m <sup>2</sup> )	Bean intercrop BY (g/m <sup>2</sup> )	Bean partial CPR	Total intercrop CPR
25	5	506	393	0.65	16	46	0.23	0.54
100	5	1131	1071	1.76	16	26	0.13	1.35
200	5	1092	1020	1.68	16	12	0.06	1.27
400	5	1217	1170	1.92	16	27	0.13	1.48
25	20	506	547	0.90	141	74	0.37	0.77
100	20	1131	832	1.37	141	185	0.92	1.25
200	20	1092	949	1.56	141	186	0.92	1.40
400	20	1217	1211	1.99	141	35	0.17	1.54
25	40	506	483	0.79	315	413	2.04	1.11
100	40	1131	776	1.28	315	449	2.22	1.51
200	40	1092	1126	1.85	315	151	0.75	1.58
400	40	1217	1156	1.90	315	168	0.83	1.63
25	80	506	303	0.50	404	568	2.81	1.07
100	80	1131	832	1.37	404	183	0.91	1.25
200	80	1092	922	1.52	404	239	1.18	1.43
400	80	1217	882	1.45	404	349	1.73	1.52

For the interaction of wsr and bean treatment, for the wheat sole crop the maximum accumulated PAR was 485.3 MJ/m<sup>2</sup> at 100-wheat seeds/m<sup>2</sup> whilst that for the intercrop was 509.6 MJ/m<sup>2</sup> at 200-wheat seeds/m<sup>2</sup> (Figure 15). The bean sole crop, accumulated PAR was 497.0 MJ/m<sup>2</sup>. Compared to the wheat sole crop, the accumulated PAR by the

total intercrop was significantly greater than that for the wheat sole crop as wsr increased, except at 100-wheat seeds/m<sup>2</sup> (SED 35.0, DF 25.09). This indicates that accumulated PAR was a major determinant of variation in BYs between the wheat sole crop and the total intercrop as wsr increased. However, within the intercrops accumulated PAR did not significantly

differ. In addition, accumulated PAR was similar for the total intercrop and bean sole crop. Moreover, the maximum accumulated PAR by the wheat sole crop did not differ significantly from that for the bean sole crop. The total intercrop accumulated PAR response to increase in wsr was not quantified because no consistent pattern was found as indicated in Figure 15. On the other hand, the wheat sole crop accumulated PAR declined parabolically (Figure 15). The response of the wheat sole crop accumulated PAR to wsr was quantified as  $Y = 355.5 + 1.92 \text{ wsr} - 0.008 \text{ wsr}^2$  ( $r^2 = 0.91$ ). Therefore, in this experiment whilst wheat sole crop BY responded asymptotically as wsr increased the response of the accumulated PAR was parabolic. As for the total intercrop BY, the total intercrop accumulated PAR was not quantified.

In Experiment 1 RUE responded significantly to wsr ( $P < 0.001$  for linear wsr effect). Intercropping also had significant effect on the RUE ( $P < 0.001$ ), and there was significant interaction detected with the wsr ( $P = 0.008$  for quadratic wsr x bean effect,  $P = 0.016$  for cubic wsr x bean effect). Averaged across wsr, for the mean effects of intercropping, RUE was 1.12 g/MJ and 1.77 g/MJ for the wheat sole crop and the total intercrop respectively (SED 0.122, DF 15). This indicates that averaged across wsr, as well as the accumulated PAR, RUE was a major determinant of variation in BY between wheat sole crop and the total intercrop.

For the wheat sole crop, RUE increased with increase in wsr reaching up to 2.04 g /MJ at 200-wheat seeds/m<sup>2</sup> (Table 4). For the intercrop, the maximum RUE of 1.82 g/MJ was obtained at 100-wheat seeds/m<sup>2</sup> (Table 4). Bean sole crop RUE was 2.11 g/MJ. This indicates that the RUE value for the bean sole crop was slightly greater than the maximum value for the wheat sole crop, and significantly greater than the value for the total intercrop. Except at 10-wheat seeds/m<sup>2</sup> where the RUE was significantly greater for the total intercrop, there was no significant difference between the wheat sole crop and total intercrop as wsr increased (Table 4; SED 0.27, DF 26. 7). Hence, in this

experiment, the variation in BYs as wsr increased between wheat sole crop and the total intercrop was determined mainly by the accumulated PAR. The low wheat sole crop RUE value at 10-wheat seeds/m<sup>2</sup> could have been due to effects of weeds presence on light interception. However, whilst weeds presence could have depleted the soil available N at the expense of the crops to the extent that light interception by the crop will be affected, such that the RUE would be overestimated. Here the values were lowered as seen in Table 4.

Effects of seed rate on radiation interception and its use in Experiment 2:

In Experiment 2 the accumulated PAR responded curvilinearly to increase in wsr ( $P = 0.043$  for cubic wsr effect). The effect of intercropping was not significant ( $P > 0.05$ ) and there was no significant interactive effect detected ( $P > 0.05$ ) as is shown in Figure 16. Averaged across bean treatment, the accumulated PAR were 458, 467, 593, 506 and 561 MJ/m<sup>2</sup> for 0, 10, 50, 100 and 200 wheat seeds/m<sup>2</sup> respectively (SED 50.3, DF 12). This indicates that accumulated PAR was significantly improved at 50-wheat seeds/m<sup>2</sup>; otherwise, there was no significant difference across wsr. Thus, accumulated PAR had less effect as a determinant of variation in BYs between the wheat sole crop and the total intercrop for the mean effect of bean treatment. Similarly, accumulated PAR was less important in the determination the variation in BY between the sole crops and the total intercrop as wsr increased.

The response of the RUE to wsr deviated from linearity ( $P = 0.012$  for quadratic wsr effect,  $P = 0.032$  for cubic wsr effect). The effect of intercropping was not significant ( $P > 0.05$ ), but there was significant interaction detected ( $P = 0.001$  for linear wsr x bean effect). For the interaction of wsr and bean treatment, RUE increases with increase in wsr reaching up to 2.12 g/MJ at 200 wheat seeds/m<sup>2</sup> (Table 5; SED 0.22, DF 27). At 10-wheat seeds/m<sup>2</sup>, intercropping significantly improved RUE (Table 5). Similarly, for the intercrop,

RUE increased with increase in wsr reaching up to 1.40 g/MJ at 200-wheat seeds/m<sup>2</sup> (Table 5).

**Table 14.** The total intercrop CPRs for accumulated PAR and RUE in Experiment 1.

Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop accumulated PAR (MJ/m <sup>2</sup> )	Bean sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop CPR for accumulated PAR	Total intercrop CPR for RUE
10	356	461.8	497	0.94	0.86
50	417	501.6		1.02	0.70
100	485	483.0		0.98	0.88
200	428	509.6		1.04	0.82

See Table 4 and/or the text for the RUE values used for calculating the CPR for the RUE.

**Table 15.** The total intercrop CPRs for accumulated PAR and RUE in Experiment 2.

Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop accumulated PAR (MJ/m <sup>2</sup> )	Bean sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop CPR for accumulated PAR	Total intercrop CPR for RUE
10	409	526	487	0.96	0.54
50	613	573		1.04	0.89
100	471	540		0.98	0.89
200	539	583		1.06	1.05

See Table 5 and/or the text for the RUE values used for calculating the CPR for the RUE.

**Table 16.** The total intercrop CPRs for accumulated PAR and RUE in Experiment 3.

Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop accumulated PAR (MJ/m <sup>2</sup> )	Bean sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop CPR for accumulated PAR	Total intercrop CPR for RUE
30	247	293	261	1.03	0.92
75	271	306		1.07	1.21
200	300	310		1.08	1.20
400	311	327		1.14	1.31
650	307	328		1.14	1.36

See Table 6 and/or the text for the RUE values used for calculating the CPR for the RUE.

**Table 17.** The total intercrop CPRs for accumulated PAR and RUE in Experiment 4.

Wheat seed rate (seeds/m <sup>2</sup> )	Wheat sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop accumulated PAR (MJ/m <sup>2</sup> )	Bean sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop CPR for accumulated PAR	Total intercrop CPR for RUE
25	357	433	398	1.06	0.90
75	359	451		1.10	1.14
150	379	436		1.07	1.02
400	421	457		1.12	1.00

See Table 7 and/or the text for the RUE values used for calculating the CPR for the RUE.

Hence, the maximum wheat sole crop RUE was significantly greater than the maximum total intercrop RUE. Within the intercrop, the maximum RUE differed significantly from values found at 10-wheat seeds/m<sup>2</sup> (Table 5). Similarly, the maximum RUE for the wheat sole crop and the total intercrop were significantly greater than the values for the bean sole crop (Table 5). In this experiment, the variation in BY between wheat sole crop and the total intercrop as wsr increased can be attributed mainly to the RUE.

*Effects of seed rate on radiation interception and its use in Experiment 3:*

In Experiment 3 the accumulated PAR responded curvilinearly to increase in wsr ( $P < 0.001$  for the quadratic wsr effect,  $P = 0.004$  for the cubic wsr effect). The effect of intercropping was highly significant ( $P < 0.001$ ), and there was significant interactive effect detected ( $P = 0.011$  for quadratic wsr x bean effect). Averaged across wsr, for the mean effects of intercropping, accumulated PAR were 266.1 MJ/m<sup>2</sup> and 304.1 MJ/m<sup>2</sup> for the wheat sole crop and the total intercrop respectively (SED 6.39, DF 18). This clearly indicates that accumulated PAR was significantly improved by intercropping. Hence, for the mean effects of intercropping, accumulated PAR was the main determinant of variation in BY between wheat sole crop and the total intercrop.

For the interaction of wsr and bean treatment, intercrops significantly accumulated more PAR at 30 and 75 wheat seeds/m<sup>2</sup>, otherwise accumulated PAR did not differ significantly between wheat sole crops and the intercrops (SED 16.28, DF 32. 10). The maximum wheat sole crop accumulated PAR of 311.4 MJ/m<sup>2</sup> at 400-wheat seeds/m<sup>2</sup> was significantly greater than that at 30 and 75 wheat seeds/m<sup>2</sup> (Figure 17). However, there was no significant difference between maximum wheat sole crop accumulated PAR and that at 200 and 650 wheat seeds/m<sup>2</sup>. Within the intercrops, except at 30-wheat seeds/m<sup>2</sup> where accumulated PAR was significantly lower than the maximum, accumulated PAR did not differ significantly. Hence, the total intercrop,

accumulated PAR was not quantified (Figure 17). Compared to the wheat sole crop, intercropping improved the accumulated PAR at the lower wsr (Figure 17). Bean sole crop accumulated PAR of 260.7 MJ/m<sup>2</sup> was significantly lower than the maximum accumulated PAR by both wheat sole crop and the total intercrop. At higher wsr, accumulated PAR was similar for the total intercrop and wheat sole crops (Figure 17). The accumulated PAR by the wheat sole crop increased asymptotically with increase in wsr and was quantified using equation 3 (Figure 17). The coefficient of determination for the equation applied is 94.3%. In this experiment wheat sole crop BYs, responses and accumulated PAR responses were asymptotic. Therefore, largely the accumulated PAR in turn influenced the BYs.

The RUE response to wsr deviated from linearity ( $P < 0.001$  for both the quadratic and cubic wsr effects). The effects of intercropping was not significant ( $P > 0.05$ ), but there was significant interaction detected ( $P = 0.007$  for quadratic x bean effect). For the wheat sole crop, RUE increased with increase in wsr reaching up to 4.6 g/MJ at 400-wheat seeds/m<sup>2</sup> (Table 6). For the intercrop, RUE increased with increase in wsr reaching up to 4.00 g/MJ at 650-wheat seeds/m<sup>2</sup> (Table 6). At 400 wheat seeds/m<sup>2</sup> wheat sole crop RUE was significantly greater than 3.8 g/MJ for the intercrop, otherwise RUE did not differ significantly between the two as wsr increased (Table 6; SED 0.32, DF 31.92). The bean sole crop RUE was significantly lower than the maximum for both the wheat sole crop and the total intercrop (Table 6). This indicates that wheat sole crop uses radiation more efficiently than both the bean and the total intercrop (Table 6). In other words, compared to the wheat sole crop, intercropping failed to improve RUE significantly across wsr (Table 6). Hence, in this experiment the variation in BYs as wsr increases can be attributed to both the RUE and the accumulated PAR. However, the comparatively high RUE estimates particularly for the wheat sole crops seen in Table 6 could have been due to indirect effects of weeds presence on the RUE estimates through its direct effects on light

interception. Other factors that could have led to these high RUE estimates include malfunctioning of

the ceptometer during the period light measurements were carried out.

**Table 18.** The total intercrop CPRs for accumulated PAR and RUE in Experiment 5.

Wheat seed rate (seeds/m <sup>2</sup> )	Bean seed rate (seeds/m <sup>2</sup> )	Wheat sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop accumulated PAR (MJ/m <sup>2</sup> )	Bean sole crop accumulated PAR (MJ/m <sup>2</sup> )	Total intercrop CPR for accumulated PAR	Total intercrop CPR for RUE
25	5	585	603	553	0.89	0.63
100	5	644	619	553	0.91	1.50
200	5	659	629	553	0.93	1.40
400	5	711	702	553	1.04	1.45
25	20	585	580	554	0.86	0.91
100	20	644	625	554	0.93	1.38
200	20	659	667	554	0.99	1.46
400	20	711	677	554	1.00	1.57
25	40	585	641	609	0.95	1.19
100	40	644	654	609	0.97	1.60
200	40	659	679	609	1.00	1.62
400	40	711	673	609	0.99	1.68
25	80	585	639	641	0.94	1.15
100	80	644	663	641	0.98	1.30
200	80	659	680	641	1.01	1.45
400	80	711	724	641	1.07	1.45

Effects of seed rate on radiation interception and its use in Experiment 4:

In Experiment 4 the response of accumulated PAR to wsr was significant ( $P = 0.003$  for linear wsr effect). The effect of bean treatment was also significant ( $P < 0.001$ ), but there was no significant interaction detected ( $P > 0.05$ ). Averaged across bean treatment, accumulated PAR were 379.7, 414.2, 427.9, 421.9 and 448.3 MJ/m<sup>2</sup> for 0, 25, 75, 150 and 400-wheat seeds/m<sup>2</sup> respectively (SED 17.98, DF 38). This indicates that accumulated PAR was significantly improved from 75 wheat seeds/m<sup>2</sup> or more. However, the maximum accumulated PAR did not differ significantly from that at 25, 75 and 150 wheat seeds/m<sup>2</sup>. Averaged across wsr, for the mean effects of intercropping, accumulated PAR was significantly improved. For the mean effects of intercropping, the accumulated PAR was 368.1 MJ/m<sup>2</sup> and 435.2 MJ/m<sup>2</sup> for the wheat sole crop and total intercrop respectively (SED 13.13, DF 38). This indicates that accumulated PAR was a major determinant of variation in BY between the wheat

sole crop and the total intercrop for the mean effects of intercropping.

For the interactive effects of wsr and bean treatment, the total intercrop accumulated PAR was not quantified as no consistent pattern was found (Figure 18; SED, 29.36, DF 38). However, wheat sole crop accumulated PAR increased linearly with increase in wsr and was quantified as  $Y = 357.4 + 0.153 \text{ wsr}$  (Figure 18; SED 35.96, DF 38),  $r^2 = 0.95$ . Therefore, in this experiment whilst wheat sole crop accumulated PAR response was linear, the wheat BY response was asymptotic to increase in wsr. Thus accumulated PAR had an influence on the BY as wsr increased to some extents.

In Experiment 4, wsr had significant effect on RUE ( $P = 0.002$  for quadratic wsr effect,  $P = 0.017$  for cubic wsr effect). The effect of intercropping was highly significant ( $P < 0.001$ ). There was significant interaction detected with the wsr ( $P = 0.006$  for quadratic x bean effect,  $P = 0.031$  for cubic x bean effect). Averaged across wsr, for the mean effects of

intercropping, RUE was 1.59 g/MJ and 2.44 g/MJ for the wheat sole crop and total intercrop respectively (SED 0.13, SED 38). This indicates that intercropping had significantly improved the RUE. Hence, in addition to the accumulated PAR, RUE was a major determinant of variation in BYs between wheat sole crop and the total intercrop.

For the interaction between wsr and bean treatment, as indicated in Table 7 intercropping significantly improved RUE at 25 and 75 wheat seeds/m<sup>2</sup> (SED 0.30, DF 38). However, within the intercrops RUE did not significantly differ (SED 0.21, DF 38). For the wheat sole crop, compared to the RUE at 25 wheat seeds/m<sup>2</sup>, wheat sole crop RUE increases significantly from 75 wheat seeds/m<sup>2</sup> or more reaching up to 2.45 g/MJ at 400 wheat seeds/m<sup>2</sup> (Table 7). The maximum wheat sole crop RUE did not differ significantly from that at 75 and 150 wheat seeds/m<sup>2</sup> (SED 0.37, DF 38). Hence, RUE was the main determinant of variation in BY between wheat sole crop and the total intercrop as wsr increased, even though accumulated PAR had an influence. However, the comparatively lower RUE estimate at 25-wheat seeds/m<sup>2</sup> was as explained previously with respect to the earlier experiments.

Effects of seed rate on radiation interception and its use in Experiment 5:

In Experiment 5, accumulated PAR increased with increase in wsr ( $P = 0.05$  for quadratic wsr). The effect of bsr on the response of accumulated PAR was also significant ( $P = 0.001$  for the bsr effect). However, there was no significant interaction detected between wsr and bsr on the response of the accumulated PAR ( $P > 0.05$ ). Averaged across bsr, mean accumulated PAR were 582.5, 609.6, 641.0, 662.4 and 697.2 MJ/m<sup>2</sup> for 0, 25, 100, 200 and 400 wheat seeds/m<sup>2</sup> respectively (SED 16.09, DF 47). This indicates that accumulated PAR was significantly improved from 100-wheat seeds/m<sup>2</sup> compared to 0-wheat seeds/m<sup>2</sup>. Hence, averaged across bsr, for the mean effects of wsr accumulated PAR was a major determinant of variation in BY as wsr increased. Similarly, averaged across wsr, for the

mean effects of bsr, accumulated PAR were 630.8, 620.8, 620.7, 651.1 and 669.3 MJ/m<sup>2</sup> for 0, 5, 20, 40 and 80-bean seeds/m<sup>2</sup> respectively (SED 16.09, DF 47). This indicates that accumulated PAR was significantly greater at 80-bean seeds/m<sup>2</sup>. This suggests that averaged across wsr, accumulated PAR was a major determinant of variation in BY as bsr increased.

For the interactive effects of wsr and bsr, wheat sole crop accumulated PAR increase linearly with increase in wsr and was quantified as  $Y = 584.5 + 0.34 \text{ wsr}$  (Figure 19),  $r^2 = 0.89$ . Fitting regression line to the total accumulated PAR did not work well. However, as can be seen in Figure 19, the total intercrop accumulated PAR responses were similar to that for the wheat sole crop. Therefore, wheat was largely responsible for the accumulated PAR by the total intercrop. In this experiment for the BY, wheat was more competitive than the beans; the response of the total intercrop accumulated PAR is not surprising. However, whilst the total intercrop and wheat BYs, were quantified using the asymptotic equations (3 and 10); the response of both the total intercrop and wheat sole crop accumulated PAR were linear.

The RUE responded significantly to wsr ( $P < 0.001$  for quadratic wsr effect,  $P < 0.001$  for cubic wsr effect). Bean seed rate also had significant effects on the RUE ( $P = 0.010$  for quadratic bsr effect). There was a significant interaction detected between the effect of wsr and bsr on RUE ( $P = 0.048$  for quadratic wsr x linear bsr effect). Averaged across bsr, RUE were 0.28 g/MJ, 1.08 g/MJ, 1.71 g/MJ, 1.72 g/MJ and 1.79 g/MJ for 0, 25, 100, 200 and 400 wheat seeds/m<sup>2</sup> respectively (SED 0.10, DF 47). Compared to the RUE at 0 and 25 wheat seeds/m<sup>2</sup>, RUE was significantly improved from 100-wheat seeds/m<sup>2</sup> or more. Consequently, RUE was a major determinant of variation in BY for the mean effects of wsr. However, there was no significant difference between RUE at 100, 200 and 400 wheat seeds/m<sup>2</sup>. Similarly, averaged across wsr, RUE were 1.19 g/MJ, 1.18 g/MJ, 1.30 g/MJ, 1.54 g/MJ and 1.38 g/MJ for

0, 5, 20, 40 and 80 bean seeds/m<sup>2</sup> respectively (SED 0.10, DF 47). Compared to the RUE at 0, 5 and 20 bean seeds/m<sup>2</sup> RUE was significantly improved at 40-bean seeds/m<sup>2</sup>. However, there was no significant difference between RUE at 40-bean seeds/m<sup>2</sup> and that at 80-bean seeds/m<sup>2</sup>. Thus, RUE was a major determinant of variation in BY for the mean effects of bsr.

For the interactive effects of wsr and bsr, the maximum wheat sole crop RUE of 1.75 g/MJ was at 100-seeds/m<sup>2</sup> (Table 8). The maximum total intercrop RUE of 1.98 g/MJ was at 400 wheat seeds/m<sup>2</sup>/40 bean seeds/m<sup>2</sup> combinations (Table 8). Although this value was significantly greater than the RUE for the sole crop beans across bsr, there was no significant difference from other intercrop RUE or that for the wheat sole crops except at 25 wheat seeds/m<sup>2</sup> (Table 8; SED 0.23, DF 47). In addition, the RUE of the bean was comparatively lower than that of wheat sole crop; the maximum bean RUE value was 0.60 g/MJ (Table 8). Similar to the previous experiments, the factors that might have been responsible for the low RUE values at the lower sr were as explained earlier.

#### *Estimate of intercrop biomass yields efficiency based on crop performance ratio*

In Experiment 1, for the BY, the total intercrops struggled compared to the sole crops (Table 9). The total CPR estimates indicate that the intercrops were less efficient than sole crops (Table 9). Although bean in the intercrops was generally more efficient than the sole crops; the low efficiency of the total intercrop can be attributed to the poorer performance of the wheat in the intercrops compared to the sole crops as indicated by the low values of wheat CPR (Table 9).

In Experiment 2, for the BY, estimates based on total intercrop CPR did not indicate better performance of intercrop compared to the sole crops, except at 200-wheat seeds/m<sup>2</sup> (Table 10). For the biomass yields, wheat in the intercrops generally performed poorer compared to the sole crops particularly at the lower

sr (Table 10). On the other hand, bean in the intercrop performed extremely well compared to the sole crops (Table 10).

In Experiment 3, for the BY, the total CPR indicate that the total intercrops were more efficient than the sole crops except at 30 wheat seeds/m<sup>2</sup> (Table 11). Wheat in the intercrops performed more efficiently than wheat sole crop except at 30-wheat seeds/m<sup>2</sup> (Table 11). On the other hand, as the wsr was increased, bean in the intercrop performed less efficiently than in sole crops (Table 11).

In Experiment 4, for the BY, the total intercrop CPR indicate that the total intercrop was more efficient than the sole crops except at 25 seeds/m<sup>2</sup> (Table 12). Wheat in the intercrops performed more efficiently than the sole crops at the higher wsr (Table 6. 24). On the other hand, bean in the intercrop performed more efficiently than the sole crop, except at 400 seeds/m<sup>2</sup> where the efficiency was similar.

In Experiment 5, for the BY, the total intercrop CPR indicate that the total intercrop was more efficient than the sole crops except at 25- wheat seeds/m<sup>2</sup> when bsr was 20 seeds/m<sup>2</sup> or less (Table 13). In general, wheat in the intercrop performed more efficiently than the sole crop except at 25-wheat seeds/m<sup>2</sup> where it struggled (Table 13). By contrast, bean in the intercrop generally performed less efficiently than the sole crop, though a few cases of extreme values of higher performance of the bean intercrop were detected (Table 13).

#### *Estimate of intercrop efficiency in radiation interception and its use based on crop performance ratio*

In Experiment 1, the total intercrop was similar to wheat sole crop in the efficiency of accumulating PAR: slightly less so at 10 and 100 seeds/m<sup>2</sup> and slightly more so at 50-wheat seeds/m<sup>2</sup> and 200 wheat seeds/m<sup>2</sup> (Table 14). As regards the efficiency of RUE, the total intercrop struggled compared to the wheat sole crop across wsr (Table 14). Clearly,

there was no benefit for intercropping with respect to RUE (Table 14).

In Experiment 2, the total intercrop was as efficient as the wheat sole crop in the efficiency of accumulating PAR: slightly less so at 10 and 100 wheat seeds/m<sup>2</sup> and slightly more so at 50 and 200 wheat seed/m<sup>2</sup> (Table 15). With respect to the RUE, the total intercrop struggled compared to the wheat sole crop with the efficiency dropping to 54%, except at the 200 wheat seeds/m<sup>2</sup> where the total intercrop performed marginally better (Table 15).

In Experiment 3, across all wheat seed rates the total intercrop was more efficient than the wheat sole crop in accumulating PAR (Table 16). Greater benefits were seen with increase in wsr such that at 400-650 wheat seeds/m<sup>2</sup>, the total intercrop was 14% more efficient (Table 16). As regards RUE, the total intercrop performed more efficiently than the wheat sole crop except at 30-wheat seeds/m<sup>2</sup> (Table 16). At 650 seeds/m<sup>2</sup>, intercropping increased the efficiency of RUE by 36 % (Table 16).

In Experiment 4, the efficiency of accumulated PAR by the total intercrop was greater than that of the wheat sole crop across all seed rates (Table 17). Although there was no consistency in the efficiency as wsr increased, at 400-wheat seeds/m<sup>2</sup> the total intercrop was 12% more efficient than the wheat sole crop with respect to accumulating PAR (Table 17). As regards RUE, although at 70-wheat seed/m<sup>2</sup> the total intercrop was 14% more efficient than the wheat sole crop, at the higher seed rate, the efficiency was similar but at 25-wheat seeds/m<sup>2</sup>, the total intercrop was only 90% as efficient as the wheat sole crops (Table 17).

In Experiment 5, as regards the efficiency of accumulating PAR, in general though the total intercrops was slightly less than the wheat sole crop, occasional instances of slightly better efficiency were found (Table 18). The total intercrop was more efficient in terms of RUE across wsr than the wheat

sole crop, except at 25-wheat seeds/m<sup>2</sup> when bsr was 20 seeds/m<sup>2</sup> or lower (Table 18).

## Discussions

### *Effects of seed rate on biomass yields*

One of the key thrust of this research was to quantify the BY response to sr and make comparisons across the experiments. Biscoe and Gallagher (1978) contended that significant biomass accumulation and high harvest index are necessary to obtain high yields. This is particularly relevant for wheat and faba bean, since they are both seed crops (Bulson *et al.*, 1997; Haymes and Lee, 1999). Thus, practically higher BY can be obtained by increasing sr and/or by intercropping (Gooding *et al.*, 2002; Awal *et al.*, 2006). My research showed that averaged across wsr, substantial BY differences were found between the sole crop and intercrop in most of the experiments. Similarly, results also indicate that substantial differences in BY were found between the sole crops and intercrops as wsr increased in most of the experiments. The maximum wheat BY of 1428g/m<sup>2</sup> and 1211g/m<sup>2</sup> for the sole crop and intercrop obtained in the present study were lower than previously reported value at the same location for the sole crop. For instance, at the same location with the present investigations, Kindred and Gooding (2005) under sole cropping obtained winter wheat BY of up to 1900g/m<sup>2</sup> when adequate N was applied. Spink *et al.* (2000) also obtained winter wheat BY of up to 1600 g/m<sup>2</sup> at a different location in the UK. Therefore, the wheat BY found here was lower than values obtained previously under UK managed conditions. Nevertheless, the fact that the sole crop wheat produced greater BY than the wheat intercrop is largely due to intense competition between wheat and bean component in the intercrop (Hongo, 1995; Bulson *et al.*, 1997; Haymes and Lee, 1999).

Biomass yield can be improved, as p is increased (Bleasdale, 1984; Gooding *et al.*, 2002). This is possible by increasing the sr of one crop species (Ellis *et al.*, 1999) or planting a second or more crop species (Dolman, 1985; Park *et al.*, 2002). However,

when the asymptotic yield is reached, increasing  $p$  is not necessary because no greater total biomass can be obtained for a given crop species at that location (Azam-Ali and Squire, 2002; Neumann *et al.*, 2009; Yahuza, 2011a). Results showed that both the wheat sole crop and wheat intercrop BY responses to  $sr$  where they deviated from linearity, were quantified using the asymptotic equations. In agreement with my findings, similar responses of wheat BY were reported previously in the UK under sole cropping conditions (Gooding *et al.*, 2002). It was interesting to note that here it was shown that the typical asymptotic responses of wheat BY to increase in density are also exhibited under intercropping with the faba bean. For example, in Experiment 3; the responses of the reciprocal of BY per plant to  $sr$  were linear in agreement with the wider literature (Bleasdale, 1984; Ellis *et al.*, 1999). This indicates that the wheat harvest index was less affected as  $wsr$  increased in agreement with the literature (Gooding *et al.*, 2002). The implication for the agronomy of wheat, is that management practices should be directly targeted at increasing the BY in order to improve the seed yields indirectly. Nevertheless, in some cases, for example Experiments 1 and 2, the disparity between the predicted asymptotic yield and maximum BYs from the results suggest that the data could have been better described using a simple linear function. However, given the curvilinear response to  $wsr$  as was indicated by ANOVA outputs, the quantification using the asymptotic equations were upheld.

Results indicate substantial differences in BY between the bean sole crop and intercrop as  $wsr$  increases in three of the experiments, whilst in two others lesser differences were found. In general, bean produces large amount of BY (Bulson *et al.*, 1997; Haymes and Lee, 1999; Lopez-Bellido *et al.*, 2005). However, as reported by Khan *et al.* (2010) such high biomass production of bean particularly when sown early could restrict the flow of air in the canopy and thereby favouring the development of diseases. Adisarwanto and Knight (1997) obtained biomass of up to 1350 g/m<sup>2</sup> in bean. Under

intercropping conditions, as was the case with wheat, the BY of bean are typically reduced (Helenius and Jokinen, 1994; Hongo, 1995; Bulson *et al.*, 1997). This research had indicated that the maximum bean BY were 1037g/m<sup>2</sup> and 772 g/m<sup>2</sup> for the sole crops and intercrops respectively. The fact that greater bean sole crop BY compare to that produced by the intercrop were found is in agreement with previous investigations (Bulson *et al.*, 1997; Haymes and Lee, 1999). However, unlike the wheat, bean exhibits greater variability in HI over different conditions (Lopez –Bellido *et al.*, 2005). Thus, for bean it cannot be concluded that greater seed yields may be obtained by simply increasing the BY. Indeed, it should be stressed that bean is more susceptible to pest, diseases and physical damages when very high BY are produced (Khan *et al.*, 2010). At least one of these factors has negative potential in decreasing the BY directly and by extension, the seed yield indirectly. Nevertheless, from my investigations, in the UK, it is unlikely that increasing  $bsr$  over 40-bean seeds/m<sup>2</sup> may be advantageous irrespective of whether it was the seed or biomass yield improvement that is the aim. In agreement with this result, others have also recommended similar  $sr$  for the bean under UK managed conditions (Bulson *et al.*, 1997; Haymes and Lee, 1999).

That the total intercrop biomass yields responses were described using similar equations as the wheat in some experiments indicates that wheat was more competitive than the bean. See for instance Figures 4, 5, 11 and 14 and compare the responses of wheat intercrop to that of the total intercrop BYs for each of the experiments. In agreement with my results, previous investigations in most cases had indicated that the cereal component was more competitive than the legume component (Harris *et al.*, 1987; Helenius and Jokinen, 1994). The greater competitive ability of the wheat over bean in some of my experiments could have been due to greater  $sr$  sown for the former compare to the latter. In addition, the fact that in most of the experiments N fertilizer were applied suggests that wheat growth and development was enhanced since bean, a legume

is less competitive for applied N (Gooding *et al.*, 2007). Intercropping may aimed at improving overall total BY compare to the component sole crops (Vandermeer, 1989; Jahansooz *et al.*, 2007). This is based on the assumption that two or more crops would intercept radiation or other growth resources better than when grown alone (Zhang *et al.*, 2007). For instance, Hongo (1995) in a study involving wheat/bean intercropping stated that though BY of both wheat and bean in the intercrop were reduced, intercrop gave higher BY and seed yield than their sole crop counterparts. This clearly indicates that greater productivity may be obtainable by wheat/bean intercrop compared to the component sole crops. It should be stressed that seed yields are determined by BY and the HI. However, the latter is less variable compared to the former (Fischer, 2007; Foulkes *et al.*, 2007). This suggests that since greater BY are achievable by wheat/bean intercrop, greater seed yields are also achievable. It is possible to obtain greater biomass by wheat/bean intercrop compared to their component sole crops because the two components crops are different in their morphological and perhaps physiological attributes, which may have implication on resource use by the two crops (Yahuza 2011b).

Physiologically, seed yields may be source and/or sink driven (Fischer, 2007; Reynolds *et al.*, 2007). In other words, the crop must produce sufficient receptors for assimilates produced by the canopy through the process of photosynthesis. For 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; Gooding *et al.*, 2002). It might be argued that whilst wheat at the lower densities may be mainly source limited, because of lower canopy coverage despite greater tillering capacity, it may not be clear whether wheat yields for plots with higher densities are source or sink limited. It may be possible that at higher densities, the main limitation would be the sink rather than the source. This is because at higher densities 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 (Gooding *et al.*, 2002). Thus, similar yields to plots with lower densities may be possible, and this may be reflected in lesser differences between plots with higher densities and the ones with lower ones. The benefits of wheat/bean intercropping system as regards source-sink relations compared to the sole crops is that the even at lower seed rates, 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.

#### *Effects of seed rate on determinants of variation in biomass yields*

Biomass production is a function of intercepted PAR multiplied by the efficiency with which PAR is used to form the biomass (Areche *et al.*, 2009; Confalone *et al.*, 2010; Carretero *et al.*, 2010). My research had indicated substantial importance of the accumulated PAR and RUE as determinants of variation in BY between the wheat sole crop and the total intercrop in most of the experiments. For instance in Experiment 1, it can be easily seen from Figure 15 that the accumulated PAR was the main determinant of variation between the sole crops and the intercrops. Although light interception in wheat/bean intercropping system was studied in only a few investigations (Hongo, 1995; Haymes and Lee, 1999), it is often argued that intercrops have the capacity to make use of resources, specifically radiation more effectively and efficiently than the sole crops (Marshall and Willey, 1983; Tsubo *et al.*, 2001). For instance, in a wheat/cotton (*Gossypium* spp.) intercrop, the productivity of intercropping was ascribed mainly to the greater accumulated PAR of the total intercrop than the wheat sole crop as the RUE was conservative (Zhang *et al.*, 2007). Here, in agreement with Zhang *et al.* (2007), averaged across wsr, accumulated PAR was a major determinant of

variation in BY. However, in addition, it was clear that in some of my investigations averaged across wsr, RUE had influence on the BY variation between the sole crops and the intercrops.

This research indicate that the accumulated PAR did not consistently follow similar linear or asymptotic pattern as the BY as wsr increased. Indeed, it was only in Experiment 3 (Figure 17) where the wheat sole crop accumulated PAR responded asymptotically, in agreement with earlier findings (Gooding *et al.*, 2002). The fact that in most of my experiments the responses of the accumulated PAR differ from that of the BYs indicates that the RUE also had influence in determining the variations in BY (Marshall and Willey, 1983) as wsr increased. Nevertheless in Experiments 2 and 3 the greater biomass production by the total intercrop at 200 wheat seeds/m<sup>2</sup> and 650 wheat seeds/m<sup>2</sup> respectively was largely due to improvement in light interception, given that the sole crop was better at RUE. On the other hand, in Experiment 5 the out-yielding of the sole crops by the total intercrop at 400 wheat seeds/m<sup>2</sup>/40 bean seeds/m<sup>2</sup> can be traced mainly to improvement in the RUE of the latter compared to the former. In Experiment 4 it was clear that the out-yielding of the sole crops by the total intercrop at 75 wheat seeds/m<sup>2</sup> can be traced to both greater light interception and RUE. Thus, that accumulated PAR determined the BY variations in some of the experiments is in agreement with the literature (Tsubo *et al.*, 2001; O'Connell *et al.*, 2004; Confalone *et al.*, 2010). In agreement with my results, it is worthy to state that at maximum canopy development, it had been demonstrated previously that sole wheat intercepted significantly less light (85%) than both sole bean and the intercrop (94% each) (Haymes and Lee, 1999). However, it should be pointed out that this investigation gave only limited indications of light interception by the two crop combinations, as light were not assessed in all the experiments they reported.

This research had indicated that in some cases wheat sole crop was better in RUE than the total intercrop and bean sole crop. For instance in Experiment 2, at 200 wheat seeds/m<sup>2</sup>, whilst wheat sole crop RUE was 2.12 g/MJ that for the total intercrop was 1.39 g/MJ. In any case, for the wheat sole crops the range of RUE obtained here was within the ranges reported previously. Wheat RUE values in the range 1.2 to 2.93 g/MJ for a range of environments had been documented (Kiniry *et al.*, 1989; Giunta *et al.*, 2009). Kiniry *et al.* (1989) gave a mean RUE value for apparent non-stressed wheat as 2.8 g/MJ. Olesen *et al.* (2002) in a simulation approach gave estimates in the range from 1.8 to 4.2 g/MJ. Thus, in the present research, for the wheat sole crops, the RUE found at the higher sr in most of the experiments are within the range reported previously. However, the extremely high RUE values for the spring experiment (Experiment 3) or low RUE values at the lowest sr for the winter experiments particularly for the sole crops are some of the unexplained errors that could have been due to factors such as error in light assessment and malfunction of the ceptometer. It could also be because of weed indirect effects on RUE through its effects on light interception (Haymes and Lee, 1999). Weeds effect on RUE estimate might be through its direct effects on light interception by competing with the crops for nitrogen, which in turn reduces the crops capacity to intercept radiation. In Experiment 3, for example, the maximum RUE value of 4.58 g/MJ was greater than the maximum estimate of 4.2 g/MJ given by Olesen *et al.* (2002). This may be because light assessment for Experiment 3, which was spring-sown, was not started soon enough after crop establishment, hence the high RUE estimates. Nevertheless, whilst weeds presence at the lower sr could have had indirect effects on the RUE through its direct effects on light interception leading to over estimation of RUE, my investigation indicates lower RUE values. Factors that could have led to opposite case here is not clear, except that in this investigations weed biomass were excluded when RUE were calculated for each plot. However, the lower RUE of the intercrop may be attributed to the

low RUE of the bean intercrop component. This is because in most cases, though bean sole crop intercepted large amount of PAR, its RUE were mostly lower than that of wheat sole crop and the total intercrop.

Here the accumulated PAR by each component crop and the RUE were not partitioned (Awal *et al.*, 2006), thus, it cannot be asserted whether wheat in the intercrop intercepted more PAR than the bean or vice versa. In most studies in which radiation interception and/or RUE are partitioned between the crop components, the component crops are usually segregated either vertically or horizontally so that the radiation measurements can be made (Marshall and Willey, 1983; Harris *et al.*, 1987). Here, even though in some of the experiments, bean were greater in heights than wheat (data not given), the ideal canopy stratification for the partitioning of radiation to be meaningful was not obtained due to the intermingling between the canopies of wheat and bean in the intercrop. In such cases, it will be valid to measure PAR interception for the whole system (Vandermeer, 1989; Azam-Ali and Squire, 2002) as I did. This is because Beer's law deals with light transmission (non-intercepted radiation (Sinoquet *et al.*, 2000). Notwithstanding, given the canopy structure of wheat/bean intercropping system found in my research, improvement on radiation interception and use might be possible because whilst wheat might use transmitted radiation to produce optimally, bean might use direct irradiance to produce.

#### *Effects of seed rate on intercrop efficiency based on evaluation using crop performance ratio*

A major finding of this research with respect to the biomass yields, indicate that intercropping was more efficient than sole cropping as indicated by the total intercrop CPR values, which were greater than unity in most of the experiments. Whilst in general, the CPR has rarely been used previously in evaluating intercrop performance in wheat/bean system; it was used for other crop combination. For instance, in the investigations of Azam-Ali *et al.* (1990) a total

intercrop CPR of 1.08 was found for a sorghum (*Sorghum bicolor*)/groundnut (*Arachis hypogaea*) intercrop BYs. In the present investigations, with respect to the BYs the total intercrop CPR found ranged from 0.53 to 1.63. Thus, it was clear intercropping was more efficient than sole cropping at least at the higher densities for each of the experiments. To my knowledge, such a high CPR value has not been reported previously for any intercrop combination, even though the index has not been widely adopted. Azam-Ali *et al.* (1990) used and reported CPR values in situations where water was the limiting resource; on the other hand, here the CPR was used in circumstance where radiation was the main driver of productivity. Contrary to Harris *et al.* (1987) who found out that maximum CPR was obtained in lower water regimes, here, the maximum CPR estimate was obtained in Experiment 5, which was established in the 2007-2008 cropping year, which was not only wetter than the previous cropping years, but was wetter than the long-term average for the site (Yahuza, 2012). The high CPR estimate in Experiment 5 could have also been due to the greater competitive ability of the intercrop wheat compare to the intercrop bean for this experiment.

A major advantage of evaluating intercropping using the CPR approach is that it allows both the physical and physiological basis of intercrop performance to be easily detected (Harris *et al.*, 1987). As was pointed out previously, physiologically biomass production is a product of radiation interception and RUE, provided water is not in short supply (Marshall and Willey, 1983; Awal *et al.*, 2006). Thus, it was not surprising that positive CPR values for radiation interception and/or RUE were found at the intercrop that produced greater biomass. For instance in confirming the analyses based on ANOVA, in Experiment 4 the out-yielding of the sole crops by the intercrop at 75 wheat seeds/m<sup>2</sup> can be traced to both the efficiency of light interception and RUE by the total intercrop compare to the sole crops as indicated by the CPR values which were greater than unity for each of these variables. On the other hand, it was clear in Experiment 5 that the CPR estimate

for the RUE largely explained the CPR value for the biomass at 400-wheat seeds/m<sup>2</sup>/40 bean seeds/m<sup>2</sup> combination. In agreement with my results, Azam-Ali *et al.* (1990) stated that the positive CPR for the BY found in their investigations was explained by positive CPR value for intercepted radiation. Thus, the significance of the approach that was used in this study to evaluate intercrop performance was clear compare to the widely used LER for evaluating wheat/bean intercropping system or other intercropping combinations (Willey, 1985; Bulson *et al.*, 1997; Haymes and Lee, 1999). In other words, unlike the LER or other indices, the CPR calculates the efficiency with which sole crops and intercrops use resources such as radiation to produce dry matter (Harris *et al.*, 1987; Azam Ali *et al.*, 1990; Azam-Ali, 1995 cited in Azam-Ali and Squire, 2002). In situations where the component crops differ in growth durations evaluation using the CPR adjusted for time may be necessary (Azam-Ali and Squire, 2002). In such cases, the estimates of the CPR will not be sufficient. However, for wheat/bean intercropping system, it is unlikely that the need for such time adjustment will be necessary since the two component crops are simultaneously sown and harvested (Haymes and Lee, 1999; Bulson *et al.*, 1997; Gooding *et al.*, 2007).

Azam-Ali and Squire (2002) asserted that knowledge of energy equivalents is necessary in intercrops systems, since they are often composed of plants products with substantially different composition. According to them by referring all CPR calculations to the energy equivalence of biomass in mega joules, it is possible to use a common currency with which to compare biological outputs of different species composed of organs, each with different energy values. In calculating the modified CPR, it is assumed that the carbohydrate and protein fractions have the same energy value and that there is no lipid in the seed (Azam-Ali 1995, cited in Azam-Ali and Squire, 2002). However, such conversion may not be necessary if none of the component crops is an oil seed crop. Indeed, since the procedures assume that protein and carbohydrates are of equal energy value

it is not sensible to make any conversion if the intercrop components involved are all mainly legumes and/or cereals, except if an oil seed legumes is involved. In this study, therefore, the approach used by Harris *et al.* (1987) was followed since neither wheat nor bean is an oil seed crop.

### Conclusions

For the wheat, the biomass yield-density relationship established in this study is consistent with previous work. Similarly, this study demonstrated that the greater biomass of the intercrops compared to the wheat sole crops was because the intercrops accumulated more PAR, given that in most cases wheat sole crop was better at RUE than the intercrops. Thus, although the accumulated PAR was the main determinant of variation in biomass yields between sole crops and intercrops, RUE had influence in some experiments. In conclusion based on evaluation using CPR, this study indicates that wheat/bean intercropping is beneficial.

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