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Effects of different sowing date and the combined effects of sowing date and seed rates on the performance of wheat (*Triticum aestivum* L.)/faba bean (*Vicia faba* L.) intercropping system

Ibrahim Yahuza

Crops Research Unit, Department of Agriculture, the University of Reading, RG6 6AR, Berkshire, United Kingdom

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Abstract

Temporal complementarity in resource use is not well understood in wheat (*Triticum aestivum*) /faba bean (bean; *Vicia faba*) intercropping system. Results from a field experiment involving this intercrop combination indicate no benefit in resource use by delaying bean sowing date (BSD), as the total intercrop (wheat + bean) seed yields were reduced with delay in BSD. Averaged across wheat seed rate, total intercrop seed yields were 586 g/m^2, 490 g/m^2 and 422 g/m^2 for simultaneous sowing of wheat with bean, 23 days delay in BSD and 37 days delay in BSD respectively. Although wheat seed yields were greater with delay in BSD, this had lesser effects on the overall total intercrop seed yields. Conversely, bean seed yields were greater the early the beans were sown and this had substantial impact on the total intercrop yield. This indicates that bean was the main determinant of variations in intercrop productivity. Biomass yields mainly determine seed yield variation in response to BSD for both wheat and bean. Biomass yields variations in response to BSD (and so seed yields) were attributed mainly to spatial complementarity in accumulated photosynthetically active radiation (PAR). For the combined effects of BSD and wheat seed rates, irrespective of the index used for evaluation, greatest intercrop performance was found when wheat and bean were sown simultaneously. Moreover, it was demonstrated that Area time equivalency ratio and crop performance ratio 'time corrected' could be calculated using thermal time to evaluate intercrop performance.

*Corresponding Author: Ibrahim Yahuza ✉ yiahmed@yahoo.co.uk

Introduction

Intercrop performance can be improved by manipulating agronomic tools for greater spatial and/or temporal complementarity in resource use (Willey, 1990; Francis 1989; Yahuza, 2011a). The temporal complementarity in resource use by the component crops in an intercrop can be improved mainly when the component crops differ in growth duration (Ofori and Gamedoagbao, 2005; Jahansooz *et al.,* 2007; Zhang *et al.,* 2007). On the other hand, spatial complementarity between the two component crops can be improved when the component crops are sown at the same time and harvested at the same time (Vandermeer, 1989; Hauggard-Nielson *et al.,* 2006). It has been widely accepted that complimentary use of growth resources by intercrop is mostly due to temporal factors (Fukai and Trenbath, 1993; Berti *et al.,* 2011; Marcos *et al.,* 2011), and light has been shown to be the most important factor when better temporal use of growth resource was found (Zhang *et al.,* 2008). The different sowing times allows one of the component crops to use resources before the later sown component is able to compete significantly (Hiebsch and McCollum, 1987; Tsay *et al.,* 1988). Wheat (*Triticum aestivum*) /faba bean (*Vicia faba*; henceforth referred to as bean) intercropping systems are usually devoid of different sowing dates (Bulson *et al.,* 1997; Haymes and Lee, 1999; Yahuza, 2011b). Thus, temporal complementarity in resource use amongst these intercrop components is not well understood, and needs to be given full attention.

However, if different sowing dates are employed, the actual time spent in the field using growth resources is not equal (Ofori and Stern, 1987; Fukai, 1993). This is because inter-specific competition for growth resources is reduced significantly because the component crops phenological requirements might not be the same (Zhang *et al.,* 2007; 2008). A straight analysis of the intercrop performance relative to the sole crops without taking into consideration the time factor may be misleading (Hiebsch and McCollum, 1987; Yahuza, 2011c). In other words, using straight analysis with indices such as the land equivalent ratio (LER), crop performance ratio (CPR) and monetary advantage (MA) derived from LER may not reflect entirely the true intercrop productivity. Nevertheless, the concept of area time equivalency ratio (ATER) was introduced to correct the time deficiency of the LER while the CPR adjusted for time (CPRT) was introduced to correct the time deficiency factor of the CPR (Azam-Ali and Squire, 2002). Yet there have been few studies that have actually applied these indices to evaluate intercrop performance. Indeed, for wheat/bean intercropping system there has not been any previous study that applied these indices together in order to understand the system well. In addition, it might be argued that given that crop growth and development have been shown to be well-quantified using accumulated thermal time (Confalone *et al.* 2010; Patrick and Stoddard, 2010) rather than days after sowing (calendar time), computation of ATER and CPRT based on thermal time may be more valid. To date this approach has not been used in computing any of these two indices for any given intercrop combination.

As well as manipulating temporal complementarity in resource use, determining optimum seed rates for the component crops is necessary in order to guarantee maximum yields and reduce wastages (Yahuza, 2011d). Whilst there has been indication of density combinations for wheat/bean intercropping systems that may give maximum yields (Bulson *et al.,* 1997; Haymes and Lee, 1999), none of these studies had temporal manipulation of resources in addition to any spatial benefit as an aim. Thus, it is clear that there is a need to determine optimum seed rates to sow for wheat/bean intercropping system as may be affected by different sowing date

The objectives of the present research are six fold: i. To decrease competition between wheat and bean component crops and improve intercrop performance by using different sowing date (delay in bean sowing date) to improve temporal use of resources. ii. To investigate the effects of bean sowing date on seed and biomass yields. iii. To determine factors responsible for any seed yield variations amongst treatments. iv. To determine optimum seed rate to sow as affected by different sowing date. v. To evaluate the adequacy of LER, ATER, CPR and CPRT in estimating the performance of intercropping, and hence to determine which treatments show advantage for intercropping. vi. To further evaluate the adequacy of ATER and CPRT computed using thermal time in estimating intercrop performance. vii. To determine the MA of intercropping based on LER and ATER estimates.

Materials and methods

Study area

The experiment was carried out at the University of Reading's Crop Research Unit, Sonning, Berkshire, (0° 56'W, 51°27'N)). The weather data during the cropping season the experiment was established as well as the long-term weather data for the site is given in Table 1. The site soil is a free-draining sandy-loam of Sonning series (Gooding *et al.,* 2002). For the purpose of the present research, soil samples were taken from 0-90 cm depth at random locations in the field using soil coroner in February 2007. The samples were then bulked and analyzed for pH, phosphorus (P), potassium (K), magnesium (Mg), available nitrogen (N) and sulphate. The results from the soil analysis indicate the following values 7.1, 35 mg/I, 79 mg/I, 67 mg/I, 9.7 kg/ha and 33.9 mg/ha for pH, P, K, Mg, available N and sulphate. On 12 September 2006 Glyphosate (*N*-(phosphonomethyl)glycine was sprayed at 5 l/ha and Dursban wg (chloropyriphos) for grassland destruction and control of microworm (*Panagrellus redivivus*). On 13 September 2006 KCl was applied by drop spreader at 225 kg per ha (135 kg K_2O).

Experimental design and treatments

The experiment consist of five wheat (cv Mallaca) seed rates (0, 25, 75, 150, 400 seeds/m^2) with or without 30 seeds/m^2 faba bean (cv Clipper) treatment as affected by three bean sowing dates. The bean treatments were simultaneous sowing of beans with wheat towards the end of October (sometimes to be referred to as SSWB), delaying bean sowing date by 23 days (sometimes to be referred to as SB23DAW) and delaying bean sowing date by 37 days (sometimes to be referred to as SB37DAW). 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 (Mead *et al.,* 2003).

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 (i.e. SSWB) was carried out on 30 October 2006. The second bean was drilled on 22 November 2006 (i.e. SB23DAW). The last bean sowing was Wednesday 6 December 2006 (SB37DAW). On 21 September 2006, the experimental area was ploughed but poor depth was achieved due to dryness and hardiness. Therefore, on 26 September 2006, the experimental area was re-ploughed after rain and a better depth of cultivation was attained.

Crop management and assessments

For weed control, n 3 November 2006 herbicide in the form of BASF 'claymore' (pendimethalin) was sprayed on pure wheat plots and plots with bean sown simultaneously with the wheat at a rate of 3.3 l/ha in 200 litres of water (pre-emergence of the bean). Similarly, pendimethalin was applied to the plots with bean sowing date delayed by 23 days (SB23DAW) on Wednesday 29 November 2006 at a rate of 3.3 l/ha in 200 litres of water (pre-emergence of the beans). The plots with bean sowing date delayed by 37 days (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). In order to manage fungal diseases, at growth stage 31 (Zadoks *et al.,* 1974), fungicide were sprayed as Clortosip (chlorothalonil) 2 l/ha, Folicur (tebuconazole) 1 l/ha and Cleancrop (fenpropimorph) 1 l/ha in 240 l/ha water. Similarly, on 7 April 2007, 159 DAS at GS 31, 250 kg/ha of Nitram fertilizer (ammonium nitrate granules, (34.5%N)) was applied. This was equivalent to 86 kg N/ha.

Table 1. Weather data during the cropping year and long term weather data for the experimental site at Sonning, Berkshire, United Kingdom.

Year	Month	Mean air monthly temperature (°C)	Long term (37 year) mean air monthly temperature (°C)	Solar radiation (MJ/m²/day)	Long term mean solar radiation (MJ/m²/day)	Mean monthly rain fall (mm)	Long term (47 year) mean monthly rainfall (mm)
2006	October	13.2	10.8	6.1	6.0	123.6	67.3
	November	7.9	7.1	3.7	3.2	107.4	63.9
	December	6.7	5.1	1.9	2.0	82.6	63.8
2007	January	7.1	4.4	2.8	2.5	65.8	58.4
	February	6.1	4.5	4.5	4.6	82.8	40.1
	March	7.1	6.5	9.9	8.0	44.4	47.9
	April	11.4	8.6	16.4	12.4	1.8	49.0
	May	12.4	12.0	13.8	16.0	92.2	49.3
	June	16.1	15.0	17.2	17.5	93.7	47.6
	July	16.3	17.3	16.3	16.5	115.6	45.1
	August	16.3	16.9	17.4	14.4	40.5	56.8

The photosynthetically active radiation (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 Gooding *et al.* (2002) and Yahuza (2011a) to calculate the total amount of PAR intercepted per day and then over the life of the crop were followed. Similarly, following the procedure described by these authors, the radiation use efficiency (RUE) (g/MJ) was calculated by dividing the final above-ground biomass (g/m²) by the accumulated PAR (MJ/m²). 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 final above-ground biomass for both wheat and bean were collected from destructive samples taken 287 DAS from 1m x 0.5m area with a quadrat. Four rows were included for sole crop plot and 8 for the intercrops and the plants were cut at the soil surface. Samples were separated into the components, weighed, sub-sampled and dried at a temperature of 85°C for 48 hours. After drying, the sub-samples were weighed. As with the biomass yields, the seed yields were obtained from the hand harvested destructive sampling taken at 287 DAS. Note that harvests were carried out simultaneously irrespective of the sowing date due to very wet weather conditions. The wheat and bean seed yields were separated in the laboratory using appropriate sieves. The seed yields for each of the crop for each plot were weighed to determine the fresh weight. Seed moisture content was determined by taking sub-samples and weighing them before and after oven drying at 85 °C for 48 hours immediately after the wheat and bean was separated in the laboratory.

Thus, except if otherwise stated throughout the paper yield data were presented in g/m² adjusted to 15% moisture content. However, for monetary evaluation, yield data were converted to tonnes per hectare (t/ha). In such cases yield was simply converted from g/m² to t/ha simply by dividing by 100.

Table 2. Effect of bean sowing date and wheat seed rate on wheat partial LER, bean partial LER and total intercrop LER to indicate that there was benefit of intercropping particularly for SSWB treatments.

Wheat seed rate (seeds/m²)	Bean sowing date treatment	Wheat sole crop seed yield (g/m²)	Wheat intercrop seed yield (g/m²)	Wheat partial LER	Bean sole crop seed yield (g/m²)	Bean intercrop seed yield (g/m²)	Bean partial LER	Total intercrop LER
25	SSWB	274	37	0.06	548	503	0.92	0.98
75	SSWB	434	119	0.20		511	0.93	1.13
150	SSWB	396	206	0.35		451	0.82	1.17
400	SSWB	588	183	0.31		370	0.68	0.99
25	SB23DAW	274	114	0.19	381	295	0.54	0.73
75	SB23DAW	434	129	0.22		492	0.90	1.12
150	SB23DAW	396	260	0.44		212	0.39	0.83
400	SB23DAW	588	270	0.46		297	0.54	1.00
25	SB37DAW	274	208	0.35	246	209	0.38	0.74
75	SB37DAW	434	254	0.43		197	0.36	0.79
150	SB37DAW	396	381	0.65		116	0.21	0.86
400	SB37DAW	588	460	0.78		40	0.07	0.86

Table 3. Effect of bean sowing date and wheat seed rate on wheat partial ATER, bean partial ATER and total intercrop ATER calculated using days and thermal time to indicate that there was benefit for intercropping particularly for SSWB treatments.

Wheat seed rate (seeds/m²)	Bean sowing date treatment	Wheat sole crop seed yield (g/m²)	Wheat intercrop seed yield (g/m²)	Wheat partial LER	Bean sole crop seed yield (g/m²)	Bean intercrop seed yield (g/m²)	Bean partial LER	Total intercrop LER
25	SSWB	274	37	0.06	548	503	0.92	0.98
75	SSWB	434	119	0.20		511	0.93	1.13
150	SSWB	396	206	0.35		451	0.82	1.17
400	SSWB	588	183	0.31		370	0.68	0.99
25	SB23DAW	274	114	0.19	381	295	0.54	0.73
75	SB23DAW	434	129	0.22		492	0.90	1.12
150	SB23DAW	396	260	0.44		212	0.39	0.83
400	SB23DAW	588	270	0.46		297	0.54	1.00
25	SB37DAW	274	208	0.35	246	209	0.38	0.74
75	SB37DAW	434	254	0.43		197	0.36	0.79
150	SB37DAW	396	381	0.65		116	0.21	0.86
400	SB37DAW	588	460	0.78		40	0.07	0.86

The harvest index (HI) was determined as the ratio between the seed yield to the biomass yield. The HI was calculated from the biomass sampling from an area 1m x 0.5m taken 287 DAS. The crop biomass sample taken was separated into stems + leaves and ears for the wheat. For the bean, the separation was stems + leaves and pods. The wheat ears were threshed and separated to chaff and seeds (F. Walter & 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.

Statistical analyses

In general, data were analysed using GENSTAT (Genstat 8.1 release, Rothamsted UK). Generally, the following were considered in the ANOVA. For analysing wheat variables, plots with zero wheat sowing treatments were restricted in the analyses. Similarly, in the case of bean variables, plots with no bean sowing were restricted from the analyses to get the sole and intercrop values. For combined wheat + bean (henceforth to be referred to as total intercrop or total) analyses were done mostly with no restriction. The variables were analysed using the General analysis of variance with the treatment structure given as pol (wsr; 3) x (bean/bean sowing date). This simply means that the bean sowing date factor was nested within the bean treatment. However, in this paper the mean effects of wheat seed rate averaged across the three beans sowing dates for the variables assessed are not presented. Those details are presented in another paper being prepared part of three-year field trials that had yield-density relations as a focus. Similarly, the mean effects of intercropping averaged across the three bean sowing dates are detailed in the paper being prepared. Nevertheless, here, an indication of the simultaneous effects of sowing dates and wheat seed rate was given.

Estimates of intercrop performance

The performance of intercrops compare to the sole crop was evaluated using LER, ATER, CPR, CPRT and MA as described by Willey (1985), Hiebsch and McCollum (1987), Harris *et al.* (1987), Azam-Ali and Squire (2002) and Yahuza (2011c) respectively. However, here both ATER and CPRT were computed using days (calendar time) and degree-days (thermal time). Weather data used for calculating the thermal time was obtained from the weather station at the site. Following Harris *et al.* (1987), 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 to be calculated (Harris *et al.,* 1987). Based on the LER estimates, MA was calculated as described by Willey (1985). Similarly, based on ATER estimates MA was calculated as proposed recently by Yahuza (2011c). Note that although the methods used in calculating the MA estimated using ATER was similar to that used for estimating MA based on LER estimates, the interpretations differ. For the ATER estimates the interpretation was in terms of increased intercrop value per unit area x time, whilst the LER estimate was in terms of increased value per unit area only (Yahuza, 2011c).

Results

Effects of bean sowing date on seed yields

Wheat seed yields responded significantly to the effect of bean sowing date ($P = 0.002$). Averaged across wsr, wheat sole crop seed yield was 423 g/m^2. Intercropping reduced wheat seed yield significantly the early the beans were sown. For the intercrops wheat seed yields were 136 g/m^2, 193 g/m^2 and 326 g/m^2 for SSWB, SB23DAW and SB37DAW respectively (SED 48.8: DF 30). Note that compared to the sole crop, wheat seed yield was not significantly reduced when bean sowing date was delayed by 37 days. There was no significant response of wheat seed yields to the interactive effects of bean sowing date treatment and wheat seed rate detected ($P > 0.05$).

Averaged across wsr, bean seed yield responded significantly to the effects of bean sowing date treatment ($P < 0.001$). Bean seed yields were 477 g/m^2, 335 g/m^2 and 162 g/m^2 for SSWB, SB23DAW and SB37DAW respectively (SED 43.9: DF 28). Note that each means is inclusive of both sole crop and intercrops bean yields due to the nested design used. The maximum bean seed yield was obtained when wheat and bean were sown simultaneously while the least bean yield was obtained when bean sowing date was delayed by 37 days. There was no significant response of bean seed yields to the interactive effects of bean sowing date treatment and wheat seed rate and detected (P > 0.05).

Table 4. Effect of bean sowing date and wheat seed rate on wheat CPR, bean CPR and total intercrop CPR, wheat CPRT, bean CPRT and total intercrop CPRT calculated using days and thermal time to indicate that there was benefit of intercropping particularly for SSWB treatments.

Wheat seed rate (seeds/ m²)	Bean sowing date treatment	Wheat CPR	Bean CPR	Total intercrop CPR	Wheat CPRT based on days	Bean CPRT based on days	Total intercrop CPRT based on days	Wheat CPRT based on thermal time	Bean CPRT based on thermal time	Total intercrop CPRT based on thermal time
25	SSWB	0.13	2.11	0.95	0.13	2.11	0.95	0.13	2.11	0.95
75	SSWB	0.40	2.14	1.11	0.40	2.14	1.11	0.40	2.14	1.11
150	SSWB	0.70	1.89	1.16	0.70	1.89	1.16	0.70	1.89	1.16
400	SSWB	0.62	1.55	0.97	0.62	1.55	0.97	0.62	1.55	0.97
25	SB23DAW	0.39	1.24	0.72	0.39	1.14	0.69	0.39	1.16	0.70
75	SB23DAW	0.44	2.06	1.09	0.44	1.90	1.05	0.44	1.94	1.06
150	SB23DAW	0.88	0.89	0.83	0.88	0.82	0.80	0.88	0.84	0.81
400	SB23DAW	0.92	1.25	1.00	0.92	1.15	0.96	0.92	1.17	0.97
25	SB37DAW	0.71	0.88	0.73	0.71	0.76	0.69	0.71	0.78	0.69
75	SB37DAW	0.86	0.83	0.79	0.86	0.72	0.74	0.86	0.74	0.75
150	SB37DAW	1.30	0.49	0.88	1.30	0.42	0.82	1.30	0.44	0.83
400	SB37DAW	1.56	0.17	0.88	1.56	0.15	0.82	1.56	0.15	0.83

See Table 2 for seed yields used for calculating CPR and CPRT. See Tables 3 for crop durations used for calculating CPRT.

Table 5. Monetary advantage based on the total intercrop LER and total intercrop ATER to indicate that there was benefit for intercropping particularly when wheat and bean were sown simultaneously (SSWB).

Wheat seed rate (seeds/m²)	Bean sowing date treatment	Wheat sole crop value(£)	Wheat intercrop value (£)	Bean sole crop value(£)	Bean intercrop value (£)	Total intercrop value(£)	MA based on LER estimates (£)	MA based on ATER estimates (£)using days	MA based on ATER estimates (£) using thermal time
25	SSWB	403	54	904	830	884	-17	-18	-18
75	SSWB	638	175		843	1018	121	117	117
150	SSWB	582	303		744	1047	155	152	152
400	SSWB	864	269		611	880	-12	-9	-9
25	SB23DAW	403	168	629	487	654	-239	-294	-280
75	SB23DAW	638	190		812	1001	105	48	57
150	SB23DAW	582	382		350	732	-151	-183	-172
400	SB23DAW	864	397		490	887	1	-37	-27
25	SB37DAW	403	306	406	345	651	-234	-292	-279
75	SB37DAW	638	373		325	698	-184	-233	-233
150	SB37DAW	582	560		191	751	-123	-154	-143
400	SB37DAW	864	676		66	742	-126	-131	-131

See Table 2 for seed yields and LER used for calculating MA. However, yields in g/m2 were converted to t/ha. See Table 3 for ATER estimates used for calculating MA.

Table 6. Effect of bean sowing date and wheat seed rate on wheat CPR, bean CPR and total intercrop CPR for the biomass yield to indicate that there was benefit of intercropping particularly for SSWB treatments.

Wheat seed rate (seeds/m²)	Bean sowing date treatment	Wheat sole crop biomass yield (g/m²)	Wheat intercrop biomass yield (g/m²)	Bean sole crop biomass yield (g/m²)	Bean intercrop biomass yield (g/m²)	Wheat CPR	Bean CPR	Total intercrop CPR
25	SSWB	469	103	1220	970	0.20	1.59	0.95
75	SSWB	763	279	1220	960	0.54	1.57	1.10
150	SSWB	763	442	1220	863	0.86	1.41	1.16
400	SSWB	1028	398	1220	750	0.77	1.23	1.02
25	SB23DAW	469	250	905	585	0.49	0.96	0.74
75	SB23DAW	763	372	905	893	0.72	1.46	1.13
150	SB23DAW	763	517	905	455	1.01	0.75	0.86
400	SB23DAW	1028	666	905	579	1.30	0.95	1.11
25	SB37DAW	469	437	718	417	0.85	0.68	0.76
75	SB37DAW	763	785	718	349	1.53	0.57	1.01
150	SB37DAW	763	673	718	231	1.31	0.38	0.80
400	SB37DAW	1028	816	718	78	1.59	0.13	0.80

Table 7. Effect of bean sowing date and wheat seed rate on wheat CPRT, bean CPRT and total intercrop CPRT for the biomass yield to indicate that there was benefit of intercropping particularly for SSWB treatments.

Wheat seed rate (seeds/m²)	Bean sowing date treatment	Wheat CPRT based on days	Bean CPRT based on days	Total intercrop CPRT based on days	CPRT wheat based on thermal time	CPRT bean based on thermal time	Total intercrop CPRT based on thermal time
25	SSWB	0.20	1.59	0.95	0.20	1.59	0.95
75	SSWB	0.54	1.57	1.10	0.54	1.57	1.10
150	SSWB	0.86	1.41	1.16	0.86	1.41	1.16
400	SSWB	0.77	1.23	1.02	0.77	1.23	1.02
25	SB23DAW	0.49	0.88	0.71	0.49	0.90	0.72
75	SB23DAW	0.72	1.35	1.07	0.72	1.38	1.09
150	SB23DAW	1.01	0.69	0.83	1.01	0.70	0.84
400	SB23DAW	1.30	0.87	1.06	1.30	0.89	1.07
25	SB37DAW	0.85	0.60	0.70	0.85	0.61	0.71
75	SB37DAW	1.53	0.50	0.93	1.53	0.51	0.95
150	SB37DAW	1.31	0.33	0.74	1.31	0.34	0.76
400	SB37DAW	1.59	0.11	0.74	1.59	0.11	0.75

See Tables 3 and 6 for crop durations and biomass yields respectively used for calculating the CPRT.

Averaged across wsr, bean sowing date treatment had a significant effect on the total intercrop seed yield (P = 0.004). Seed yields were 586 g/m², 490 g/m² and 422 g/m² for SSWB intercrop, SB23DAW intercrop and SB37DAW intercrop respectively (SED 45. 8: DF 38). Note that given the nested design used; these values cannot be simply derived by adding wheat intercrop and bean intercrop yields presented earlier. In other words, these values were obtained from ANOVA outputs based on the treatment structure the experiment was analyzed. Same applies to the total intercrop biomass yields and accumulated PAR presented in the subsequent sections. As for the wheat, there was no significant response of the total intercrop seed yields to the interactive effects of bean sowing date treatment and wheat seed rate detected (P > 0.05).

Effects of bean sowing date on biomass yields and harvest index

Averaged across wsr, wheat biomass yields followed similar pattern as the seed yield in response to the effects of bean sowing date (P < 0.001). Wheat biomass yields were 756 g/m², 306 g/m², 451 g/m² and 678 g/m² for wheat sole crop, SSWB, SB23DAW and SB37DAW respectively (SED 67.1:30). Intercropping reduced wheat biomass yield significantly except when bean-sowing date was delayed by 37 days. There was no significant response of wheat biomass yields to the interactive effects of bean sowing date treatment and wheat seed rate detected (P > 0.05). By contrast, averaged across wsr, bean-sowing date did not have significant effect on wheat harvest index (P > 0.05). There was no significant response of the wheat HI to the interactive effects of bean sowing date treatment and wheat seed rate detected (P > 0.05). Mean wheat harvest index averaged across all plots was 0.46.

Averaged across wsr, for the mean effects of bean sowing date treatment, bean biomass yield was significantly greater (P < 0.001) the early the beans were sown following the pattern for the seed yields. Bean biomass yields were 952 g/m², 683 g/m² and 359 g/m² for SSWB, SB23DAW and SB37DAW respectively (SED 70.0: DF 28). Following similar pattern as the bean seed yields, there was no significant response of bean biomass yields to the interactive effects of bean sowing date treatment and wheat seed rate (P > 0.05). Bean HI did not respond significantly to bean sowing date treatment (P > 0.05). Mean bean harvest averaged across all plots was 0.49.

Averaged across wsr, bean-sowing date had significant effects on the total intercrop biomass yields (P < 0.001). Total intercrop biomass yields were 604 g/m², 1197 g/m², 1045 g/m² and 901 g/m² for sole crops, SSWB intercrop, SB23DAW intercrop and SB37DAW intercrop respectively (SED 64.1: DF 38). Note that total intercrop biomass yield did not differ between the 23 and 37 days delay in bean sowing. There was no significant response of the total intercrop biomass yields to the interactive effects of bean sowing date treatment and wheat seed rate detected (P > 0.05).

Effects of bean sowing date on accumulated photosynthetically active radiation and radiation use efficiency

Averaged across wsr, bean sowing date had significant effects on the accumulated PAR (P < 0.001). In response to bean sowing date, wheat sole crop PAR was 368.1 MJ/m². Intercropping significantly improved accumulated PAR, except when bean sowing date was delayed by 37 days. For the intercrops, accumulated PAR were 491.8 MJ/m², 449.5 MJ/m² and 364.2 MJ/m² for SSWB intercrop, SB23DAW intercrop and SB37DAW intercrop respectively (SED 16.08: DF 38). Thus, for the intercrops, the maximum accumulated PAR was obtained when wheat and bean were sown simultaneously. As for the biomass and seed yields, there was no significant response of the accumulated PAR to the interactive effects of bean sowing date treatment and wheat seed rate detected (P > 0.05). By contrast, averaged across wsr, bean-sowing date did not have a significant effect on the radiation use efficiency (P = 0.40). Mean RUE averaged across all plots was 2. 2 g/MJ. There was no significant response of the RUE to the interactive effects of bean sowing date treatment and wheat seed rate detected (P > 0.05).

Estimates of seed yield performance in response to the combined effects of bean sowing date and wheat seed rate

Despite the insignificant interaction of all variables assessed here to the interactive effects of bean sowing date and wheat seed rate, intercrop performances in response to the combined effects of the two factors were assessesed using five indices. It was assumed that the lack of significant interaction of the variables to the combined effects of bean sowing date and wheat seed rate was attributed to the complexity of the design used here. Consequently, intercrop performance were compared to that of the sole crops using five indices.

Table 8. Total intercrop CPR and CPRT for accumulated PAR to indicate that the total intercrop was more efficient than wheat sole crop in accumulating PAR mainly when wheat and bean were sown simultaneously.

Wheat seed rate (seeds/m²)	Bean sowing date treatment	Wheat sole crop accumulated PAR (MJ/m²)	Total intercrop accumulated PAR (MJ/m²)	Bean sole crop accumulated PAR (MJ/m²)	Total intercrop CPR	Total intercrop CPRT based on days	Total intercrop CPRT based on thermal time
25	SSWB	357.4	476.1	442.4	1.10	1.10	1.10
75	SSWB	358.5	528.2		1.22	1.22	1.22
150	SSWB	378.7	497.7		1.15	1.15	1.15
400	SSWB	421.3	514.5		1.19	1.19	1.19
25	SB23DAW	357.4	423.3	419.0	0.98	0.94	0.95
75	SB23DAW	358.5	456.5		1.06	1.01	1.02
150	SB23DAW	378.7	478.2		1.11	1.06	1.07
400	SB23DAW	421.3	470.4		1.09	1.04	1.06
25	SB37DAW	357.4	399.9	332.7	0.93	0.86	0.87
75	SB37DAW	358.5	368.4		0.85	0.79	0.80
150	SB37DAW	378.7	333.0		0.77	0.72	0.73
400	SB37DAW	421.3	387.0		0.90	0.83	0.85

See Table 3 for crop durations used for calculating the CPRT.

For the seed yield based on LER estimates there were benefits for intercropping mainly when wheat and bean were sown simultaneously (Table 2). The total intercrop advantage can be attributed to the higher partial LER values of the bean, particularly when sown simultaneously with the wheat (Table 2). The maximum LER of 1.17 was obtained at 150-wheat seeds/m² for SSWB. For the treatment that gave the maximum LER estimate, bean partial LER value was greater than that of the wheat; indicating that bean was more competitive than the wheat (Table 2). Similarly, using ATER, seed yield advantage from intercropping with simultaneous sowing was noticed even though the estimates based on LER were reduced when bean sowing date was delayed (Table 3). This indicates that spatial factors were responsible for intercropping advantages. However, when wheat and bean were sown simultaneously ATER estimates were similar to the LER estimates (Table 3). When ATER, was calculated using thermal time similar values were found with the ATER calculated using calendar time (Table 3). Again, the LER estimates were reduced (Table 3).

Based on the CPR as regards seed yields, wheat in the intercrop struggled compared to the wheat sole crop particularly when wheat was sown simultaneously with the bean (Table 4). As bean sowing date was delayed, the seed yield efficiency of the wheat in the intercrop was improved such that when bean sowing date was delayed by 37 days, wheat in the intercrop improves the efficiency by as much as 56% (Table 4). On the other hand, with respects to the seed yields, bean in the intercrop performed extremely well mainly when sown simultaneously with the wheat (Table 4). Delay in bean sowing date by 37 days decreased the seed yield efficiency of the bean in the intercrop substantially (Table 4). Consequently, at 400-wheat seeds/m² when bean-sowing date was delayed by 37 days, bean in the intercrop was only 17% as efficient as the sole crop (Table 4). Due to the poor performance of wheat in the intercrop, the total intercrop was more efficient mainly when wheat and bean were sown simultaneously (Table 4). The maximum CPR estimate of 1.16 was obtained at 150-wheat seeds/m^2. Given that for the seed yields wheat in the intercrop struggled when sown simultaneously with the wheat, this indicates that bean in the intercrop was mainly responsible for the yield benefits of intercropping for the treatment that gave maximum intercrop benefits (Table 4).

For the seed yields, wheat CPRT values were similar to that of the CPR (Table 4). On the other hand, for the beans with respect to seed yields, CPRT values were similar to the CPR only when bean was sown simultaneously with the wheat (Table 4). When bean sowing date was delayed, CPRT reduced the CPR estimates even though bean in the intercrop were found to be more efficient than the sole crop particular when sown simultaneously with the wheat or when bean sowing date was delayed by 23 days (Table 4). Based on the CPRT estimates, the efficiency of the total intercrop based on CPR was reduced even though benefit was found particularly when bean was sown simultaneously with the wheat (Table 4). As with ATER, when CPRT was calculated using thermal time similar values were found with the CPRT calculated using days (Table 4).

The MA calculated based on LER suggests that intercropping was able to improve income mainly when wheat and bean were sown simultaneously or when bean-sowing date was delayed by 23 days (Table 5). Delaying bean-sowing date by 37 days decreased income substantially (Table 5). Similarly, based on ATER, income improvement due to intercropping estimated using LER was adjusted slightly when bean-sowing date was delayed (Table 5). Similar estimates were found when MA was calculated based on ATER computed using thermal time (Table 5).

Estimates of determinant of yields performance in response to the combined effects of bean sowing date and wheat seed rate

For the biomass yield, based on the CPR, wheat in the intercrop was more efficient than the sole crop mainly when bean sowing date was delayed (Table 6). On the other hand, with respect to the biomass yield, bean in the intercrop was more efficient than the sole crop when wheat and bean were sown simultaneously (Table 6). The total intercrop was more efficient than the sole crop mainly when wheat and bean were sown simultaneously (Table 6). The maximum CPR estimate of 1.16 was obtained at 150-wheat seeds/m^2 for SSWB (Table 6). The poor performance of the total intercrop when bean-sowing date was delayed by 37 days can be attributed to the poorer performance of the bean given that wheat in the intercrop performed more efficiently with delay in bean sowing date (Table 6).

Evaluations using CPRT indicate that wheat CPRT estimates were similar to the CPR estimates (Table 7). By contrast, bean CPRT values were similar to the CPR estimates only when wheat and bean were sown simultaneously (Table 7). With respect to the biomass yields, the total intercrop CPRT estimates were similar to the total intercrop CPR estimates when wheat and bean were sown simultaneously (Table 7). However, when bean-sowing date was delayed, CPR estimates were reduced using CPRT (Table 7). Using the thermal time to calculate the CPRT provided similar estimates as evaluations based on days (Table 7).

Compared to the wheat sole crop, the total intercrop was more efficient in accumulating PAR mainly when wheat and bean were sown simultaneously (Table 8). When the bean sowing date was delayed by 37 days, the total intercrop struggled with respect to the accumulation of PAR (Table 8). Based on the CPRT (Table 8) and CPRT calculated using thermal time (Table 8), similar conclusions could be drawn.

Discussion

The main objective of the present research was to investigate the possibility of improving the productivity of wheat/bean intercrop by manipulating bean sowing date to reduce competition and improve temporal complementarity in resource use. Vandermeer (1989) and Fukai and Trenbath (1993) stated that intercrop performance in most cases are greater where the component crops differ in growth duration or in sowing dates. This is because the first sown crop is able to capture resources such as nutrient, water and radiation before the later component is sown (Ofori and Gamedoagbao, 2005; Zhang *et al.,* 2008). Although wheat/bean intercropping system has been investigated previously in the UK (Haymes and Lee, 1999; Bulson *et al.,* 1997), previous studies did not manipulate sowing date of the component crops. Here results have shown that performance of wheat/bean intercrop was greater when the two component crops were sown simultaneously. This clearly indicates that spatial complimentarily in resource use was more important than any temporal complimentarily that may exist. Thus, the optimum density of the intercrop was greater than of the individual sole crops, suggesting that a given area of land would be able to support a greater number of plants (Hauggard-Nielson *et al.,* 2006). Moreover, results indicate that optimum seed rate for intercropping wheat with bean in the UK is lower than the recommended rate for the sole crops in agreement with earlier conclusions (Bulson *et al.,* 1997; Haymes and Lee. 1999). Therefore, the assertion that intercropping performance is usually greater when the two component crops were not sown together was not confirmed (Tsay *et al.,* 1988; Berti *et al.,* 2011; Marcos *et al.,* 2011). Thus, this research is in agreement with Bulson *et al.* (1997) and Haymes and Lee (1999) that intercrop performance in wheat/bean intercropping systems can largely be due to spatial complementarity in resource use. Since water and nutrient were not limiting, it can be easily concluded that radiation was the main driver of productivity (Jahansooz *et al.,* 2007).

Results indicate that wheat intercrop seed yields were improved as bean sowing date was delayed. Had improving wheat seed yield in the intercrop the main objective of the present research, these results would have been a satisfactory conclusion. However, the main thrust was to improve the overall performance of intercropping and this was not the case when bean sowing date was delayed. Clearly, given the poor performance of wheat particularly for SSWB, wheat was not the main determinant of intercrop performance. On the other hand, results showed bean seed yields were decreased as bean sowing date was delayed which is consistent with the literature. For instance, under sole cropping conditions Adisarwanto and Knight (1997) found out that bean seed yields was deceased as sowing date was delayed. Recently, Confalone et al. (2010) had shown that bean-sowing date had significant effect on bean seed yields as well. This research is in agreement with these earlier conclusions. Similarly, Launay *et al.* (2009) research indicates that sowing barley (*Hordeum vulgare*) before pea (*Pisum sativum*) reduced seed yields of the latter by up to 30%. Berti *et al.* (2011) also investigated the effects of sowing date in camelina (*Camelina sativa*) and showed that at some of the locations in their research, seed yields were greater the early the seeds were sown. Nevertheless, elsewhere low performance of later sown bean has been attributed to water deficit, due to low availability of soil water particularly at the reproductive stages (Confalone *et al.,* 2010). Indeed, Mwanamwenge *et al.* (1999) in a glass house experiment investigated the effects of water stress on growth and yield of three genotypes of bean and found out that early podding stage of development was the most sensitive to water deficit, causing a reduction in HI and seed yields of at least 50% in all the three genotypes studied. In my experiment, it is unlikely that competition for water was responsible for the later sown bean crops poor productivity. The inability of the later sown bean to compete substantially with the relatively well-established wheat for radiation, might explains the poor performance observed. Indeed, delay in bean sowing date was associated with improvement in wheat intercrop seed yields. In contrasts to result found here, Sun *et al.* (2007) concluded that sowing date did not have significant effect on seed yields in winter wheat/summer maize (*Zea mays*) rotations; even though it had effects on wheat development. Here that intercrop performance was greatest for SSWB where maximum total intercrop seed yields were obtained indicate that bean was largely responsible for variation in intercrop performance. This argument is sensible given that result showed bean intercrop seed yields were greatest for the early sown bean.

That biomass yields responses to bean sowing date followed similar pattern as the seed yield indicate that seed yields were satisfactory fractions of the biomass yields (Tsubo *et al.,* 2001; Awal *et al.,* 2006). Indeed, the insignificant response of both wheat and bean HI to bean sowing date further indicates that biomass yields were the main determinant of variation in seed yield between the sole crops and the intercrops as bean sowing date was delayed. Similarly, that the total intercrop accumulated more PAR than wheat sole crop particularly for SSWB indicates that spatial factors were responsible for intercrop performance. In other words, unlike the views of Vandermeer (1989) in the present research spatial complementarity rather than temporal complementarity in radiation interception was largely responsible. The literature indicates that biomass yields depends on the accumulated radiation and the RUE, provided the crops is not short of water and is well nourished (Awal *et al.,* 2006; Confalone *et al.,* 2010). Here, since bean sowing date did not had a significant effect on RUE it can be easily concluded that accumulated PAR was the main determinant of variation in biomass yields between the sole crops and the total intercrop. In agreement with the results found here, Baumann *et al.* (2001) attributed the performance of celery (*Apium graveolens*)/leek (*Allium porrum*) intercrop systems to spatial complementarily in radiation interception mainly. They attributed the greater importance of spatial effects to the fact that celery has horizontal leaves while leek has a narrow upright leaf habits. Although typically the canopy structure of wheat/bean intercropping system (Haymes and Lee, 1999) is different from that of the combinations of crops they studied, results found here is in agreement with their conclusions that spatial effects were more important than temporal effects with respect to intercrop productivity. Recently under sole crop conditions, Confalone *et al.* (2010) showed that bean sowing date had significant effect on both accumulated PAR and RUE. Here whilst accumulated PAR was influenced by sowing date, sowing date had less significant effect on the RUE. The conservative nature of RUE found in response to bean sowing date in the present research tallies with the widely accepted views that RUE may be stable over a wide range of growing conditions (Vandermeer, 1989; Azam-Ali and Squire, 2002).

One of the objectives of the present investigation was to evaluate the adequacy of LER, ATER, CPR and CPRT in estimating the performance of intercropping involving wheat/bean combinations with different sowing dates. Despite the insignificant ANOVA outputs for the interactive effects of bean sowing date and wheat seed rate, further evaluations showed that intercrop performance was greatest when wheat and bean were sown simultaneously indicating spatial complementarity irrespective of the index used. As expected, ATER reduced the LER estimates. The present research is therefore in agreement with Hiebsch and McCollum (1987) that LER estimates can be reduced when time factor is taken into consideration using ATER. Similarly, CPRT reduced the CPR estimates to account for time factor. This is in agreement with Azam-Ali (1995) cited in Azam-Ali and Squire (2002) that CPRT is more efficient than CPR in intercrops with differing durations or sowing dates. Nevertheless, evaluating the performance of intercropping using several indices might look repetitive and unnecessary. Indeed, one index would have been sufficient to measure the performance of intercropping. However, since the result of the present research was meant to be of relevant to wider readers, it may be argued that the use of more than one index was justified. This is because indices used by investigators differ. Moreover, the interpretations of the indices are not the same. For instance, whilst an LER of 1.1 indicates that 10% more land would be required if sole crops of the crops intercropped were sown (Willey, 1985), an ATER of 1.1 showed that intercropping used area x time 10% more efficiently than the sole crop (Hiebsch and McCollum, 1987). Similarly, a CPR value of 1.1 indicates that the intercrop was 10 % more efficient than the sole crop in using resource (Azam-Ali *et al.,* 1990) while a CPRT value of 1.1 showed that if time is also taken into account intercrop was 10% more efficient than the sole crop in using resources. There has not been any wheat/bean intercropping investigation that has used all these indices together previously. Indeed, CPR and CPRT had rarely been applied in a temperate environment as was demonstrated in this research. However, I have shown that the benefits of wheat/bean intercropping system are mainly due to spatial complementarity in resource use irrespective of the index used for evaluation. Previous investigations also indicated performance of wheat/bean intercropping system to be greater than that of the component sole crops (Bulson *et al.* 1997; Haymes and Lee, 1999). Unlike the earlier studies, my conclusion was based on evaluation using different indices with different interpretations.

One additional and novel element of the present investigation was that thermal time was used in addition to calendar time (days) in computing ATER and CPRT. This was based on the premise that thermal time has been found to be efficient in describing crop growth and development (Confalone *et al.,* 2010; Patrick and Stoddard, 2010). The fact that the accumulated PAR was calculated using thermal time rather than calendar time, further justifies this approach. Moreover, thermal time is more efficient in quantifying accumulated PAR than calendar time and has been recently applied even in investigations of pathological nature (Elliot *et al.,* 2011). Results showed similar estimates for ATER and CPRT irrespective of whether days or thermal time was used. This further validates the approach of evaluating intercrop performance using more than one index. Although ATER and CPRT have been applied previously (Azam-Ali, 1995 cited in Azam-Ali and Squire 2002), no one has used the approach of calculating ATER and CPRT from thermal time as was demonstrated in the present research. Previous investigation that applied both ATER (Hiebsch and McCollum, 1987) and CPRT (Azam-Ali and squire, 2002) used calendar time rather than thermal time. That both ATER and CPRT were well computed using thermal time is sensible. In other words, it is physiologically more sensible to quantify any effects of time on crop growth and development using thermal time rather than calendar time. Therefore, others should uphold this novel approach of estimating both ATER and CPRT based on thermal time.

The present research was intended to be of relevance to the growers. In this regard, evaluation based on MA may be relevant in addition to other physical analysis (Willey, 1985; Yahuza, 2011c). Results showed that irrespective of whether MA was calculated using LER estimates or ATER estimates; intercropping performance was greatest when the two crops were sown simultaneously. It was clear that growers would be unable to increase their income by delaying bean sowing date. In other words, income improvement was greatest when the two crops were sown simultaneously. Whilst MA has been calculated based on LER estimates, similar approach has not been used to calculate MA from ATER estimates. For wheat/bean intercropping system, there have been few evaluations of the performance based on monetary value. However, Bulson *et al.* (1997) in an organic system demonstrated monetary advantage of intercropping wheat with bean. In agreement with their conclusions, here, it was demonstrated that wheat/bean intercropping might be financially more viable than growing sole crops provided the crops are sown simultaneously under conventional management. Even though a different approach was used to evaluate financial performance, the conclusions of Bulson *et al.* (1997) that financial performance was due to spatial factors was supported. Moreover, it was assumed that the MA estimated using ATER estimates was more valid than that estimated using LER estimates. This was because different sowing dates are involved, which the ATER estimates had adequately taken into consideration (Yahuza, 2011c). Had the crops been sown simultaneously, then MA based on LER would have been sufficient.

Conclusions

The present research suggests that it may not be possible to benefit from temporal complementarity in wheat/bean intercropping system by delaying bean sowing date. The total intercrop seed yields were ranked SSWB > SB23DAW > SB37DAW with wheat seed yields SSWB < SB23DAW < SB37DAW < wheat sole crop and bean seed yields SSWB > SB23DAW > SB37DAW for both the sole crop and intercrop. This indicates that bean was the main determinant of variations in intercrop productivity. Biomass yields mainly determine seed yield variation in response to bean sowing date for both wheat and bean as the HI was stable. Biomass yields variations (and so seed yields) were attributed mainly to spatial complementarity in accumulated PAR than to the RUE. For the combined effects of bean sowing date and wheat seed rate, irrespective of the index used for evaluation, greatest intercrop performance was found when wheat and bean were sown simultaneously. However, whilst here the indices were calculated from derived variables, it is recommended that future trials should calculate the indices within the replicate trials of any experiment of this nature and then subject to an analysis of variance.

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