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Simple yield-density equations for quantifying additive intercrops

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Abstract

Yield-density equations are not well explored in additive intercrops. A modification of the standard asymptotic yield-density equation for application to additive intercrops was proposed, and in turn, derived equations were found. With wheat (*Triticum aestivum* L.)/faba bean (bean; *Vicia faba* L.) intercropping systems, as an example, the equations were applied to quantify seed yields in three field experiments. Although, the standard asymptotic yield-density equation quantified each of the sole crop and the intercrop yields of the major component (wheat) well for all the three experiments, the modified version worked well in only one of the experiments. Even though the response of the minor component (bean) was not consistent across the experiments, in one of the experiments, in addition to using modified standard yield-density equation to quantify the total intercrop (wheat + bean) yield (plus sole crop of the minor component; bean), the wheat intercrop and bean intercrop yield were quantified simultaneously using the equations proposed here. In conclusion, for a standard additive intercrop, the proposed yield-density equations can quantify the yields well and should be adopted by others using similar design.

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Introduction

It had been well accepted that yield-density equations based on the reciprocal relationships between yield per plant and densities have been shown to be better than other equations in theory (Willey and Heath, 1969; Heath, 1970; Watkinson and Freckleton, 1997; Ellis *et al.,* 1999) and under experimental conditions for sole crops (Counce, 1987; Khah *et al.,* 1989; Shirtliffe and Johnston, 2002) and intercrops (Baumann *et al.,* 2001; Park *et al.,* 2002; Neumann *et al.,* 2009). For the sole crops, it is widely accepted that where yield response to density deviated from linearity, standard asymptotic yield-density equation (Equation 1) has better adaptability than other equations because it has meaningful biological interpretations (Heath, 1970; Salahi, 2002; Yahuza, 2011a; b).

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

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).

In an additive intercrop, plants of one component crop species are sown in addition to the normal population of a sole crop (Law and Watkinson, 1987; Connolly *et al*., 2001). Here, the population and usually the spatial arrangement of one crop are fixed whilst varying the population of the other (Vandermeer, 1989; Jolliffe, 2000). Nevertheless, a major peculiarity of any given intercropping system is the existence of both inter-specific and intra-specific competition for growth resources (Bellostas *et al.,* 2003). Although Equation 1 had been applied to quantify yields for some intercropping experiments, greater attention appeared to have been paid to intercrops designed based on response surface. Response surface design is based on factorial combinations of a range of densities of the component crops involved in the intercrop (Connolly *et al*., 2001; Neumann *et al.,* 2009). Both Wright (1981) and Dolman (1985) have made landmark contributions as regards developing inter-specific yield-density equations for application to intercrops designed using the response surface design. However, for the standard additive intercrops, there has been little attention to explore yield-density equations. Thus, there is a need to explore yield-density equations for additive intercrops.

The present research was carried out with the following objectives. i. To propose yield-density equations for simple additive intercrops (s). ii. To apply the proposed equations to quantify yields of simple additive intercrops, using wheat (*Triticum aestivum* L.)/ Faba bean (bean; *Vicia faba* L.) intercropping system as an example.

Materials and methods

The three experiments reported in this paper were carried out at the University of Reading's Crop Research Unit, Sonning, Berkshire, United Kingdom (0° 56′ W, 51° 27′ N). See Yahuza (2012) for other site details.

Experimental design, treatments and crop management

Experiment 1 (autumn-sown conventional experiment 2005-2006) was a complete factorial combination of five wheat seed rates (wsr) (0, 10, 50,100, 200 seeds/m^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. Experiment 2 (autumn-sown organic experiment 2005-2006), was similar to Experiment 1 in design, except that this experiment was managed organically. In addition, the two experiments were further complicated by sulphur treatment as detailed in Yahuza (2012). However, for each of the two experiments here the effects of sulphur were ignored. For both Experiments 1 and 2, other details regarding experimental design and treatment as well as crop management, see Yahuza (2012).

Experiment 3 consist of spring wheat (cv. Paragon) seed rate (0, 30, 75, 200, 400 and 650) seeds/m^2 with or without 40 seeds/m^2 spring bean (cv. Hobbit) randomized in four blocks in a split-plot with wsr as the main plot and the bean treatment as the subplot factor. For the intercrop, there were equidistant alternate rows between wheat and bean. Plot layout for this experiment comprised 8 rows of wheat and 8 separate rows of bean for the intercrop plots (i.e. not mixed together within a row), whereas the sole crop had only 8 rows. The experiment had 48 plots each with an area of 10m x 2m and was drilled on 2 March 2006. The crops were sprayed with 3.3 litres BASF 'Claymore' (pendimethalin) per ha in 200 litres water on 11 March 2006 (pre-emergence of the bean). Fungicide was applied on Wednesday 7 June 2006 as Folicur (tebuconazole) at 1 litre per ha, Clortosip (chlorothalonil) at 2 litres per ha and Cleancrop (fenpropimorph) at 1 litre per ha all in 260 litres/ha water. On 25 May 2006, 84 DAS, 177 kg/ha of Nitram (ammonium nitrate granules, (34.5%N)) was applied. This was equivalent to 60 kg N/ha. The final combine harvest was carried out on 16 August 2006, 168 DAS. The approximate harvested area was 1.25m x 7m per plot. The final harvest was carried out with a combine harvester (Wintersteiger Nursery Master Elite, Inkreis, Austria). 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. 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 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 as follows. The analyses were done using the General analysis of variance. The treatment structure was pol (wsr; 3) x bean. The block structure was block/wheat/bean with all interactions.

Regressions mainly using hyperbolic yield-density equations (Willey and Heath, 1969; Heath, 1970; Ellis *et al.,* 1999; Salahi, 2002; Yahuza, 2011a; b) 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.

Proposed equations

For a major component of an additive intercrop (i.e. wheat in the present research), where the sole crop response to density is curvilinear, following Willey and Heath (1969), it was assumed yield can be well-quantified using Equation 1. Thus, if yield of the major component of an additive intercrop (i.e. wheat in the present research) responded asymptotically to increase in density, and was well quantified using Equation 1. It is possible to quantify only the total intercrop yield using Equation 1 where the major component intercrop yield was also quantified using Equation 1. However, for clarity, subscripts are introduced to distinguish the equation applied to quantify the response of the major component (Equation 1) from that applied to quantify the total intercrop (Equation 2).

$$Y = \left(\frac{wsr}{a_{wt} + b_{wt} wsr} \right) \qquad 2$$

In respect of the total intercrop response, a further parameter y_0 can be introduced to describe the sole crop yield of the minor component (i.e. bean in the present research). In this case, it is proposed that yields can be well-quantified using Equation 3.

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

Provided, both the major component and the total intercrop responded asymptotically and where quantified using Equations 1 and 2 respectively, the difference between the fits for the total and major component responses (wheat) quantifies the minor component intercrop response (bean). Thus, Equation 4 describes bean intercrop yield of an additive intercrop in response to wsr.

$$Y = \left(\frac{wsr}{a_{wt} + b_{wt} wsr} \right) - \left(\frac{wsr}{a_{wi} + b_{wi} wsr} \right) \qquad 4$$

Assuming the minor component (bean) sole crop yield need to be described, the responses of the minor component intercrop yield can be quantified using Equation 5

$$Y = \left(y_o + \left(\frac{wsr}{aw_t + bw_t wsr} \right) \right) - \left(\frac{wsr}{aw_i + bw_i wsr} \right) \qquad 5$$

In Equations 2-5, Y = yields (g/m²), y_o refers to bean sole crop yield (g/m²). a_w and b_w are constants such that $1/a_w$ represents yield per plant in a competition free environment, y_o+ $(1/b_w)$ represents the predicted asymptotic (maximum) yield and wsr refers to wheat sowing rate (seeds/m²). The subscript t and i refers to the total intercrop and wheat intercrop yields respectively.

Results

Application of the proposed equations to quantify yields in Experiment 1

In Experiment 1, as wheat seed rate was increased so did wheat sole crop seed yield increase ($P = 0.004$ for quadratic effect). For the wheat sole crop seed yield, the two parameter asymptotic equation (Equation 1) was fitted. The parameter values are a_w (estimate 0.07280 s.e 0.00500) and b_w (estimate 0.0016551 s.e 0.0000505). The coefficient of determination was 99.7 %. Averaged across wsr intercropping significantly reduced wheat seed yields ($P < 0.001$). As was the case with the wheat sole crop, wheat intercrop seed yield increases with increase in wsr. There was an interactive effect of wsr and intercropping ($P = 0.024$ for quadratic wsr x bean treatment). Equation 1 fitted the responses of wheat intercrop seed yield with the coefficient of determination of 98 %. The parameter values are a_w (estimate 0.663 s.e 0.115) and b_w (0.002222 s.e 0.000734). In Experiment 1, wsr did not had significant effect ($P = 0.271$) on bean seed yield (SED 34.1; DF 12). However, as was the case with the wheat seed yield, the total intercrop seed yield increased with increase in wsr ($P < 0.001$ for quadratic wsr). However, further analysis showed that the total intercrop seed yield was found to increases linearly with increase in wsr and was quantified as Y = 172.9 + 0.76 wsr ($r^2 = 0.92$).

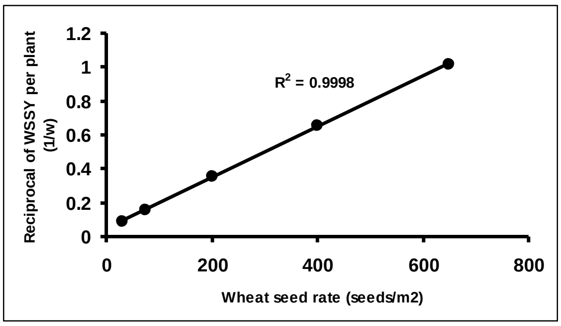

Fig. 1. Effect of wheat seed rate on the reciprocal of wheat sole crop seed yield (WSSY) per plant ● (solid line) for Experiment 3. See text for fitted equation and parameter values.

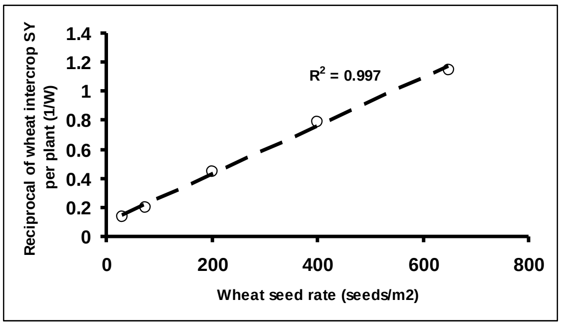

Fig. 2. Effect of wheat seed rate on the reciprocal of wheat intercrop seed yield (SY) per plant ○ (broken line), for Experiment 3. See text for fitted equation and parameter values.

Application of the proposed equations to quantify yields in Experiment 2

In Experiment 2, wheat seeds yield increased with increase in seed rate ($P < 0.001$ for linear wsr).

Equation 1 quantified the response of wheat sole crop seed yield to wsr. The coefficient of determination was 89.3 %. The parameter values for the fits are a_w (estimate 0.1209 s.e 0.0466) and b_w (estimate 0.000984 s.e 0.000348). Similarly, Equation 1 quantified the response of the wheat intercrop seed yield to wsr. The coefficient of determination was 99.1%. The parameter values for the fits are a_w (estimate 0.4191 s.e 0.0463) and b_w (estimate 0.002045 s.e 0.000311). The bean sole crop did not out-yield the bean intercrop substantially and yield increases ($P = 0.035$) as wsr increased. Further analysis showed that bean intercrop seed yields increases with increase in wsr and was quantified as $Y = 47.4 + 0.208$ wsr, $r^2 = 0.89$. As for the response of the wheat, the total intercrop seed yield increase with increase in wsr ($P = 0.031$ for quadratic wsr). Further analysis indicate that the total intercrop seed yields increases linearly with increase in wsr and was quantified as $Y = 81.8 + 1.29$ wsr, $r^2 = 0.98$.

Application of the proposed equations to quantify yields in Experiment 3

In Experiment 3, wheat seed yields increased with seed rate ($P < 0.001$ for quadratic wsr). Equation 1 quantified the response of wheat sole crop seed yield well, with a coefficient of determination of 99.7%. The parameter values are a_w (estimate 0.04424 s.e 0.00172) and b_w (estimate 0.0015142 s.e 0.0000129). However, the total intercrop (plus bean sole crop), wheat intercrop, and bean intercrop seed yields responses were quantified simultaneously using Equations 3, 1 and 5 respectively. The coefficient of determination for the simultaneous fit of the equations was 98. 9%. Table 1 shows the parameter values for the simultaneous fits.

The predicted wheat intercrop seed yield was determined as 584 g/m². The observed maximum yield of 566.10 g/m² was obtained at 650-wheat seeds/m². This indicates that the equations applied had satisfactorily described the data. The bean seed yield response to wsr was curvilinear ($P < 0.001$ quadratic wsr). The bean intercrop seed yield was quantified initially as $Y = 211.6 - 0.49$ wsr $+ 0.0005$ wsr², $r^2 = 0.87$. However, further analysis indicate that the difference between the asymptotic fits for the total intercrop and the wheat intercrop seeds yields (Equation 5) quantified bean intercrop seed yield responses better The parameter values are presented in Table 1. The total intercrop seed yields increases as wsr increased ($P < 0.001$ for quadratic wsr). Equation 3 described the total seed yields and was done simultaneously with the fitting of wheat intercrop seed yields (the parameter values in Table 1). The predicted total asymptotic seed yield was determined as 657 g/m² and was defined as $y_o + 1/b_{wt}$. This simplifies to $1/b_{wt}$ if bean sole crop (y_o) was not quantified.

Table 1. Parameter values and standard errors (s.e) for the simultaneous fits of Equations 3, 1 and 5 to the total intercrop (plus bean sole crop), wheat intercrop and bean intercrop seed yields for the spring sown experiment (Experiment 3).

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

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

Moreover, given that the establishment of seed yield-density asymptotic relationship was clearer and more precise in Experiment 3, further analysis of the yields of this experiment were carried out to confirm the validly of the equations applied.

$$1/w = a_w + b_w wsr \qquad 6$$

In Equation 6, w = yield per plant, a_w and b_w are constants as defined in Equation 1.

The response of the reciprocal of wheat sole crop and wheat intercrop seed yield per plant to wsr was linear (Figures 1 and 2), supporting the fitting of asymptotic equations to the seed yields per unit area. Note that the parameter values for fitting the linear reciprocal equations for the wheat sole crop and wheat intercrop using Equation 6 are the same for Equation 1. See the parameters for the fits using Equation 1 for estimates of a_w and b_w in Table 1.

Discussions

The main thrust of this study was exploring yield-density equations in additive intercrops using wheat/bean intercropping systems as an example. Even though some of the equations that were used to quantify seed yields response were obtained from the literature (Heath, 1970; Bleasdale, 1984; Ellis *et al.,* 1999; Salahi, 2002), new ones were proposed. Equations 3, 4 and 5 are some of the new equations proposed here. These equations it is hoped would be of relevance to other researchers working on similar treatments irrespective of the location of their work. This is based on the facts that the equations are derivatives of other equations that have successfully been applied in several locations and are known to have good biological foundations (Bleasdale, 1984; Watkinson and Freckleton, 1997; Yahuza, 2011a, b). Establishing the quantitative relationships between two or more variables using mathematical equations, helps to reduce the need for multi location density trials (Willey and Heath, 1969; Heath, 1970). For instance in situation where an asymptotic equation was fitted to a data in one location, if the asymptote was reached it can help other researchers in choosing appropriate density combinations in their trials. This is particularly helpful where there are similarities in weather and soil (Bleasdale, 1984; Gooding *et al.,* 2002). Thus, density trials are more efficiently described using the modelling approach for both the sole crop (Heath, 1970; Ellis and Salahi, 1997; Shirtliffe and Johnston, 2002) and intercrops (Wright, 1981; Dolman, 1985; Park *et al.,* 2002). In other words, applying biologically meaningful equations as was demonstrated in the present research has been adjudged the most appropriate approach in determining optimum density or density combinations (for the intercrops)

For intercropping, modified versions of these biologically meaningful equations have been developed (Wright, 1981; Helenius and Jokinen, 1994; Baumann *et al.,* 2001; Neumann *et al.,* 2009). The modified equations were meant to account for the peculiarities of intercropping where both intra-specific and inter-specific competition exists (Watkinson, 1981; Dolman, 1985; Park *et al.,* 2002). Whilst these modified equations have found particular relevance in intercropping experiments designed using the response surface designs (Dolman, 1985; Park *et al.,* 2002), they have limited adaptability in intercrops designed using simple additive design (Yahuza, 2011a, b). Here new yield-density equations that can easily and efficiently quantity data of simple additive intercrop were proposed, and were found to be of relevance in at least one of the three experiments the equations were applied to. The equations would be of relevance to others doing similar work and are recommended for investigators in analysing yield data from additive intercrops irrespective of their location.

It was demonstrated that both wheat sole crop and intercrop seed yields responded asymptotically to increase in wsr. Wheat seed yield response to density in the United Kingdom is typically asymptotic under sole cropping conditions provided wide seed rate was included in the investigations (Ellis *et al.,* 1999; Gooding *et al.,* 2002; Salahi, 2002). Therefore, the asymptotic response of wheat to increase in density under contrasting production system is confirmed here. However, previous investigations have rarely quantified wheat intercrop seed yield responses using reciprocal equations. Present research had demonstrated that as with the wheat sole crops, similar asymptotic responses are followed. As depicted in Figures 1 and 2, the linear relationships found between the reciprocal of yield per plant and density for both the wheat sole crop and intercrop further indicate that the equations proposed here had quantified yield satisfactorily (Ellis *et al.,* 1999; Salahi, 2002). On the other hand, bean seed yield declined with increase in wsr except in Experiment 2 where the opposite was the case. The response of bean to increase in wsr is typical of faba bean results. The crop is well known to show high variability in seed yields year-to–year, even within the same location (Adak *et al.,* 1999; Lopez –Bellido *et al.*, 2005). In Experiment 3, Equation 5, proposed here, described bean seed yields satisfactorily. As far as I am aware, this equation has not been used previously in quantifying yield response. Thus, suggesting the novelty of the present research as it relates to yield-density equations. The results have shown that the total intercrop seed yield responses were found to be asymptotic in Experiments 3 and linear in Experiments 1 and 2. Indeed, in Experiment 3, Equation 3, proposed by the present researcher, was applied. This further illustrates the novelty of the present yield-density investigations. Nevertheless, the fact that the total intercrop seed yield response followed similar asymptotic responses as the wheat in Experiments 3 indicates that wheat was the better competitor compared to the bean as regards seed yields. Helenius and Jokinen (1994) also found out that cereal was more competitive than the legume in agreement with the results obtained here.

In general, the choice of density has implication on resource use (Bleasdale, 1984; Ellis *et al.,* 1999; Salahi, 2002). Thus, it is necessary to sow as much seeds as possible to make use of available resources, particularly radiation (Vandermeer, 1989). However, at extreme densities there may be excessive shading between leaves leading to a reduction on overall productivity, suggesting a more efficient use of resources may be achieved with a lower density (i.e. optimum density) (Heath, 1970; Lopez –Bellido *et al.,* 2005). Determining optimum density combinations for intercrop that are composed of two or more crops of different species and/or variety is even more difficult (Watkinson, 1981; Neumann *et al.,* 2009). However, as Willey and Heath (1969) indicate, the need for multi location trial would be reduced if meaningful yield-density equations were applied to quantify data from density investigations as were demonstrated in the present research.

Conclusions

Since yield-density relationships for both the sole crops and intercrops can be better understood by applying biological meaningful equations, it was concluded that the equations proposed and applied in the present research would be of relevance to others doing similar work.

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