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Review of some methods of calculating intercrop efficiencies with particular reference to the estimates of intercrop benefits in wheat/faba bean system

Ibrahim Yahuza

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

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Abstract

Intercropping (growing two or more crops together simultaneously) is increasing being adopted worldwide, probably because there have been suggestions that the system is beneficial in terms of land use efficiency compared to sole cropping. There are several indices for estimating intercrop performance compared to the component sole crops, but as reviewed in this paper, the land equivalent ratio (LER) is the most widely adopted. Yet the LER is constrained because it is not able to account for the relative duration each component in the intercrop spent in the field may have had on intercropping performance. Area time equivalency ratio (ATER) appears to have solved this problem well. However, neither ATER nor LER can account for the physiological or physical basis for the intercropping performance. The crop performance ratio (CPR) is more appropriate in this regard, even though CPR 'adjusted for time', (CPRT) is more efficient where the component crops differ in growth duration. In addition, particularly for intercrops with commercial value, there may be a need to compute a monetary advantage (MA) for intercropping. This paper concludes that in addition to the LER, for certain intercrops such as wheat/faba bean system that has not been widely adopted, there may be a need to use other indices such as ATER, CPR, CPRT and MA as may be applicable in order to understand more fully the nature of intercrop benefits that may exist. Indeed such type of information may help to attract potential growers.

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

Introduction

Intercropping which is the growing of two or more crops together simultaneously in the same piece of land (Fukai, 1993) has been shown to be beneficial in terms of yield stability (Rao and Willey, 1980), increase in total yield (Li *et al.*, 1999), pest and disease control (Sahile *et al.,* 2008), weed management (Haymes and Lee, 1999), soil fertility (Innis, 1997; Hauggard-Nielson *et al.,* 2006) among others. Sole cropping, growing a single crop in a given area often with high inputs is more pronounced where mechanized agriculture is at its advance stage (see Vandermeer, 1989; Francis, 1989). Indications show benefits of wheat (*Triticum aestivum*)/faba bean (*Vicia faba*) (sometimes referred simply as bean in this paper) intercropping in terms of land use efficiency (e.g. Bulson *et al.,* 1997; Ghanbari-Bonjar and Lee, 2002). In general, there has been suggestions that intercropping benefits are usually greater when the growth duration between the component crops differs widely (suggesting temporal effects) than when the crops durations are similar (suggesting spatial effects) (Fukai and Trenbath, 1993).

Irrespective of the intercropping design involved, the analyses of intercropping data is not complete without a comparison between the performance of the intercrops to that of the component sole crop using at least one index (Vandermeer, 1989; Innis, 1997). The literature has shown the three criteria for assessing performance of intercropping, hence will not be restated here (see Willey, 1979; 1985). In most cases irrespective of the index used, the performance of intercrops relative to sole crops is usually assessed in terms of the seed or biomass yields (Fukai, 1993), but the possibility of making comparisons based on resource use and other attributes has also been demonstrated (see Harris *et al.,* 1987). Several indices for estimating intercrop efficiencies have been proposed by investigators (see Willey, 1979; Vandermeer, 1989; Azam-Ali and Squire, 2002; Banik *et al.,* 2006). Whilst land equivalent ratio (LER) is the most widely used index (Fukai, 1993), this paper indicate that in certain cases other indices may be more appropriate to use. Despite the numerous indices available for estimating intercrop efficiencies, the focus here was on only five indices with particular reference to the analysis of intercropping performance in wheat/bean system. The choice of this two-crop combination for emphasises was because this intercrop combination has not been widely adopted despite positive benefits as indicated by analysis using LER (e.g. Haymes and Lee, 1999).

Land equivalent ratio

Land equivalent ratio (LER) is defined as the relative land area growing the sole crop that is required to produce the yields achieved when growing intercrops (Mead and Willey, 1980; Baumann *et al.,* 2001). Osiru and Willley (1972) first proposed the LER. With the LER, different crops, whatever their type or level of yield are put on a relative and directly comparable basis (Willey, 1979). Despite the fact that LER is the most widely used index available (Fukai, 1993), there is need to give data on absolute yields and where appropriate some economic evaluation when LER is presented (Willey, 1979; Ofori and Stern, 1987). Some of the reasons why LER is commonly used by researchers have been well-documented (Willey, 1979; Oyejola, 1983; Vandermeer, 1989; Azam-Ali and Squire, 2002). Hence, this will not be dealt with here.

In computing the LER, the sole crop yields to be used as divisor defines the method of standardization and this depends largely on the agronomic objectives (Oyejola and Mead, 1982; Fukai, 1993). Three choices of sole crop yields researchers usually use for standardizations were documented previously (Oyejola and Mead, 1982; Oyejola, 1983). First is the average yield of all sole crop yields. Second is the average yield for the individual sole crop treatment. Lastly, the yield of the best sole crop treatment averaged over blocking. For example, the LER for intercrops of crop types X and Y in an intercrop is given by summing the partial

LER values of X (Equation 1) and Y (Equation 2) to give the total LER values (Equation 3).

$$L_X = \frac{XY_i}{XY_s} \quad 1$$

And

$$L_Y = \frac{YY_i}{YY_s} \quad 2$$

Such that

$$LER = \left(\frac{XY_i}{XY_s}\right) + \left(\frac{YY_i}{YY_s}\right) \quad 3$$

In Equations 1-3, XY and YY refer to X and Y yields respectively. The subscript i, refers to the intercrop and the subscript s the sole crop.

In computing the LER, both sole crop yields are given the value of 1 (Willey, 1985; Ofori and Stern 1987). It has been argued that this helps to indicate the relative competitive abilities of the component crops, but also shows the relative value of any intercropping yield advantage (Willey, 1979). If the value is greater than 1, the intercrop is more efficient whilst if it is less than 1, the sole crop is more efficient (Baumann *et al.,* 2001). Hence, the value 1 is the critical value above which the intercrop is favoured, and below which the sole crops are favoured (Vandermeer, 1989).

Interestingly, it is possible to compute LER from values obtained after regression of yield on density (see Willey, 1979; Oyejola, 1983). However, the approach has rarely been used except the study of Dolman (1985). He stated that given that the sole crop yields per unit area that are used to calculate LER should be the yields obtained from the optimum sole crop density at the same level of management as the intercrop. He assumed that this would correspond to the maximum yield potential of the sole crop as indicated by the fitted function 1/b (see Willey and Heath, 1969; Helenius and Jokinen, 1994). If the X and Y examples shown above are used again this can be stated as follows

$$L_X = \frac{Y_i}{\left(1/b_x\right)} \quad 4$$

And

$$L_y = \frac{Y_i}{\left(1/b_y\right)} \quad 5$$

The total LER can be computed by summing the expression for the two components crops.

$$LER_{x+y} = \left(\frac{Y_i}{\left(1/b_x\right)}\right) + \left(\frac{Y_i}{\left(1/b_y\right)}\right) \quad 6$$

In Equations 4-6 Y_i, $1/b_x$ and $1/b_y$ are the fitted intercrop yields, predicted sole crop asymptotic yield of component X and predicted sole crop asymptotic yield of component Y respectively.

Despite its wide adoption by researchers, the LER has had its drawbacks (Willey, 1979; Ofori and Stern, 1987; Fukai, 1993). However, it is worth stating here that a major criticism of the LER is that it takes no account of the relative duration of each species within the intercrop or sole crop system (Hiebsch and McCollum, 1987). Hence, published estimates of LER often exaggerate intercropping performance since the land left unused after the harvest of the shorter duration sole crop is not included in the calculations (Fukai, 1993). Moreover, a limitation of the LER is that the index is not able to identify the physiological or physical processes responsible for any differences that may occur between intercrops and sole crops (Harris *et al.*, 1987; Azam-Ali *et al.,* 1990). This is because most indices do not present the absolute or relative biological efficiencies of the system in terms of the amount of biomass or yield fixed relative to the energy captured during the season (Azam-Ali and Squire, 2002). Despite the drawbacks, the LER remains the most widely used index among researchers to date. Indeed, in wheat/bean intercropping system and other wheat and/or bean based investigations positive benefits of intercropping were reported when LER was used for evaluation as is shown in Table 1.

Table 1. Examples of some intercropping experiments with emphasises on systems in which wheat and/or bean were one of the component crops to indicate that land equivalent ratio is the main index used for standardization.

System, region and reference	Relevant Index (ices) used for evaluation	Major conclusions based on a relevant index or indices used
Wheat/bean; United Kingdom (UK) ; Haymes and Lee (1999)	LER	LER value of up to 1.4 was obtained
Wheat/bean; UK ;Bulson *et al.* (1997) under organic system	LER and 1 other index.	Maximum LER value of 1.29 was obtained when both wheat and beans were sown at 75% recommended density.
Wheat/bean; Italy; Tosti and Guiducci (2010)	None	
Wheat/Cotton (*Gossypium hirsutum*); China; Zhang *et al.* (2007)	LER	LER value of up to 1.39 was obtained.
Wheat/chickpea (*Cicer arietinum*); India; Banik *et al.* (2006)	LER, and five other indices.	LER value of up to 1.55 was obtained.
Maize (*Zea mays*)/bean ; China; Li *et al.* (1999)	LER	Maximum LER values were 1.23 and 1.34 for the biomass and seed yields respectively.
Bean/ pea (*Pisum sativum*); Ethiopia ; Abera and Feyisa (2008)	LER and 3 other indices.	Mean LER value of up to 1.53 was obtained.
Wheat/pea ; Denmark; Ghaley *et al.* (2005)	LER	LER calculated based on total biomass decreased from a maximum of 1.34 to as low as 0.85 as N fertilizer applied increased.
Oat (*Avena sativa*)/ bean ; UK; Willey *et al.* (1997)	LER	Maximum LER value was 1.34.

Area time equivalency ratio

Hiebsch and McCollum (1987) proposed the area time equivalency ratio (ATER) because crop production uses both time and land. The concept, which defines yield as a function of both land area and time was developed to correct the time deficiency in the LER concept (Ofori and Stern, 1987; Fukai, 1993). To present ATER mathematically an expression is needed, which includes the duration of land occupied by an intercrop as well as the duration for each component sole crop. The details of derivation of ATER are not presented in this paper (see Hiebsch and McCollum, 1987). However, ATER could be computed simply from absolute yields (Ofori and Stern, 1987; Fukai, 1993; Hongo, 1995). For example for an intercrop composed of two components crops of the types X and Y the partial ATER for component X can be computed as follows

$$ATER = \left(\left(t_{mx}/t_{ti}\right)\left(y_{xi}/y_{xm}\right)\right) \qquad 7$$

Where t_{mx} is the growing period of component X in sole crop, t_{ti} is the total time of intercropping system, y_{xi} is the yield of component X in intercropping. On the other hand, y_{xm} is the yield of component x in sole crop.

Similarly, partial ATER can be computed for component Y as follows

$$ATER = \left(\left(t_{my}/t_{ti}\right)\left(y_{yi}/y_{ym}\right)\right) \qquad 8$$

Where t_{my} is the growing period of component Y in sole crop, t_{ti} is the total time of intercropping system, y_{yi} is the yield of component Y in intercropping. On the other hand, y_{ym} is the yield of component x in sole crop.

Hence, the total intercrop ATER can be computed as follows

$$\text{Total ATER} = \left(\left(t_{mx}/t_{ti}\right)\left(y_{xi}/y_{xm}\right)\right) + \left(\left(t_{my}/t_{ti}\right)\left(y_{yi}/y_{ym}\right)\right) \qquad 9$$

Where t_{mx}, t_{ti}, y_{xi}, y_{xm}, t_{my}, y_{yi} and y_{yi} are as defined in Equations 7 and/or 8 above.

Hiebsch and McCollum (1987) stated that when time was included in the calculations, of intercropping advantage using ATER the large land use advantage usually ascribed to intercrops relatives to the sole crops disappeared. Therefore, they concluded that most intercrops use land and area with the same efficiency as sole crops of the same species. Tsay *et al.* (1988) applied ATER to analyze yield of a cassava (*Manihot esculenta*)/sorghum (*Sorghum bicolor*) intercrop and found positive benefits for intercropping even though ATER adjusted intercropping benefits. However, Fukai (1993) stated that it is likely that ATER underestimated the advantage of intercropping when component crops differ in growth duration. This is because it is not common to be able to plant a crop immediately after the harvesting of a preceding one. Consequently, there is a lost time in terms of biological productivity in sole cropping. However, he contended that ATER appears to have better and justifiable application in humid tropical areas where there is continuous growing season.

There have been few studies that have applied ATER in analysing intercropping experiments despites its advantages. For instance, wheat/bean intercrop experiments have been carried out in the past and positive values of LER have been reported as was indicated in Table 1, but in all cases, ATER was not applied. This may be because in most of these investigations the two crops were sown and harvested simultaneously. Indeed, Hiebsch and McCollum (1987) stated that the LER gives valid estimates when all intercrop component have equal durations. Thus, LER estimates are valid when sowing and harvesting of the intercrops coincide with sowing and harvesting of their counterpart sole crops. There have been reports that wheat seed yields are often substantially reduced when intercropped with bean (e.g. Haymes and Lee, 1999). Probably such substantial wheat yield reduction may be because the usual practice is to sow and harvest the two crops simultaneously (e.g. Bulson *et al.,* 1997). It is possible that this tremendous yield reduction can be overcome by delaying bean sowing date compared to the sowing time for the wheat, which is mostly the major component. In such cases, the application of ATER in analysing results would be more valid than the use of LER.

Perhaps a major limitation of ATER as with the LER is that it is unable to detect the physiological or physical processes responsible for any differences that may occur between intercrops and sole crops regardless of whether intercropping was beneficial or not (Azam-Ali and Squire, 2002). In addition, these authors contended that neither ATER nor LER presents the absolute or relative biological efficiencies of the system in terms of the amount of biomass or yield fixed relative to the energy captured during the season. Despite its drawbacks, ATER appears more efficient than LER in estimating intercrop efficiencies when the sowing dates of the component crops differ. In such cases, this paper advocates for the use of ATER rather than LER in estimating intercrop efficiency. However, where the component crops are sown at the same time, it is assumed that the LER values also represent values for ATER following the conclusions of Hiebsch and McCollum (1987).

Crop performance ratio

Harris *et al.* (1987) first proposed the concept of crop performance ratio (CPR) to assess the performance of sorghum /groundnut (*Arachis hypogaea*) intercrops. They developed the index because available indices were incapable of determining the physiological or physical factors responsible for the yield difference between the sole crops and the intercrops. This is regardless of whether intercropping produces an advantage or not. In using CPR, the performance of a component of an intercrop is compared to that of the sole crop (Harris *et al.*, 1987). Thus, the CPR has been argued to be the appropriate bases for calculating the biological efficiency of an intercrop compared to its component sole crops, than the LER, because CPR calculates the efficiency with which sole crops and intercrops use resources (e.g. radiation) to produce dry matter (Azam Ali *et al.*, 1990; Azam-Ali and Squire, 2002). Harris *et al.* (1987) stated that to evaluate the benefits of intercrops using CPR, the yield per unit area of a component of the intercrop Y_{ix} was divided by the proportion P_{ix}, of that component in the intercrop to give the yield per unit area sown to that component Y/P. This quantity was then expressed as a fraction of the same component in a sole plot, Y_{sx} to give crop performance ratios. The CPR for species X, in an intercrop composed of species X and Y, (CPR_x) is given as shown in Equation 10.

$$CPR_x = \frac{Y_{ix}}{P_{ix}Y_{sx}} \quad 10$$

Where Y_{ix} and Y_{sx} are its yields per unit area (g/m^2) in the intercrop and sole crop respectively, and P_{ix} is the proportional sown area of species X in the intercrop.

Similarly, for component Y CPR_y can be calculated as follows

$$CPR_y = \frac{Y_{iy}}{P_{iy}Y_{sy}} \quad 11$$

Where Y_{iy} and Y_{sy} are its yields per unit area (g/m^2) in the intercrop and sole crop respectively, and P_{iy} is the proportional sown area of species Y in the intercrop.

So that the total CPR for both component crop species X and Y can be calculated using Equation 12. However, it should be understood that unlike total intercrop LER (i.e. Equation 3), total intercrop CPR cannot be simply calculated by summing Equations 10 and 11 (see Harris *et al.*, 1987; Azam-Ali and Squire, 2002).

$$CPR_{xy} = \frac{Y_{ia} + Y_{ib}}{P_{ia}Y_{sa} + P_{ib}Y_{sb}} \quad 12$$

Where Y_{ix}, Y_{sx}, Pix, Y_{iy}, Y_{sy} and P_{iy} are as defined previously.

It should be understood that because the sole crop values are multiplied by their sown proportions in the intercrop, this provides their expected productivity if unit area of land had been sown with sole crops in the same proportions as in the intercrops (Azam-Ali, 1995 cited in Azam-Ali and Squire, 2002). Similar to the LER, a value of CPR greater than 1 indicates an intercrop advantage and a CPR less than 1 an intercrop disadvantage (Harris *et al.*, 1987; Azam Ali *et al.*, 1990; Azam-Ali and Squire, 2002).

Similar calculations, but with several different variables instead of yield per unit area, can be made to evaluate photosynthetically active radiation (PAR) interception, radiation use efficiency (RUE) harvest index (HI), transpiration, nutrient uptake, yield components, tiller number just to mention a few using the CPR approach (see Harris *et al.,* 1987; Azam-Ali and Squire, 2002). In addition, with respect to the calculation of CPR for HI and RUE given that these variables are not necessarily affected by density, the CPR can be calculated simply by dividing by the sole crop that gave the maximum HI or RUE as may be applicable (see Harris *et al.,* 1987 for details). Therefore, the most important advantage of the CPR concept is that it can be extended to analyze the capture or use of any resource by an intercrop compared with its constituent component crops (Azam-Ali and Squire, 2002).

Both Harris *et al.* (1987) and Azam-Ali *et al.* (1990) evaluated the performance of intercrops relative to the sole crops using the procedures shown above. Harris *et al.* (1987) found CPR was greater when water was less reaching up to 1.21 even though sorghum produced higher yields than the groundnut. They concluded that groundnut performed poorer than the sorghum, and was therefore less efficient than sorghum. In other words, groundnut in the intercrop was physiologically less efficient than the sorghum in the intercrop. Similarly, Azam-Ali *et al.* (1990) worked with sorghum/groundnut intercrop and reported that the

CPR for the biomass was 1.08 and that for the seed yield was 1.27. They explained that the positive CPR was because the intercrop produced more dry matter and intercepted more PAR (Azam Ali *et al.*, 1990). They added that the advantage to the seed yield was attributed to increase in the HI in the sorghum component (0.64) compared with its sole crop (0.55) (Azam Ali *et al.*, 1990).

Azam-Ali and Squire (2002) asserted that knowledge of energy equivalents is necessary in intercrops systems, which are often composed of plants products with substantially different composition. They stated that by referring all CPR calculations to the energy equivalence of biomass in mega joules (MJ), it is possible to use a common currency with which to compare biological outputs of different species composed of organs, each with different energy values. In calculating the modified CPR, it is assumed that the carbohydrate and protein fractions have the same energy value and that there is no lipid in the seed (Azam-Ali 1995, cited in Azam-Ali and Squire, 2002). In the investigations of Azam-Ali, 1995 cited in Azam-Ali and Squire (2002) energy equivalent for the total biomass and seed yield (MJ) were calculated by multiplying the vegetative and reproductive components of sorghum by 17.51 KJ/g (Passmore and Eastwood, 1986 cited in Azam-Ali, 1995 cited in Azam-Ali and Squire, 2002). On the other hand, for the groundnut seed yield was multiplied by 23.41 KJ/g (McCance and Widdowson, 1978 cited in Azam-Ali and Squire, 2002) whilst the vegetative component was multiplied by 17.51 KJ/g as for the sorghum. However, such conversion may not be necessary if none of the component crops is an oil seed crop. Indeed, since the procedures assume that protein and carbohydrates are of equal energy value it is not sensible to make any conversion if the intercrop components involved are all mainly legumes and/or cereals, except if an oil seed legumes is involved. Indeed, for wheat/bean intercropping system such conversions are not necessary. Hence, the CPR can still be calculated from absolute seed and/or biomass yields as was demonstrated by Harris *et al.* in their study.

As stated earlier, despite the importance of the concept in explaining the physical and/or physiological basis for yield difference between the intercrops and sole crops, the concept has not been widely adopted by workers on intercropping. The writer is not aware of any wheat/bean intercropping system experiment where evaluation was done using the CPR. Hongo (1995) in a wheat/bean investigation did review both LER and CPR but concluded that LER was more appropriate index to use for analysing his results. My opinion is that given that, the main thrust of Hongo's research was resource use (water and radiation), additional information using CPR would have been useful. Although in general for most agronomic purposes it has been suggested that analysis using LER may be sufficient, a further data on intercrop performance based on physical or physiological indices as represented by CPR may be useful particularly in some intercrops where extremely high positive LER values are often obtained. Indeed, for wheat/bean intercrop where there have been indications of positive performance based on LER, a further analysis that has physiological interpretation using CPR is worthy. Therefore, the CPR should be one of the main indices to use in estimating the performance of intercropping where data on resource capture were taken. Nevertheless, as with the LER, where the component crops involved are of different durations in the field the estimates of CPR may be exaggerated (Azam-Ali and Squire, 2002).

Crop performance ratio 'time corrected'

The deficiency of the CPR to account for the different time spent in the field by the component crops in evaluating the performance of intercropping necessitated the modification of the concept (Azam-Ali, 1995 cited in Azam-Ali and Squire, 2002; Azam-Ali and squire, 2002). In this case, for intercrops composed of species with different durations, there is need to account for the duration t_x and t_y for species X and Y respectively (Azam-Ali and Squire, 2002). The duration for each component crop species is assumed to be the same whether it was grown as a sole crop or intercrop and $t_x > t_y$.

With respect to the sole crop for component X, the rate of productivity can be calculated using Equation 13 (see Azam-Ali and Squire, 2002).

$$R_{sx} = \frac{Y_{sx}}{t_x} \qquad 13$$

Where R_{sx}, Y_{sx} and t_x refers to rate of productivity of sole crop of component X, sole crop yield of component X and duration of component X respectively.

Similar calculations can be made for sole crop of component Y as follows (Azam-Ali and Squire, 2002).

$$R_{sy} = \frac{Y_{sy}}{t_y} \qquad 14$$

Where R_{sy}, Y_{sy} and t_x refers to rate of productivity of sole crop of component Y, sole crop yield of component Y and duration of component Y respectively.

As regards the intercrops, the rate of productivity can be calculated using Equation 15 for component X.

$$R_{ix} = \frac{Y_{ix}}{t_x} \qquad 15$$

Where R_{ix}, Y_{ix} and t_x refers to rate of productivity of sole crop of component X, sole crop yield of component X and duration of component X respectively.

Similar calculations can be made for sole crop of component Y as follows

$$R_{iy} = \frac{Y_{iy}}{t_y} \qquad 16$$

Where R_{iy}, Y_{iy} and t_y refers to rate of productivity of sole crop of component Y, sole crop yield of component Y and duration of component X respectively.

However, it should be emphasised that the rate of productivity of species Y depend on the duration of species X since land is occupied by the intercrop for this length of time (Azam-Ali and Squire, 2002). Hence, the 'time corrected' crop performance ratio (CPRT) for species X is given by

$$CPRT_x = \frac{R_{ix}}{P_{ix} R_{sx}} = CPR_x \qquad 17$$

Where $CPRT_x$ refers to CPR of component X adjusted for time, R_{ix} and R_{sx} refers to rate of productivity of component X in the intercrop and sole crop respectively. P_{ix} and CPR_x refers to the proportional sown area of component X in the intercrop and crop performance ratio of component X respectively.

This was because X occupied land throughout the duration of intercrop system (see Azam-Ali and Squire, 2002).The CPRT for component Y can be calculated as follows

$$CPRT_y = \frac{R_{iy}}{P_{iy} R_{sy}} = CPR_y \left(t_y / t_x \right) \qquad 18$$

Where $CPRT_y$ refers to CPR of component Y adjusted for time, R_{iy} and R_{sy} refers to rate of productivity of component Y in the intercrop and sole crop respectively. P_{iy} and CPR_y refers to the proportional sown area of species Y in the intercrop and crop performance ratio of component Y respectively. The duration of component X and Y is represented by t_x and t_y respectively.

So that the time corrected crop performance ratio for the intercrop, $CPRT_{xy}$ is given by Equation 19 (see Azam-Ali and Squire, 2002 for details).

$$CPRT_{xy} = \frac{(Y_{ix} + Y_{iy}) t_y}{P_{ix} Y_{sx} t_y + P_{iy} Y_{sy} t_x} \qquad 19$$

Where Y_i and Y_s are yields per unit area (g/m²) in the intercrop and sole crop respectively, P_{ix} and P_{iy} is the proportional sown area of species X and Y in the intercrop, t_x and t_y refers to the duration for species X and Y respectively. The subscripts x and y refers to components X and Y respectively.

Similar to ATER, Azam-Ali (1995) as cited by Azam-Ali and Squire (2002) showed that when the time corrected CPR (i.e. CPRT) was used to re-evaluate intercropping experiments the apparent advantage in the intercrop performance expressed in terms of CPR were always reduced substantially. Thus, CPRT needs to be used to evaluate the performance of intercropping where there are differences in sowing times/duration and resource captures were investigated. Yet, the CPRT as with CPR has not been well adopted by most intercropping researchers. Despite the fact that yield advantages have been reported for wheat/bean intercropping systems, no study has evaluated performance using the CPRT. This may be because in the previous studies both wheat and bean were sown and harvested simultaneously (e.g. Bulson *et al.,* 1997; Haymes and Lee, 1999). In situations where the component crops are of similar growth durations evaluation using the CPRT may not be necessary (see Azam-Ali and Squire, 2002). In such cases, the estimates of the CPR may be sufficient. Nevertheless, clearly, a further work to evaluate the validity of the concept alongside other indices is timely.

Monetary advantage

Irrespective of the indices that was used to assess intercropping advantages, there may be need to indicate some monetary values for intercropping if at least one of the component crops is a cash crop. The economic evaluation is needed in addition to whatever analysis is carried out on straight yield (e.g. Willey, 1979; Willey, 1985). Clearly, for wheat and faba bean intercropping such economic analysis is necessary given that the two crops are mainly cash crops (Nix, 2009). Willey (1985) stated monetary advantage (MA) can be calculated using Equation 20.

$$MA = \left[TIV \left(\frac{LER - 1}{LER} \right) \right] \qquad 20$$

Where TIV= total intercrop value, and LER is the land equivalent ratio.

The calculation assumes that the appropriate economic assessment of intercropping should be in terms of increased value per unit area (Willey, 1979). In Greece, Dhima *et al.* (2007) used MA in evaluating common vetch (*Vicia sativa* L) intercropped with wheat, Triticale (*Secale cereale* x *Triticum durum*) or barley (*Hordeum vulgare*) and indicated positive benefits of intercropping. Previous wheat/bean intercropping experiments have rarely done monetary evaluation, except the study of Bulson *et al.* (1997). They did some economic analysis based on gross margin (Nix, 2009). Gross margin is the return of the crop (yield /tonne x value /tonne) less variable input costs (Nix, 2009). In their study, computing gross margin was easy because seeds were the only variable costs, since the experiments were organically managed. A major limitation of Equation 20 is that it does not take account time durations since it is a derivative of LER. In addition, the value of the index does not indicate profitability or otherwise since not all input costs are included in the computation. In any case, the index has the potential use of indicating economic viability of a given intercrop system.

Recommendations for future research

The foregoing has confirmed previous assertions by others that LER remained the most widely used index in the analyses of intercrop system (e.g. Vandermeer, 1989), despite the limitations of the index, as was reviewed earlier. Besides LER, the need to apply ATER, CPR and CPRT, in addition to MA in evaluating intercropping system, particularly where data on resource capture were taken is justified. Indeed, such analyses may be very relevant for intercrop combinations such as wheat plus bean, which has not been well adopted yet.

As argued by Vandermeer (1989) whether the design was additive or a replacement is largely an issue of population pressure. Therefore, for most agronomic aims it is necessary to use the maximum yielding sole crops for comparison with the intercrops, with the assumption that it was at the optimal density. This means that an initial analysis to determine the yield-density relationships may be necessary. Indeed, there may be need to evaluate the performance of intercropping relative to the sole crops after establishing yield-density relationship (see Wright, 1981; Dolman, 1985). In other words, intercrop efficiencies are determined after meaningful biological equations have been applied to quantify yields. In doing such evaluations, it may be necessary to use more than one index for comparative purposes, and to better understand the intercrop system well. However, curves fitted using yield-density equations are able to show clearly the responses of both the intercrop and sole crop to increase in density. It therefore, allows the impact of intercropping on yields to be apparent to some extent. However, in a practical sense the curves fitted using any given yield-density equation cannot tell us by how much intercropping was beneficial or not. What is required therefore is to have a synergy between the fitting of the equations using biologically meaningful equations (see Willey and Heath, 1969) and further evaluations using some of the well-accepted indices for evaluating intercropping performance (e.g. Willey, 1979). For instance, it is possible to fit either an asymptotic curve or a parabolic curve to a given dataset, (see Willey and Heath, 1969), thereafter; the performance of intercropping can be evaluated from the fitted values using one or more of the indices. As discussed earlier, except Dolman (1985) who evaluated the performance of intercropping based on LER using this approach, such procedures have rarely been used by intercropping researchers. The approach has the advantage in that we will know the yield-density response. In additions, appropriate combinations of intercrop densities that would be beneficial can be easily determined. This is because the intercrop does not have to outyield the component sole crops at all densities for intercropping to be beneficial (Vandermeer, 1989).

Moreover, 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. What this simply means is that with respect to ATER and CPRT, in the equations shown above, days should be replaced with thermal time. Even where ATER and CPRT have been applied previously, the thermal time approach was not used. The approach appear to be more sensible, given that accumulated PAR has also been shown to be better quantified using thermal time rather than days. Indeed, in any experiment involving different sowing dates and/or different growth durations in which the accumulated PAR was calculated using thermal time, it appears more efficient to calculate both ATER and CPRT using thermal time as well. Moreover, the need to use MA to evaluate crops with commercial significance was detailed earlier. However, given that ATER has been shown to be more efficient than LER where different sowing date are involved, I proposed that MA based on ATER estimates as shown in Equation 21 may be more tenable.

$$MA_{ATER} = \left[TIV\left(\frac{ATER-1}{ATER} \right) \right] \qquad 21$$

Where TIV= total intercrop monetary value and ATER is the Area time equivalency ratio.

Note that though Equation 21 proposed here for calculating the MA using ATER is similar to Equation 20 that is used for estimating MA based on LER estimates (e.g. Willey, 1985), the interpretations differ. For the MA based on ATER estimates the interpretation is assumed to be in terms of increased intercrop value per unit area x time, whilst for the MA based on LER estimate it is in terms of increased value per unit area only. For wheat/bean intercropping research, MA has never been calculated based on ATER estimates. Indeed, evaluation of MA of intercropping based ATER estimates has shown above has rarely been done using other crops combinations as well. For wheat/bean intercropping research, such information may be relevant to the growers since the two crops have significant commercial value.

Conclusion

This paper concludes that in addition to LER, which is widely used for the estimating of intercrop performance, there may be a need to evaluate intercrop performance with other indices such as ATER, CPR, CPRT and MA using both results and fitted values as may be applicable in order to understand intercrop benefits well. Clearly, this might help to avoid reporting exaggerated intercrop benefits, which may be largely due to the use of inappropriate index for evaluation.

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