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Productivity of wheat/faba bean intercropping systems in response to sulphur fertilization and seed rate under contrasting management conditions

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Abstract

Two field experiments carried out in contrasting production system (conventional versus organic) investigated the effects of sulphur (S) fertilization and wheat seed rate in wheat/faba bean (bean) intercropping system. For the conventional experiment, S fertilization reduced wheat seed yields and biomass yields substantially. Maximum wheat seed yields were 278 g/m^2 and 391 g/m^2 for S applied and S withheld respectively. On the other hand, at 200 wheat seeds/m^2 application of S significantly increased bean intercrop seed yield. Bean seed yields were 195.8 g/m^2 and 81.9 g/m^2 for S and without S respectively. For the seed yield, based on crop performance ratio (CPR), wheat in the intercrop was more efficient than the sole crop only at 200 wheat seeds/m^2 when S was withheld as indicated by CPR value of 1.11. The maximum CPR for the bean of 1.87 was obtained at 200 wheat seeds/m^2 when S was applied. For both wheat and bean, application of S had no substantial effects on harvest index. Whilst application of S had a positive effects on accumulated photosynthetically active radiation by the intercrop, radiation use efficiency was conservative in response to S fertilization. For the conventional experiment, it was concluded that bean competed with the wheat intensely for S than for N leading to higher yields for the bean when S was applied than when S was withheld. Hence, wheat intercrop seed yields were substantially reduced when S was applied. By contrast, in the organic experiment, S fertilization had no significant effects on the above-mentioned variables.

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Introduction

Sulphur (S) is one of the macronutrients essential for crop production and its requirement by the crop is similar to that for phosphorous (Thomas *et al.,* 2003; Tellec *et al.,* 2008). Deficiency of S has been shown to affect protein synthesis and enzymatic activities of crops (Wieser *et al.,* 2004). This is because S has an important role in the formation of amino acids such as methionine and cysteine, which are building blocks for proteins (Gooding and Davies, 1997; Scherer, 2001). Previously S was not a critical nutrient element and is usually not applied to crops (Asare and Scarisbrick, 1995; Mathot *et al.,* 2008). Indeed, S from wet and dry deposition and from S-containing fertilizers, S-containing fungicides etc has been sufficient historically to satisfy the crop's needs (Flaete *et al.,* 2005; Salvagiotti *et al.,* 2009). However, despite the increasing importance of S for crop production, it is usually difficult to dictate when S is limiting. This is because in the field symptoms, indicating deficiency may be mistaken for those of nitrogen (N) (Gooding and Davies, 1997; Scherer, 2001).

Report indicates that S requirements differ between crops and even for a given crop between the development stages (Thomas *et al.,* 2003). Sulphur application has been shown to increase the percentage of N as well as the yield of legumes on S-deficient soils (Scherer, 2001). Indeed, faba bean (bean; *Vicia faba* L.) has been shown to respond positively to S application (Scherer and Lange, 1996). However, there have been few investigations carried out on the effects of S fertilization in bean grown as a sole crop or intercrops. Wheat (*Triticum aestivum* L.) has a relatively low S requirement (Zhao *et al.,* 1999; Flaete *et al.,* 2005; Garrido-Lestache *et al.,* 2005). Indeed, recently application of S has been shown to increase biomass and seed yields in wheat (Salvagiotti and Miralles, 2008; Salvagiotti *et al.,* 2009), and this was attributed to the positive interaction between N and S, which was reflected in greater nitrogen use efficiency (NUE) (Salvagiotti *et al.,* 2009). Therefore, these authors concluded that there is need for simultaneous management of N and S to increase N recovery from the soil and sustain high NUE. Others have previously reached similar conclusions (Flaete *et al.,* 2005; Tellec *et al.,* 2008). However, Garrido-Lestache *et al.* (2005) reported that simultaneous application of N and S did not have significant effect on wheat seed yield. They concluded that the main effect of N was responsible for the yield differences.

Under intercropping conditions sometimes cereals, absorbs more S at the expense of legumes; indicating that S deficiency promotes the disappearance of legumes (Scherer, 2001). However, only a few studies have investigated the effect of S fertilization in wheat/bean intercropping systems (Gooding *et al.,* 2007). Recently, in an organic system Gooding *et al.* (2007) stated that N concentration of the cereal seeds was increased by intercropping irrespective of the location and design. They stated further that S concentration of the cereal was also increased by intercropping but less regularly and to a lesser extent compared with the effects on N concentration. In their study N concentration in the intercrop was associated with lower wheat seed yields. Intercropping also had effects on some quality parameters in their investigations. However, the effect of S on productivity of wheat/bean intercropping system under contrasting cropping systems has rarely been compared. Inorganic S is generally much less abundant in most agricultural soils than is organically bond S (Scherer, 2001). Therefore, it is possible to have different response of wheat/bean intercrop between the contrasting environments of conventional to that of organic management systems. This is because organic S compounds are unavailable to crops and must be mineralized to the inorganic form before crop uptake (Scherer, 2001).

As well as the seed yield, S fertilization has been demonstrated to have positive effects on biomass yields in wheat (Salvagiotti and Miralles, 2008; Salvagiotti *et al.,* 2009). However, the literature indicates less effect of S application on harvest index (HI). For instance, Salvagiotti and Miralles

(2008) and Salvagiotti *et al.* (2009) reported that S application had no significant effect on HI in wheat as N levels were increased. Yet, little is known on the effect of S fertilization on HI in wheat/bean intercropping systems under both conventional and organic management. Thus, a comparison of the effects of S fertilization on HI under the two contrasting systems in the same study is necessary.

The literature indicates that provided the crops is not short of water and is well nourished biomass yields depend on the accumulated photosynthetically active radiation (PAR) and the efficiency with which the accumulated PAR is used, (i.e. radiation use efficiency (RUE)) (Confalone *et al.,* 2010; Yahuza , 2011a). Salvagiotti and Miralles (2008) explained that greater accumulated PAR with concurrent application of S with N was responsible for the variation in biomass and to some extent seed yield in their investigation. They emphasised that the greater accumulated PAR when S and N were simultaneously applied was largely due to an improvement in leaf area index. However, similar to the HI, S fertilization has been shown to have less effect on the RUE. For instance, Salvagiotti and Miralles (2008) showed that simultaneous application of S and N significantly improved accumulated PAR in wheat but not the RUE. Although Salvagiotti and Miralles (2008) investigated the effects of S fertilization on accumulated PAR and RUE in wheat under sole cropping, such effects has rarely been investigated under intercropping conditions, and wheat/bean intercropping systems to be specific. To explain the effect of S fertilization on seed and biomass yields in wheat/bean intercropping systems, data on main determinants of yields such as the accumulated PAR and RUE are necessary. Given the contrasting growing conditions of conventionally and organically managed crops, clearly, there is a need to compare the effects of S fertilization on yields and determinants of yields under the two systems.

Agronomically, in terms of land equivalent ratio (LER) (Bulson *et al.,* 1997; Haymes and Lee, 1999) reports indicate positive benefits of wheat/bean intercropping system when S was applied under organic management (Gooding *et al.,* 2007). This indicates that more land would have been required had sole crops of each of the two crops were sown. However, the physical and/or physiological basis (Azam-Ali *et al.,* 1990) of intercrop performance in response to applied sulphur in wheat/bean intercropping systems has not yet been investigated. Thus, there is a need to evaluate the efficiency of wheat/bean intercropping system response to S fertilization using crop performance ratio (CPR) (Harris *et al.,* 1987; Yahuza, 2011b).

The objectives of this study were i. To investigate the effects of S fertilization and wheat seed rate (wsr) on seed yields, determinants of seed yields and determinants of biomass yields in wheat/bean intercropping system under contrasting production systems. ii. To evaluate the performance efficiency based on CPR of wheat/bean intercropping systems for the items mentioned above (i.e. objective i.).

Materials and methods

Study area

The two experiments reported in this paper were carried out at the University of Reading's Crop Research Unit, Sonning, Berkshire, (0^o 56ˊW, 51^o 27ˊ 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^2/day and 5.1-17.3 ^{o}C respectively. The study location had a land area of 10 hectares (ha), with a portion (2.5 ha) that is not a certified organic field (i.e. *sensu stricto* organic) but since 2001 has been managed organically. The organic portion is split into smaller areas, to allow for a six-course rotation. The soil at the experimental field has 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 at random locations in the field using a using a soil corer. Soils were collected from 0-90 cm depth. Samples were then bulked and analyzed for pH, P, K, Mg, available N and sulphate. In the conventional area, soil properties were 7.1, 45 (mg/I), 138 (mg/I), 50 (mg/I), 28.9 (kg N/ha) and 68. 1 (mg/I) for pH, P, K, Mg, available N and sulphates respectively. In the organic area, soil properties were 6.3, 35 (mg/I), 119 (mg/I), 48 (mg/I), 66.7 (kg N/ha) and 66.7 (mg/I) for pH, P, K, Mg, available N and sulphates respectively. This indicates that the available N in the organic area was higher than the conventional area.

Experimental design and treatments

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^2) with or without 40 seeds/m^2 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. The sulphur treatment main plots had an area 10m x 20m. Sulphur treatment were with and without 40 kg SO_4 /ha. The wheat seed rate 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 on 4 April 2006, 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 is equivalent in total to 92 kg N/ha and 35 kg SO_4/ha.

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, 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 spaying 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_4/ha.

Crop management

In Experiment 1, 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 often referred to as conventional experiment in contrast to Experiment 2, which was organically managed. In Experiment 1 fungicide was applied on 5 April 2006 at GS 31 (Zadoks *et al.,* 1974) 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 was not sprayed with any herbicides and fungicides. The experiment was treated as an organic experiment and hence the application of such chemicals was not allowed.

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, 2011a) to calculate the total amount of PAR intercepted per day and then over the life of the crop was followed. The RUE (g/MJ) was calculated by dividing the final biomass (g/m^2) by the accumulated PAR (MJ/m^2) as described by Yahuza (2011a). Note that in this paper except if otherwise stated RUE (g/MJ) refers to the efficiency of conversion of accumulated PAR from sowing until maturity.

The above-ground biomass for both wheat and bean were collected from destructive samples taken from 1m x 0.5m area with a quadrat. 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 biomass yield, the seed yield was divided by the HI as described by Gooding *et al.* (2002). Similarly, following the method described by these authors, harvest index was determined as the ratio between the seed yield to the biomass yield. The HI was calculated from the final destructive sampling prior to the combine harvest. The final destructive crop biomass sample taken was separated into stems + leaves and ears for the wheat. For the bean, the separation was stems + leaves and pods. Each of these separate categories was oven dried and weighed separately. The wheat ears were threshed and separated to chaff and seeds (F. Walter and H. Wintersteiger K G, Austria). Thereafter, the chaff was added to the stem + leaf. The seeds were weighed and used to calculate the HI for the wheat. Similarly, the bean pods were separated into chaff and seeds by threshing. The chaff was then added to stems and leaves while the seeds were used for calculating the HI.

The final harvest was carried out with a combine harvester (Wintersteiger Nursery Master Elite, Inkreis, Austria). The central 1.25m of each plot was harvested. Both wheat and bean were harvested at the same time. The two outer rows and the destructive sampling areas were left as discards. The length of the harvested plot was then measured. Wheat seeds and bean were then separated in the laboratory with the aid of different sieves. The final harvest was carried out on 10 August 2006, 315 DAS. The approximate harvested area for each of the two experiments was 1.25m x 7m per plot. Later the seed yields were adjusted to 15% moisture content.

Statistical analyses

In general, data were analysed using GENSTAT (Genstat 8.1 release, Rothamsted UK). Generally, the following were considered in the ANOVA. For wheat-only responses plots with wsr = 0 were excluded from the statistical analyses. Similarly, in the case of bean variables, plots with no bean sowing were restricted from the analyses to get the sole and intercrop values. For combined wheat + bean (henceforth to be referred to as total intercrop or total) analyses were done mostly with no restriction. The variables were analysed as follows. The analyses were done using the General analysis of variance. The treatment structure was: sulphur treatment x pol (wheat seed rate; 3) x bean treatment with all interactions. The block structure was: block/sulphur treatment/wheat seed rate/bean treatment. Regressions mainly using hyperbolic yield-density equations (Willey and Heath, 1969; Yahuza, 2011c) were performed across wsr particularly for wheat yields where the response to wsr deviated from linearity. Hence, for all the data sets for which the regression was performed, the adjusted R^2 was compared with the two-parameter asymptotic equation (Equation 1) to determine whether it fitted better when the response to wsr deviated significantly from linearity.

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

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

Intercrop performance was evaluated based on CPR. For the biomass, seed yield and accumulated PAR, CPR was calculated according to the procedures described by Harris *et al.* (1987) and Yahuza (2011b). The proportion-sown area was 50% (0.5) wheat and 50% (0.5) bean for each of the two experiments. This was because for the intercrops, a row of wheat was usually 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 (wheat + bean) CPR (TCPR) to be calculated. Hence, wheat CPR, bean CPR and total intercrop CPR were calculated using Equations 2, 3 and 4.

Wheat CPR (CPR_{wheat}) was calculated using Equation 2

$$CPR_{wheat} = \frac{WY_i}{P_{iw} WY_s} \qquad 2$$

Bean CPR (CPR_{bean}) was calculated using Equation 3.

$$CPR_{bean} = \frac{BY_i}{P_{ib} BY_s} \qquad 3$$

The total intercrop CPR (TCPR) for both wheat and bean was calculated using Equation 4

$$TCPR_{wheat+bean} = \frac{WY_i + BY_i}{P_{iw} WY_s + P_{ib} BY_s} \qquad 4$$

In Equations 2-4, 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).

Results

Weather data during the growing period at the experimental site

Weather data during the growing period for the two experiments showed that the mean monthly temperature during the winter growing season (October-February) was comparatively lower than the long-term average for the site (Table 1). Similarly, the total mean monthly rainfalls (October-December) were lower than the long-term mean monthly average for the site (Table 1). The mean monthly solar radiations received were similar to the long-term average for the site (Table 1). This indicates that water stress because of lower rainfall received might have had negative effects on both yields and overall productivity of the crops.

Effect of sulphur fertilization and its interactions with wheat seed rate and/or bean treatment on seed yields

In Experiment 1 (conventional experiment), application of S reduced wheat seed yields significantly (P = 0.023): 188 g/m^2 and 241 g/m^2 for S and no S respectively. The standard error of difference (SED) was 8.1 with a degree of freedom (DF 2). The main effect of wsr on wheat seed yield deviated from linearity (P = 0.002 for the quadratic wsr effect), and there was a significant interactive effect detected between wsr and S (P = 0.028 for S x linear wsr effect). For the interaction between S and wsr, seed yields were 66 g/m^2, 171 g/m^2, 239 g/m^2 and 278 g/m^2 for 10, 50 100 and 200 wheat seeds/m^2 when S was applied respectively. When S was withheld, seed yields were 58 g/m^2, 209 g/m^2, 306 g/m² and 391 g/m² for 10, 50 100 and 200 wheat seeds/m² respectively (SED 26.9; DF 7.05). For the interaction of wsr and S, application of S significantly reduced wheat seed yields at 100 wheat seeds/m² or more. The maximum wheat sole crop seed yield of 391 g/m² was obtained at 200 wheat seeds/m² without S. This differed significantly from the seed yield at other wsr without S. The maximum wheat yield with S applied was obtained at 200 wheat seeds/m² (278 g/m²), but this did not differed from the 239 g/m² seed yield obtained at 100 wheat seeds/m² with S applied. The effect of bean treatment was also significant ($P < 0.001$) and there was significant interactive effect detected between wsr and bean treatment ($P = 0.027$ for quadratic wsr x bean treatment). However, S did not interact significantly with the bean ($P > 0.05$), and no significant interaction between S treatment, wsr and been treatment was detected ($P > 0.05$). However, despite the insignificant ANOVA outputs wheat seed yields were reduced from 50 wheat seeds/m² by intercropping mainly when S was applied (Fig. 1: SED 50. 5; DF 13.24). Interestingly, Equation 1 was fitted to quantify wheat sole crop with S applied and wheat sole crop without S applied seed yield responses (Fig. 1). The parameter values for the sole crop wheat responses are presented in Table 2. On the hand, wheat intercrop with S applied seed yield response was quantified more simply as $Y = 23 + 1.30$ wsr (Fig. 1), $r^2 = 0.97$ and without S applied as $Y = 21 + 0.33$ wsr (Fig. 1), $r^2 = 0.89$.

The mean effect of S was not significant on bean seed yields ($P > 0.05$). The main effect of wsr was also not significant on bean seed yields ($P > 0.05$), but there was a significant interactive effect detected between S and wsr ($P = 0.048$ for S x linear wsr effect). At 200 wheat seeds/m², application of S significantly improved bean intercrop seed yield. Seed yields were 195.8 g/m² and 81.9 g/m² for S and without S respectively (SED 48.4; DF 8.79). Hence, bean intercrop seed yield without S applied was quantified as $Y = 146.8-0.30$ wsr (Fig. 1), $r^2 = 0.91$, whilst the response of bean intercrop seed yield with S applied was not quantified because there was no consistent trend observed (Fig. 1).

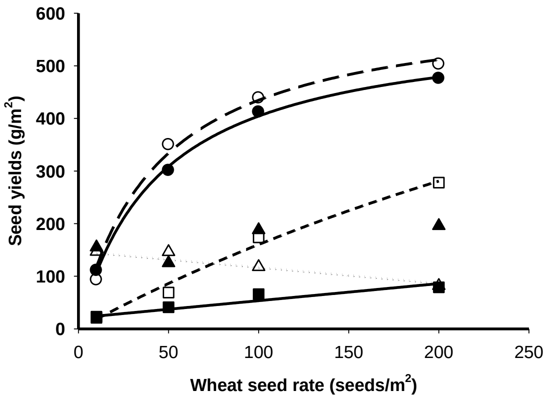

Fig. 1. Effect of wheat seed rate on seed yields (g/m2) for winter wheat (cv. Mallaca) sole crop with sulphur (S) applied ● (solid curve), sole crop without S applied ○ (broken curve), intercrop with S applied ■ (solid line), intercrop without S applied □ (broken line), faba bean (bean; cv Clipper) with S applied ▲ and bean without S applied Δ (dotted) seed yields for the conventional experiment (Experiment 1). The fitted equations are described in the text and parameter values for the wheat sole crops are given in Table 2. For the wheat SED S treatment = 8. 1 DF 2 and SED S treatment x wsr = 26.9 DF 7. 05. For the bean SED S treatment = 28. 58 DF 2 and SED S treatment x wsr = 48. 40 DF 8.79.

In general, with respect to seed yields, S application reduced performance as estimated by CPR of wheat in the intercrop as wheat seed rate increased (Table 3). On the other hand, S application improved the performance of bean in the intercrop as wsr increased (Table 3). With respect to the seed yields, the total intercrop was less efficient than the wheat sole crop except at 200 wheat seeds/m² when S was withheld (Table 3). Poor performance of the wheat, particularly when S was applied was responsible for the overall under performance of the total intercrop (Table 3).

In Experiment 2 (organic experiment), S had no significant mean effect on wheat seed yield (P >

0.05). Even though the effect of wsr was significant (P< 0.001), there was no significant interaction with S (P > 0.05). The effect of bean treatment was highly significant (P < 0.001) and there was significant interactive effect with the wsr detected (P = 0.001 for linear wsr x bean treatment effect). However, S did not interact significantly with the bean (P > 0.05). Similarly, S application did not have significant effects on bean seed yield (P > 0.05). The effect of wsr was significant (P = 0.045 for linear wsr), but there was no significant interactive effect detected with S treatment (P > 0.05). Since the effects of sulphur was the main thrust of this research and there was no significant mean effects of S, first order interaction with the wheat seed rate or bean treatment and/or second order interaction with wsr and bean treatment detected, no further details are presented.

Table 1. Mean monthly air temperatures and long term mean monthly air temperatures, mean monthly solar radiation, long-term mean monthly solar radiation, total mean monthly rainfall and long-term mean monthly rainfall for the experimental site at Sonning.

Year	Month	Mean air monthly temperature (ºC)	Long term mean air monthly temperature (37 year mean) (ºC)	Solar radiation ($MJ/m^2/day$)	Long term mean solar radiation ($MJ/m^2/day$)	Total rain fall (mm)	Long term mean monthly rainfall (47 year mean) (mm)
2005	September	15.4	14.2	10.1	10.2	37.4	56.8
2005	October	13.4	10.8	4.8	6.0	56.0	67.3
2005	November	5.9	7.1	3.4	3.2	31.9	63.9
2005	December	4.0	5.1	2.2	2.0	52.0	63.8
2006	January	4.4	4.4	2.4	2.5	13.9	58.4
2006	February	3.9	4.5	4.1	4.6	47.2	40.1
2006	March	5.3	6.5	7.1	8.0	45.6	47.9
2006	April	9.1	8.6	10.5	12.4	25.7	49.0
2006	May	12.6	12.0	12.8	16.0	79.7	49.3
2006	June	16.4	15.0	19.8	17.5	11.1	47.6
2006	July	20.6	17.3	21.0	16.5	32.0	45.1
2006	August	16.8	16.9	13.7	14.4	36.2	56.8

Table 2. Parameter values and standard errors for the hyperbolic equation (equation 1) fitted to the wheat sole crop seed yields with sulphur (S) applied and with S withheld for the conventionally managed experiment (Experiment 1) to indicate the equation quantified the yield satisfactorily.

Sulphur treatment (SO_4 kg/ha)	Parameter	estimate	Standard error	Coefficient of determination (%)
40	a_w	0.07667	0.00489	99.7
	b_w	0.0017065	0.0000491	
0	a_w	0.0694	0.0106	98.6
	b_w	0.001607	0.000108	

Effect of sulphur fertilization and its interactions with wheat seed rate and/or bean treatment on determinants of seed yields

In Experiment 1 (conventional experiment), similar to the effects on seed yields, S treatment reduced wheat biomass yields and the effect was greater for the intercrop than the sole crop. The mean effect of S treatment on wheat biomass yield was significant (P = 0.022). For the mean effects of S application, wheat biomass yields were 340 g/m² and 435 g/m² for S and without S respectively (SED 14. 5; DF 2). This indicates that S application significantly reduced wheat biomass yield. The effect of wsr on biomass yield deviated from linearity ($P < 0.001$ for the quadratic wsr effects). There was significant interactive effect between S and wsr (P = 0.001 for S x linear wsr effects). When S was applied, wheat biomass yields were 130 g/m², 306 g/m², 429 g/m² and 495 g/m² for 10, 50, 100 and 200 wheat seeds/m² respectively (SED 25.8; DF 7.82). Similarly, when S was withheld wheat biomass yields were 125 g/m², 381 g/m², 544 g/m² and 691 g/m² for 10, 50, 100 and 200 wheat seeds/m² respectively. The mean effect of bean treatment was also significant ($P < 0.01$), but S did not interact significantly with bean ($P > 0.05$). There was significant interaction between wsr and bean (P = 0.038 for quadratic wsr x bean effects). However, there was no significant interaction detected between wsr, S and bean treatment ($P > 0.05$; SED 79. 3; DF 9.86). Nevertheless, despite insignificant ANOVA outputs, similar to the seed yields, Equation 1 quantified wheat sole crop with S applied and wheat sole crop without S applied biomass yield responses (Fig. 2). The parameter values are presented in Table 4. On the other hand, wheat intercrop with S applied biomass yield response was quantified simply as $Y = 51 + 1.34\ wsr - 0.0048\ wsr^2$ (Fig. 2), $r^2 = 0.94$, whilst without S as $Y = 56 + 2.31\ wsr$ (Fig. 2), $r^2 = 0.98$. Hence, wheat biomass yields followed similar pattern as the seed yield.

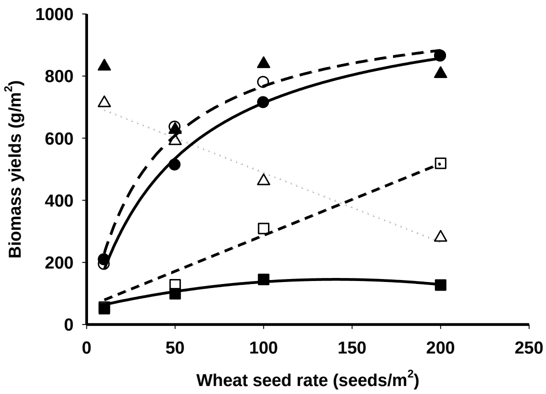

Fig. 2. Effect of wheat seed rate (wsr) on biomass yields for winter wheat (cv. Mallaca) sole crop with sulphur (S) applied ● (solid curve), sole crop without S applied ○ (broken curve), intercrop with S applied ■ (solid curve), intercrop without S applied □ (broken line), faba bean (bean; cv Clipper) with S applied ▲ and without S applied Δ (dotted) for the conventional experiment (Experiment 1). The fitted equations are described in the text and parameter values for the wheat sole crop are given in Table 4. For the wheat SED S treatment = 14.5 DF 2 and SED S treatment x wsr = 25. 8 DF 7.82. For the bean SED S treatment = 56.8 DF 2 and SED S treatment x wsr = 264.9 DF 8.71.

Following similar patterns as the seed yields, in general, bean biomass yield increased with the application of S but the effect was greater at the higher wsr (Fig. 2). For the mean effects of S, bean biomass yields were 855 g/m² and 590 g/m² for S applied and S withheld respectively (SED 56.8, DF 2). Wheat seed rate did not had a significant effect on bean biomass yield ($P > 0.05$), and there was no significant interactive effect detected with S ($P > 0.05$). Nevertheless, the response of bean intercrop biomass yield without S applied was quantified simply as $Y= 713 -2.24\ wsr$ (Fig. 2), $r^2 = 0.98$. On the other hand, the response of bean intercrop biomass yield with S applied was not quantified because no consistent effect of wsr was observed (Fig. 2: SED 264. 9; DF 8.71).

In Experiment 1, S treatment had no significant effect on wheat and bean HI (P > 0.05 in each case). Mean HI for all plots was 0.44 and 0.20 for wheat and bean respectively. This indicates that the mean effects of S on determinant of variation in wheat and bean seed yields between the sole crops and the intercrops were on the biomass yields.

Table 3. Wheat crop performance ratio (CPR), bean CPR and the total intercrop CPR for the seed yields in Experiment 1 (conventional experiment) to show that there was no benefit for intercropping except at 200 wheat seeds/m2 when sulphur was withheld.

Sulphur treatment (SO_4 kg/ha)	Wheat seed rate (seeds/m²)	Wheat CPR for seed yields	Bean CPR for seed yields	Total intercrop CPR for seed yields
40	10	0.08	1.48	0.49
	50	0.16	1.20	0.47
	100	0.26	1.80	0.71
	200	0.31	1.87	0.77
0	10	0.09	1.40	0.48
	50	0.27	1.40	0.60
	100	0.69	1.13	0.82
	200	1.11	0.78	1.01

Bean sole crop seed yield used for standardizations were 206.8 g/m² and 209.2 g/m² for treatments with and without S applied respectively. For the wheat sole crop and intercrops yields as well as bean intercrop yields used for calculating the CPR, see Fig 1.

Table 4. Parameter values and standard errors for the hyperbolic equation (equation 2) fitted to the wheat sole crop biomass yields with sulphur (S) applied and without S applied for the conventionally managed experiment (Experiment 1) to indicate that the equation quantified yield satisfactorily.

Sulphur treatment (SO_4 kg/ha)	Parameter	estimate	Standard error	Coefficient of determination (%)
40	a_w	0.04697	0.00523	99.1
	b_w	0.000932	0.0000504	
0	a_w	0.03402	0.00502	98.6
	b_w	0.000963	0.0000551	

Table 5. Wheat crop performance ratio (CPR), bean CPR and the total intercrop CPR for biomass yields in Experiment 1 to show that there was no benefit for intercropping across wheat seed rate due to poor performance of the wheat in the intercrop.

Sulphur treatment (SO_4 kg/ha)	Wheat seed rate (seeds/m²)	Wheat CPR for biomass yields	Bean CPR for biomass yields	Total intercrop CPR for biomass yields
40	10	0.12	1.42	0.87
	50	0.23	1.07	0.71
	100	0.34	1.43	0.97
	200	0.29	1.38	0.92
0	10	0.13	1.22	0.76
	50	0.30	1.01	0.71
	100	0.72	0.79	0.76
	200	1.20	0.48	0.78

Bean sole crop biomass yield used for standardizations were 1172 g/m² and 901 g/m² for treatments with and without S applied respectively. For the wheat sole crop and intercrops biomass yields as well as bean intercrop biomass yields used for calculating the CPR, see Fig 2.

In Experiment 1, evaluations of the biomass yields based on CPR indicates that wheat in the intercrop was less efficient than the sole crop across wsr particularly when S was applied (Table 5). On the other hand, bean in the intercrop was more efficient than the sole crop particularly when S was applied (Table 5). Indeed, when S was withheld, the performance of bean in the intercrop decreased substantially at 200-wheat seeds/m^2 (Table 5). Consequently, with respect to the biomass yields, due to the poor performance of wheat in the intercrop, the total intercrop struggled across all wsr (Table 5).

In Experiment 2 (organic experiment), the mean effect of S treatment on wheat biomass yield was not significant ($P > 0.05$). The effect of wsr on wheat biomass yield deviated from linearity ($P = 0.044$ for the cubic wsr effect), but there was no significant effect between wsr and S detected ($p > 0.05$). The mean effect of bean treatment was significant ($P < 0.001$) but S did not interact with the bean treatment ($P > 0.05$). Wheat seed rate interacted significantly with the bean ($P = 0.031$ for the cubic wsr effect). Similarly, the effect of S on bean biomass yield was not significant ($P = 0.46$). The effect of wsr on bean biomass yield was not significant either ($P > 0.05$). There was no significant interactive effect between wsr and S detected ($P > 0.05$). In addition, in Experiment 2, the application of S was not significant on wheat and bean HI ($P > 0.05$ in each case). As was the case with the seed yields, given that the effects of sulphur was the main thrust of this experiments, and there was no significant response to the mean effects of S, first order interaction with the wsr or bean treatment and/or second order interaction with wsr and bean treatment detected, no further details are given.

Effect of sulphur fertilization and its interactions with wheat seed rate and/or bean treatment on determinants of biomass yields

In Experiment 1 (conventional experiment), the mean effect of S treatment on the accumulated PAR was not significant ($P > 0.05$). The main effect of wsr on the accumulated PAR deviated from linearity ($P = 0.026$ for the quadratic wsr effect). There was a significant interactive effect between wsr and S ($P = 0.047$ for linear wsr x S effect). When S was applied, accumulated PAR were 395.2 MJ/m^2, 417.0 MJ/m^2, 468.0 MJ/m^2, 525.3 MJ/m^2 and 506 MJ/m^2 for 0, 10, 50, 100 and 200 wheat seeds/m^2 respectively (SED 33.19; DF 9.99). On the other hand, when S was withheld, accumulated PAR were 422.3 MJ/m^2, 400.3 MJ/m^2, 451.0 MJ/m^2, 443.0 MJ/m^2 and 430.6 MJ/m^2 for 0, 10, 50, 100 and 200 wheat seeds/m^2 respectively. This indicates that application of S significantly improved accumulated PAR at 100 wheat seeds/m^2 or more. The maximum PAR accumulated when S was applied did not differed significantly from that at 50 and 200 wheat seeds/m^2. Note that when S was withheld, accumulated PAR did not differ significantly. Bean treatment also had a significant effect on accumulated PAR ($P < 0.001$), and there was significant interaction with the wsr ($P = 0.017$ for quadratic wsr x bean treatment effect). As is indicated in Table 6, S did not interact significantly with wsr and bean treatment ($P > 0.05$). In Experiment 1, S had no significant effect on the RUE ($P > 0.05$). There was no significant interaction of S with the wsr ($P > 0.05$). Sulphur did not interact significantly with the bean treatment ($P > 0.05$), and no second order significant interactive effect between S, wsr and the bean treatment detected ($P > 0.05$). The overall mean RUE value was 1.44 g/MJ. This indicates that the effect of S application on biomass yields was on its effects on accumulated PAR. Thus, evaluations based on the CPR indicate that the total intercrop was as efficient as the wheat sole crop in accumulating PAR, particularly when S was applied (Table 6). However, at 200 wheat seeds/m^2 when S was applied the total intercrop was more efficient than the sole crop in accumulating PAR (Table 6).

In Experiment 2, S did not have significant mean effect on the accumulated PAR ($P > 0.05$). The effect of wsr was not significant either ($p > 0.05$)

and there was no significant interactive effect between wsr and S detected (P > 0.05). Sulphur had no significant effect on the RUE (P > 0.05). Wheat seed rate had a significant effect on the RUE (P < 0.001 for the linear wsr effect), but there was no significant interaction with S (P > 0.05). Bean treatment did not had significant mean effect on the RUE (P > 0.05) but there was no significant interaction between bean treatment and wsr (P = 0.015 for the linear wsr x bean effects). Sulphur did not interact significantly with the bean (P > 0.05), and there was no significant interaction between wsr, S and bean treatment detected (P > 0.05). As was the case with the seed and biomass yields, given that the effects of S was the main thrust of this investigations, and there was no significant response to the mean effects of S, first order interaction with the wsr or bean treatment and/or second order interaction with wsr and bean treatment detected, no details are provided.

Table 6. Wheat sole crop accumulated photosynthetically active radiation (PAR), total intercrop accumulated PAR, bean sole crop accumulated PAR and total intercrop crop performance ratio (CPR) for accumulated PAR in Experiment 1 (conventional experiment) to show that the intercrops were more efficient than the wheat sole crop in accumulating PAR at 200 wheat seeds/m² when S was applied.

Sulphur treatment (SO_4 kg/ha)	Wheat seed rate (seeds/m²)	Wheat sole crop accumulated PAR (MJ/m²)	Total intercrop accumulated PAR (MJ/m²)	Bean sole crop accumulated PAR (MJ/m²)	Total intercrop CPR for accumulated PAR
40	10	355.7	478.3	500.0	0.91
	50	425.2	510.7		0.98
	100	547.4	503.2		0.96
	200	463.2	550.7		1.05
0	10	355.3	445.4	494.1	0.85
	50	409.5	492.4		0.94
	100	423.2	462.8		0.88
	200	392.6	468.5		0.89

SED S x wsr x bean treatment = 48. 21 DF 19.93.

Discussion

The interrelationships between crops response to applied S and N has been demonstrated previously (Thomas *et al.,* 2003). Previous findings at Reading showed that both N and S concentration of the wheat (for the Reading experiment) was increased by intercropping with bean under organic systems (Gooding *et al.,* 2007). My results showed effects of S application under conventional cropping system to be substantial. Such that S application decreased performance in terms of wheat seed yields. It was interesting to see that the maximum yield was obtained at 200 wheat seeds/m² when sulphur was withheld. This further confirms earlier recommendations that optimal seed rate for winter wheat in the UK is between 200 -250 seeds/m² (Gooding *et al.,* 2002). On the other hand, result showed that bean intercrop seed yield was improved when S was applied. Previous research had indicated positive response of wheat to S fertilization under conventional production system particularly under sole cropping (Zhao *et al.,* 1999; Flaete *et al.,* 2005). Here, this assertion was not supported because both sole cropped wheat and the intercropped wheat responded negatively to S application. Apparently, this study agrees with Garrido-Lestache *et al.* (2005) who found that simultaneous application of N and S did not have significant effect on wheat seed yield under conventional production systems. Asare and Scarisbrick (1995) also reported negative effects of S fertilization on the biomass yields in an oil seed rape (*Brassica napus*) investigation.

Zhao *et al.* (1999) asserted that the S requirement of wheat is about 15-20 kg/ha. In my experiments, applied S was up to 40 kg/ha of SO_4 (approximately 16 kg/ha of S), suggesting that S was not limiting. This indicates that reductions in wheat seed yields with the application of S may be because of the lower N applied. Indeed, Zhao *et al.* (1999) contended that due to strong interrelationship between N and S, crop response to S fertilization often depends on the amount of N applied. They emphasised that deficiency of S may be induced by a high amount of applied N. They also reiterated that responses to S application are usually greater when abundant amount of N are applied. The insignificant difference between the wheat sole crop to which S was applied and that which S was withheld indicates that wheat S requirement was small. In agreement with Zhao *et al.* (1999) the low N applied might be responsible for the negative response of wheat intercrop to applied S, as was seen by the similar responses of sole crop wheat to applied S even though the difference was not significant. In other words, it was demonstrated that practically for the wheat sole crop application of S might not be necessary if not accompanied with sufficient application of N.

My research has shown that bean seed yields were improved under the conventional system in response to S and wheat seed rate. This is in agreement with previous findings that sulphur can have positive effects on performance of bean under sole cropping (Scherer and Lange, 1996) and under intercropping conditions with wheat (Gooding *et al.,* 2007). In particular, while the latter study was organically managed, the present research had both conventional and organic experiments involved; but the effects of S on seed yields and other variables was not substantial in the organic experiment. That sulphur application decreased wheat seed yields substantially, whilst bean intercrop seed yields was increased here indicates that beans were more competitive for S than N which is in agreement with earlier conclusions (Gooding *et al..,* 2007).

That faba bean benefited positively from applied S compared to the wheat is not surprising. It is well established that both N and S are critical for protein synthesis because they are constituents of amino acids such as methionine, which are building blocks for proteins (Gooding and Davies, 1997). Indeed, Zhao *et al.* (1999) asserted that because of the strong interdependence of N and S metabolism, it is not surprising that plants tend to maintain a relatively constant ratio of organic N to organic S, mainly in the vegetative tissues, even though the ratio of total N to the total S can vary widely in response to N and S application. They emphasised that when S is deficient in relation to the N supply, accumulation of non-protein compounds such as amides occurs, resulting in an N to S ratio greater than 15:1. According to them, however, when S supply is greater than required for protein synthesis sulphates accumulates in plant tissues, leading to an N to S ratio smaller than 15:1.

In this research, it is possible that whilst bean competed intensely with wheat for applied S throughout the growing periods, wheat was unable to compete significantly at the reproductive periods due to N limitations. This assertion is sensible since neither wheat nor bean has the capacity to fix S, even though the latter can fix N (Gooding *et al.,* 2007). For instance studies indicated that application of S improved N fixing rate and hence the seed yields of legumes (Zhao *et al.,* 1999). Indeed, Sexton *et al.* (1998) demonstrated that S assimilation continue late into seed filling in soya bean (*Glycine max*). They emphasised that S assimilation during seed filling appears to be the main source of S containing amino acids for synthesis of seed proteins. Therefore, whilst N would not have had any substantial effects on the capture and assimilation of S by the beans, it is likely that the low applied N might have reduced wheat ability to capture and assimilate S. Indeed, the contrasting responses of wheat and bean to S in my research are in agreement with earlier conclusions. For instance, Andersen *et al.* (2007) in intercrop experiment composing barley (*Hordeum* *vulgare*) and peas (*Pisum sativum*) demonstrated that only peas responded positively to S fertilization.

That rainfall during the growing period of these experiments particularly during the winter months were lower than the 47-year long-term average of the site (Table 1) suggests that besides the effects of sulphur and seed rates, water limitations might have had negative effects on yields and overall productivity of the two crops. For instance for the wheat sole crop, my research indicates that seed yields were 390 g/m² in the absence of S and 280 g/m² with S applied. These values were about 40 – 50 % of the 800 g/m² UK national average yield for winter wheat under sole cropping, and indeed were extremely lower than yields obtained previously at the same location (Gooding *et al.,* 2002). Unfortunately, these trials were not repeated in the following year with sulphur applied. Had sulphur being investigated alongside seed rates in the second year, it may well results in a different outcome. Therefore, here the possibility that weather factors might have had detrimental effects on seed yields and overall productivity of the crops was not ruled out.

As regards biomass yields, results have shown similar yield-density relationship, as was the case with the seed yields in the conventional experiment. This clearly indicates that wheat and bean seed yields were satisfactory fractions of the biomass yields regardless of whether S was applied or not. Salvagiotti and Miralles (2008) and Salvagiotti *et al.* (2009) found that S fertilization increases both biomass and seed yield in wheat when applied together with N. They attributed similar responses of both the seed and biomass yields found in their research to the conservative nature of HI across S treatment. In contrast to their investigations, this research had indicated that wheat biomass yields were reduced when S was applied. In addition, in my research, application of S improved bean biomass yields. The positive response of beans biomass yields to applied sulphur under the conventional system found here is in agreement with previous findings (Scherer and Lange, 1996). However, S fertilization had no significant effect on wheat and bean HI for both the conventional and organic experiment. Therefore, my research is in agreement with Salvagiotti and Miralles (2008) and Salvagiotti *et al.* (2009) that wheat HI may be conservative across S treatment. Here I have demonstrated that such conservative effects on HI by S treatment to be true for bean as well.

Accumulated PAR was improved when S was applied in the conventional experiment. Salvagiotti and Miralles (2008) explained that greater accumulated PAR with concurrent application of S with N was responsible for the biomass and to some extent seed yield variations with the control treatments in their study. Whilst, in their study they found positive effects of S fertilization on accumulated PAR by the wheat sole crop, in this research I found a positive interactive effect of S with the wheat seed rate on the accumulated PAR by wheat/bean intercrop. Thus, the conclusion of Salvagiotti and Miralles (2008) that S application can improve accumulated PAR is confirmed. The effects of S on accumulated PAR and RUE in intercropping and wheat/ bean systems in particular, has rarely been investigated. For instance whilst the effects of S on some quality attributes of wheat/bean intercropping systems has been well researched at Reading and indeed over a wide area (Gooding *et al.,* 2007), the effects of S on accumulated PAR and RUE has not. In my conventional experiment, S and /or N application may have had a positive effect on bean ability to accumulate PAR due to an improvement in its ability to fix N. Although legumes and bean in particular has the capacity to produce high yields without N application (Confalone *et al.,* 2010), sometimes a small amount of applied N may be required to enhance biological nitrogen fixation by the legumes. If bean N fixation capacity is improved, then bean S responsiveness may also likely be improved since S has been shown to be linked to NUE (Flaete *et al.,* 2005; Tellec *et al.,* 2008). NUE is an indication of how efficiently crops transfer available N into seed and/or biomass yield, and has two components namely recovery efficiency and internal efficiency (Salvagiotti *et al.,* 2009). Salvagiotti *et al.* (2009) defined recovery efficiency as the relation between N uptake and applied N. On the other hand, they defined internal efficiency as the relation between yield and N uptake. The study of Salvagiotti *et al.* (2009) indicated that no changes in internal efficiency in response to S fertilization was observed, but the application of S increased NUE by increasing N recovery from the soil, particularly as N fertilizer rate increased. In other words, S fertilization had less significant effects at lower N levels indicating that the crop S demand at the lower N rate was met. Therefore, since N has been shown to have substantial effects on accumulated PAR by the crops, it follows that where bean N fixation is improved, and the crops accumulated PAR may also be improved. In addition, in the study of Salvagiotti and Miralles (2008), RUE was not affected by S fertilization. This indicates that the effect of S was mainly on the accumulated PAR. In my conventional experiment, I found S did not have a substantial effect on the RUE, even though effects on accumulated PAR were found in agreement with Salvagiotti and Miralles (2008).

The insignificant response of seed yields and other variables to sulphur fertilization in my organic experiment is not surprising. It is well established that under organic management N supply relies largely on non-synthetic sources, such as by crop rotation, intercropping etc (Huxham *et al.,* 2005). Therefore, it may be unlikely that the N requirement of organically grown crops may be supplied as at when due in adequate or optimal levels with phenological requirements of the crops (David *et al.,* 2005). In other words, for example it may be that during the reproductive period of wheat for example when N is most needed, N requirement may not be met under organic system. Since crops S responsiveness may depend on N responsiveness and NUE, it is sensible to expect S to have lesser effects under organic system as was exemplified in my organic experiment. To improve S responsiveness of crops in an organic system, then N must not be limiting at anytime during crop development. However, in my organic experiment N did not appeared to be in short supply. This can be exemplified by the greenish looking foliage of the wheat in the organic experiment throughout the growing season before the crop senesced (compared to the conventional experiment). However, that beans in the organic experiment was infected by chocolate spot disease (*Botrytis fabae*) at the reproductive stages, suggest that the disease might have out masked any effects S application might have had on both wheat and beans. However, it should be pointed out that ammonium sulphate applied to the conventional experiment in the present investigation might not have the same effects as the application of elemental sulphur in the form of Thiovit to the organic experiment. Therefore, future trials should consider other sources for sulphur to apply for the organic experiments besides the materials used here.

The final objective of my research was to evaluate the performance efficiency of yield and its determinants based on CPR in response to S, wsr and bean treatment under conventional and organic production system. For the seed yields, in my conventional experiment the total intercrop was slightly more efficient than the sole crop only at 200 wheat seeds/m^2 when S application was withheld as indicated by CPR value of 1.01. For the seed yields, wheat in the intercrop was more efficient than the sole crop only at 200-wheat seeds/m^2 when sulphur was withheld as indicated by CPR value of 1.11. The maximum CPR for the bean of 1.87 was obtained at 200 wheat seeds/m^2 when S was applied. Thus, due to poor performance of the wheat when S was applied, despite positive bean CPR values the total intercrop struggled. It was interesting that the efficiencies of the biomass and accumulated PAR followed similar pattern as the seed yields, thus making these variables the main determinant of yields variations in response to applied sulphur.

Based on evaluations using LER, wheat/bean intercropping systems has been shown to be beneficial (Haymes and Lee, 1999; Bulson *et al.,* 1997). In addition, recently, Gooding *et al.* (2007) reported benefits of S application on performance of wheat/bean intercropping system suggesting positive LER values when S was applied. As was the case, in the present research, they also found out that bean partial LER was improved by S fertilization.

The present investigations indicate slight efficiency of the overall intercrop only when S was withheld even though the efficiencies of the two component crops differed in response to S application. Whilst wheat/bean intercropping system has been found to be beneficial under both conventional (Haymes and Lee, 1999) and organic systems (Bulson *et al.,* 1997), the effects of S on productivity have rarely been investigated. In additions, the conclusions of the previous studies were based on agronomic interpretations as indicated by a positive LER values (Yahuza, 2011b). Simply, an LER value greater than 1 indicates that more land would have been required had sole crops of the two or more intercrops were sown (Haymes and Lee, 1999; Yahuza, 2011b). Here I was interested in the physical and physiological basis of intercrop productivity, as indicated by my choice of CPR for evaluation of intercrop performance (Harris *et al.,* 1987). To my knowledge, no wheat/bean intercropping system performance has been evaluated using CPR as was demonstrated here. However, both Harris *et al.* (1987) and Azam-Ali *et al.* (1990) evaluated the performance of intercropping using the CPR. Harris *et al.* (1987) found out that CPR was greater in water deficits situations reaching up to 1.21, and the cereal was more competitive than the legume. Azam-Ali *et al.* (1990) later reached similar conclusions. They explained that the positive CPR was because the intercrop produced more biomass and accumulated more PAR. They added that the advantage of the seed yield was attributed to increase in the HI of the cereal component in the intercrop. My research agrees with Harris *et al.* (1987) and Azam-Ali *et al.* (1990) that the total intercrop may be more efficient than sole crop in using resources to produce yield. However, unlike their studies that demonstrated the cereal component to be always more efficient than the legume component, my research has shown that the legume component (bean) performed more efficiently than the cereal component (wheat) in response to applied sulphur. In addition, I have not found any evidence of improvement of the HI of any component in the intercrop in response to applied sulphur. Thus, suggesting that biomass yields were the main determinant of variation in seed yields in response to applied sulphur (Yahuza, 2011d).

Conclusions

In conclusion, for the conventional experiment, it was demonstrated that S fertilization reduced wheat seed yields and biomass yields substantially. On the other hand, S fertilization increased bean seed yields and biomass yields positively. For the seed yields, application of S decreased the performance of the wheat significantly in the intercrop; the highest wheat CPR estimate of 1.11 was obtained when S application was withheld. On the other hand, the maximum bean CPR estimate of 1.87 was obtained when S was applied. It was concluded that bean competed with the wheat intensely for S than for N leading to higher seed yields for the bean when S was applied than when S was withheld. Thus, due to intense competition by the beans for S wheat intercrop seed yields was significantly reduced. For both wheat and bean, the effects of S on seed yields were on the biomass yields. Although the mean effect of S application on accumulated PAR was not substantial, S significantly interacted with wheat seed rate. Thus, whilst application of S had positive effects on accumulated PAR by the intercrop, RUE was conservative in response to S application. In the organic experiment, my results indicate that the effects of S fertilization on the above-mentioned variables were not significant.

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