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The Robustness of Land Equivalent Ratio as a Measure of Yield Advantage of Multi-Crop Systems over Monocultures

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Abstract

Land equivalent ratio (LER) is most widely used indicator of yield advantage of multi-crop farms over sole-crop farms, and usually measured using crop biomass yield .per unit area. Most often, crop yields are compared between both systems using the same area. In this paper we demonstrate that although the yield per unit area and the yield per plant are widely different, LER remains invariant. As a corollary, area time equivalent ratio (ATER) and land use efficiency (LUE), derived from LER, also remain unchanged when using the two different measures of crop yields. We recommend that when the estimation of the exact land area is difficult due to complex crop planting designs, yield per plant estimate is much easier and equally valid for estimation of LER and its derivatve indices.

1. Introduction

There is a general consensus that multiple cropping systems have superior yield potential over monocultures in agriculture and forestry (Gliessman 2015; Huang et al. 2015; C.L.C. Liu et al. 2018; Maitra et al. 2021). However, experimental evidence of crop productivity enhancement in multi-crop (MC) systems has predominantly been confined to intercrops of no more than 2 species, compared to monocultures (e.g. Hamzei and Seyedi 2015; Morales-Rosales and Franco-Mora 2009; Raza et al. 2019; Runkulatile 1998; and citations in Maitra et al. 2021, Table 1). Evidence from combinations of 3 crops is scarce (Dapaah et al. 2003; Andersen et al. 2007). The first experimental evidence of yield comparisons between MC farm plots with 7 crop species and sole-crop (SC) plots of the same crops species, appeared in Deb (2021), which revealed different degrees of efficiency of yield in different planting designs.

Deb's (2021) study measured the yield advantage of MC over SC plots by the land equivalent ratio (LER) based on edible biomass yield per plant, although it is usually estimated by measuring yield per unit of land area under crop cover (Mead and Willey 1980; Weigelt and Jolliffe 2003; Khanal et al. 2021). Here we use both *per* plant (Y_{ir}[p]) and *per* unit area (Y_{ir}[a]) yields of the data from Deb (2021) to examine the sensitivity of LER with scaled units of measurement. In addition, we attempt to examine two more indices of yield advantages of MC farms planted to 7 crops.

2 Methods and Materials

2.1 *Study Sites*

A total of eight farms in the State of Odisha, India were selected for our experiments, whose details are given in Deb (2021). All these 8 farms are owned by indigenous farmers, who traditionally grow 6 to 12 crop species on their farms every season. We chose 7 crop species (S = 7) most commonly cultivated in the region, with zero synthetic agrochemical input. In addition to the 7 species chosen for this experiment, a legume cover crop was planted on the farm margins. The yield of legumes was not included in this study, focusing instead on the 7 different crops in each farm, compared to an SC plot of each of these 7 species, separately grown. In this study, each replication of 8 farms includes 3 MC plots and 7 SC plots.

2.2 *Crop planting designs*

As replacement designs are not practised in real farms, and because replacement designs alter the individual crop densities, we chose to plant each crop species in equal proportions in all MC plots.

2.2.1 *SC Plot Design*:

Two species of fruit crops (okra *Abelmoschus esculentum* and brinjal *Solanum nigricum*), 3 cereal crops (rice *Oryza sativa* ssp. *indica*, little millet *Panicum sumatrense* and finger millet *Eleusine coracana*), and two leaf crops (red amaranth *Amaranthus cruentus* and green amaranth *Amaranthus viridis*) were planted in separate SC plots. The same cropping design was replicated in all the 8 farms.

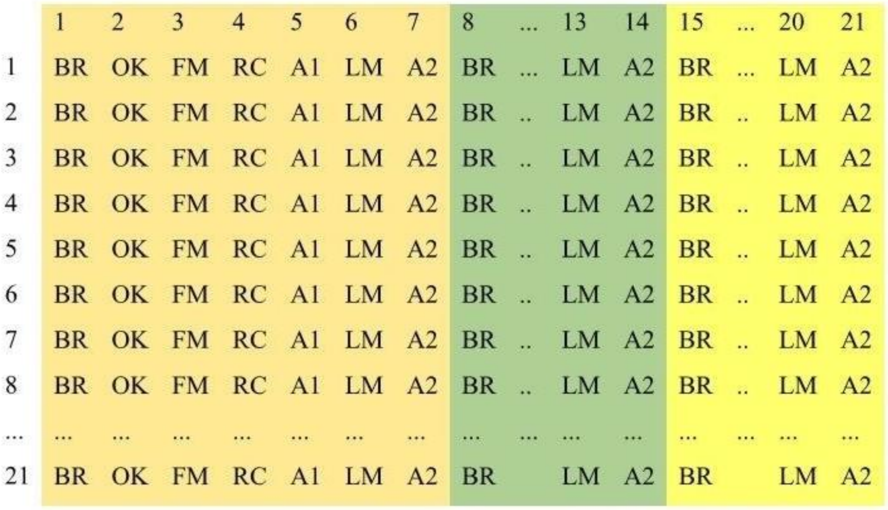
The SC plots were of the same size, and the crop plants were planted at a uniform spacing, with a planting density of 625./sq.m for brinjal saplings (40 cm x 40 cm), and 16/sq.m for all other crops (25 cm x 25 cm).

2.2.2 *MC Plot Designs:*

A total of 7 crop species were chosen for the MC farms. The crop species chosen for growing in the MC plots are: brinjal (BR), okra (OK). green amaranth (A1), red amaranth (A2), finger millet (FM), little millet (LM), and rice (RC).

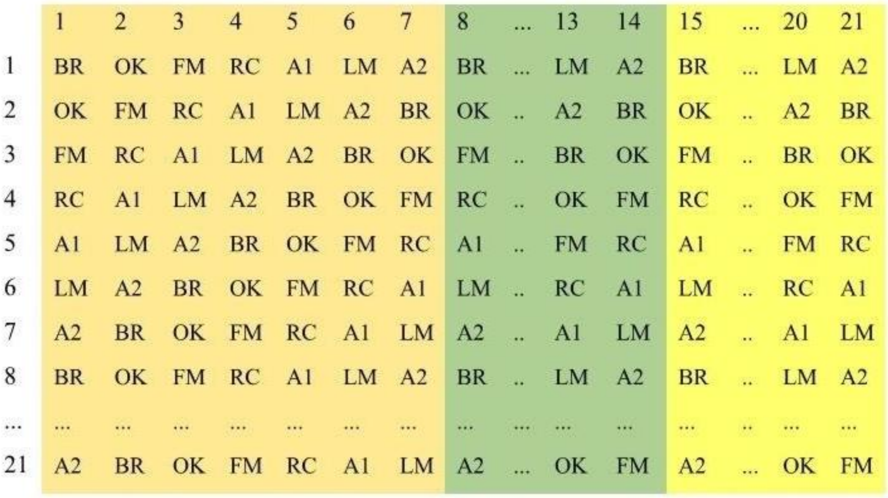
In each farm, 3 designs (designated A, B, and C) of MC plots, composed of 21 x 21 cells, were established (**Fig. 1**). Crop plants in design *A* were arranged in a row intercropping system, planted to all the 7 species arranged in successive rows, repeated 3 times over. Design *B* is non-random mixed cropping, where 7 crop species were ped in a fixed order, with each cell diagonally matching the species in the previous row and column. Thus, each row and each column differed in crop combination, although the order remained the same, repeated 3 times over. Design C was also non-random mixed cropping, albeit with a different arrangement of crop species. Like that of design *B*, diagonal cells repeated each crop, matching the previous row and column, repeating the arrangement 3 times over in both dimensions.

DESIGN A



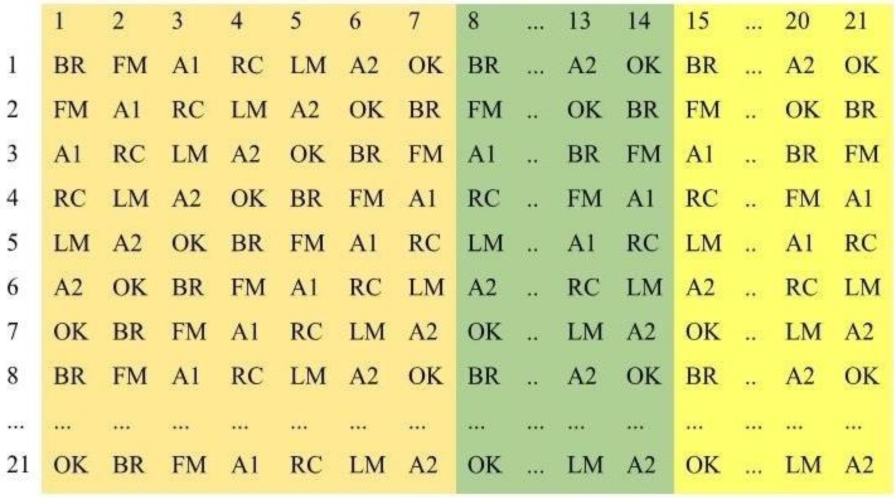
	1	2	3	4	5	6	7	8	...	13	14	15	...	20	21
1	BR	OK	FM	RC	A1	LM	A2	BR	...	LM	A2	BR	...	LM	A2
2	BR	OK	FM	RC	A1	LM	A2	BR	..	LM	A2	BR	..	LM	A2
3	BR	OK	FM	RC	A1	LM	A2	BR	..	LM	A2	BR	..	LM	A2
4	BR	OK	FM	RC	A1	LM	A2	BR	..	LM	A2	BR	..	LM	A2
5	BR	OK	FM	RC	A1	LM	A2	BR	..	LM	A2	BR	..	LM	A2
6	BR	OK	FM	RC	A1	LM	A2	BR	..	LM	A2	BR	..	LM	A2
7	BR	OK	FM	RC	A1	LM	A2	BR	..	LM	A2	BR	..	LM	A2
8	BR	OK	FM	RC	A1	LM	A2	BR	..	LM	A2	BR	..	LM	A2
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
21	BR	OK	FM	RC	A1	LM	A2	BR		LM	A2	BR		LM	A2

DESIGN B



	1	2	3	4	5	6	7	8	...	13	14	15	...	20	21
1	BR	OK	FM	RC	A1	LM	A2	BR	...	LM	A2	BR	...	LM	A2
2	OK	FM	RC	A1	LM	A2	BR	OK	..	A2	BR	OK	..	A2	BR
3	FM	RC	A1	LM	A2	BR	OK	FM	..	BR	OK	FM	..	BR	OK
4	RC	A1	LM	A2	BR	OK	FM	RC	..	OK	FM	RC	..	OK	FM
5	A1	LM	A2	BR	OK	FM	RC	A1	..	FM	RC	A1	..	FM	RC
6	LM	A2	BR	OK	FM	RC	A1	LM	..	RC	A1	LM	..	RC	A1
7	A2	BR	OK	FM	RC	A1	LM	A2	..	A1	LM	A2	..	A1	LM
8	BR	OK	FM	RC	A1	LM	A2	BR	..	LM	A2	BR	..	LM	A2
...	...	...	...	...	...	...	...	...	...	...	...	...	..	...	...
21	A2	BR	OK	FM	RC	A1	LM	A2	...	OK	FM	A2	...	OK	FM

DESIGN C



	1	2	3	4	5	6	7	8	...	13	14	15	...	20	21
1	BR	FM	A1	RC	LM	A2	OK	BR	...	A2	OK	BR	...	A2	OK
2	FM	A1	RC	LM	A2	OK	BR	FM	..	OK	BR	FM	..	OK	BR
3	A1	RC	LM	A2	OK	BR	FM	A1	..	BR	FM	A1	..	BR	FM
4	RC	LM	A2	OK	BR	FM	A1	RC	..	FM	A1	RC	..	FM	A1
5	LM	A2	OK	BR	FM	A1	RC	LM	..	A1	RC	LM	..	A1	RC
6	A2	OK	BR	FM	A1	RC	LM	A2	..	RC	LM	A2	..	RC	LM
7	OK	BR	FM	A1	RC	LM	A2	OK	..	LM	A2	OK	..	LM	A2
8	BR	FM	A1	RC	LM	A2	OK	BR	..	A2	OK	BR	..	A2	OK
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
21	OK	BR	FM	A1	RC	LM	A2	OK	...	LM	A2	OK	...	LM	A2

Fig. 1:

The Planting Design A, B and C for 7 Crop Species. Numbers in the first column denote respective row numbers, and the numbers in the top row denote respective column numbers. [*Legends*: BR: Brinjal, A1: Green Amaranth, A2: Red Amaranth, FM: Finger Millet, LM: Little Millet, OK: Okra, RC: Rice.]

2.3 *Crop area estimation*

In all plots, the spacing on each side of a crop is 40 cm for BR, and 25 cm for all other crops. Any crop sitting next to BR must be 40 cm apart, so for all non-BR species, the spacing of 25 cm is subsumed in the 40 cm spacing for BR.

2.3.1 *SC plots*

Each SC plot consisted of 98 crop plants, sown in 14 rows and 7 columns. Adding a space of 40 cm (for BR) or 25 cm (for all other crops) on the outer margin, the area under brinjal was estimated as

$$A_{\mathrm{BR}} = (8 \text{ x } 40 \text{ cm}) \text{ x } (15 \text{ x } 40 \text{ cm}) = 192000 \text{ cm}^2 = 19.2 \text{ m}^2,$$

while that for each the other 6 crops,

$$A_{i \neq \mathrm{BR})} = (8 \text{ x } 25 \text{ cm}) \text{ x } (15 \text{ x} 25\text{cm}) = 75000 \text{ cm}^2 = 7.5 \text{ m}^2.$$

2.3.2 *MC plots*

Because the number of plants and the density of each crop are the same in all MC plots, all the plot areas in designs A, B and C are identical. The general formula we used for calculating the land area (*A*) in the MC plot design is

$$\mathrm{A}_{r\text{-}MC} = \sum_{i=1}^{7} A_i = G_i^2(\mathrm{R}+1)[\mathrm{X} + \mathrm{Y}] \qquad \text{(Eq. S4)}$$

where C_i is the number of columns in which crop *i* is repeatedly planted in each row, and is uniformly 3 in our experiments, R is the number of rows in each plot, which is uniformly 21, and G_i is the spacing between each pair of plants, with the following conditions:

$\mathrm{G}_i = 40$ cm, $\mathrm{X} = 2\mathrm{C}_i$ and $\mathrm{Y} = 0$ for $i = \mathrm{BR}$,

$\mathrm{G}_i = 25$ cm, $\mathrm{X} = 0$ and $\mathrm{Y} = 1 + \mathrm{C}_i\,(\mathrm{S} - 1)$ for $i \neq \mathrm{BR}$, where S (= 6) is the number of non-BR species planted in each row. The derivation of Eq. S4 is given in **Supplementary Material S1**.

The actual area (AA) of each replicate MC plot was calculated as:

$$AA_{r\text{-}MC} = \sum_{i=1}^{7} A_{ir}\,(N_{ir}/C_i\,R) = \sum_{i=1}^{7} A_{ir}\,N_{ir}/63 \qquad \text{(Eq. 1)}$$

where A_{ir} is the land area for the ith crop in the replicate r; and N_{ir} (≤ 63) is the number of surviving plants belonging to crop species i in the replicate $r = 1,2, ..., 8$.

2.4 *Quantification of crop yield*

The edible parts of each crop were harvested after maturity, and the quantity of the edible biomass harvested from each crop was separately weighed using a spring balance. The total crop harvest from each SC farm was weighed together, whereas the produce from the crops from each row and column from MC plots were separately weighed. As the fruits of brinjal and okra were harvested multiple times, the total weight of the fruits from each plant was estimated by successively adding their weights after each harvest (Deb 2021).

2.4.1 *Yield per plant*

Considering the mortality of a few plants in different plots, we counted the number of surviving plants of each crop species in each farm plot, and estimated the per-plant productivity ($Y_{ir}[p]$) of crop i in the replicate plot r, as:

$$Y_{ir}[p] = P_{ir}/N_{ir} \qquad \text{(Eq. 2)}$$

where P_{ir} is the absolute yield of the ith crop in replicate r and N_{ir} is the number of surviving plants belonging to crop species i in the replicate plot r.

2.4.2 *Yield per unit area*

Yield per unit area ($Y_{ir}[a]$) for crop i harvested from the replicate plot r was calculated by the standard procedure of dividing the absolute yield per unit area by the proportionate area in each plot:

$$Y_{ir}[a] = P_{ir}/\, AA_{ir} \qquad \text{(Eq. 3)}$$

where AA_{ir} is the actual area of the r^{th} replicate plot under the i^{th} crop, and P_{ir} is the absolute yield of the ith crop in replicate r.

To scale the yield of each SC plot at par with MC plots (with 63 plants), we calculated

$$Y_{ir\text{-}SC} = 63\ (P_{ir\text{-}SC}/\, N_{ir\text{-}SC}) \qquad \text{(Eq. 4a)}$$

where P_{ir} is the absolute yield of the ith crop in the replicate plot r. The yield per unit area of each sole crop i in the replicated SC plots was then calculated as:

$$Y_{ir\text{-}SC}\ [a] = Y_{ir\text{-}SC} / A_{r\text{-}MC} \qquad \text{(Eq. 54b)}$$

with $A_{r\text{-}MC}$ obtained from Eq. S4. The Eq. 4b thus enables comparison between the yields of each crop from an equal area of SC and MC plots.

2.5 *Indices of relative yield performance*

2.5.1 *Land equivalent ratio* (LER):

Yield efficiency of MC with S = 7 crop species, compared to SC systems was measured by LER (Mead and Willey 1980):

$$\text{LER} = \sum_{i=1}^{7} (Y_{iMC}/Y_{iSC}) \qquad \text{(Eq. 5)}$$

where Y_{iMC} is the yield of the i^{th} crop in the MC system (see Eq. 2-3), and Y_{iSC} is the yield of the same crop in SC plots. The total number of crop species planted to the poly-crop farm plots, $\Sigma i = 7$. An LER >1 indicates that the amount of land required by the MC system is less than that of the SC farm to produce an equal yield. Conversely, an LER < 1 signifies more amount of land required for the MC farm to be as productive as the SC farm. Although LER is usually estimated using the yield of each crop per unit area, we made use of both $Y_{ir}[a]$ and $Y_{ir}[p]$ for each planting design.

2.5.2 *Area time equivalent ratio* (ATER)

A more realistic comparison of the yield advantage of MC over SC considering the time duration of the component crops in the s$\sum_{i=1}^{7}$em, ATER (Hiebsch and McCollum 1987; Aasim et al. 2008) is calculated as

$$\mathrm{ATER} = \mathrm{ATER}_i \qquad \text{(Eq. 6a)}$$

$$\mathrm{ATER}_i = (\mathrm{Y}_{iMC}/\mathrm{Y}_{iSC})\ (\mathrm{T}_i/\mathrm{T}_L) \qquad \text{(Eq. 6b)}$$

where T_i is the duration (in days) of the growth cycle of the i^{th} crop species, and T_L is the duration of the species with the longest growth cycle. In our experiments, $\mathrm{T}_L = 155$ days.

2.5.3 *Land use efficiency* (LUE)

The arithmetic average of LER and ATER is likely to give a more precise estimation of yield advantage than LER and ATER (Mason et al. 1986):

$$LUE = \frac{(LER+ATER)}{2} \qquad \text{(Eq. 7)}$$

Originally put forward by Mason et al. (1986), the Eq. 7 has been wrongly cited, and also corrupted by several authors. For instance, Yaseen et al. (2014), and Gitari et al. (2020) cited Mead and Willey (1980) as the progenitor of the formula, and also used a spurious formula for LUE, which vitiated the results and interpretations of their experiments. Clearly, these authors and their peer reviewers had ignored to check up the cited works of Mason et al. (1986) and Mead and Willey (1980). Our present work intends to rectify these grave flaws.

3 Results and Discussion

The data of edible biomass yield of each crop from all the SC and MC plots are given in (Deb 2021). The area and edible biomass yield per unit of land area (Y[a]) under each crop species from all plots are given in **Supplementary Tables A1-A4**. Data of edible biomass yield per plant (Y[p]) of all crops are available in (Deb 2021, Table **S1**), and therefore not repeated here.

Fig. **2** and Tables **S1, S2 and S3** show that the yield of each of the 7 crops in MC farms is less than that of the same crops in SC plots. However, LER analyses reveal that the mean yields of the crops planted in mixed designs B and C are considerably greater than when the same crops are planted in either SC plots or in row intercropping (design A), as discussed in detail in Deb (2021). The mean LER for the 8 MC farms planted in design B is 5.15, with a 95% confidence interval of (4.6, 5.7); the mean LER for design C is design is 5.67, with a 95% confidence interval of (5.0, 6.3).

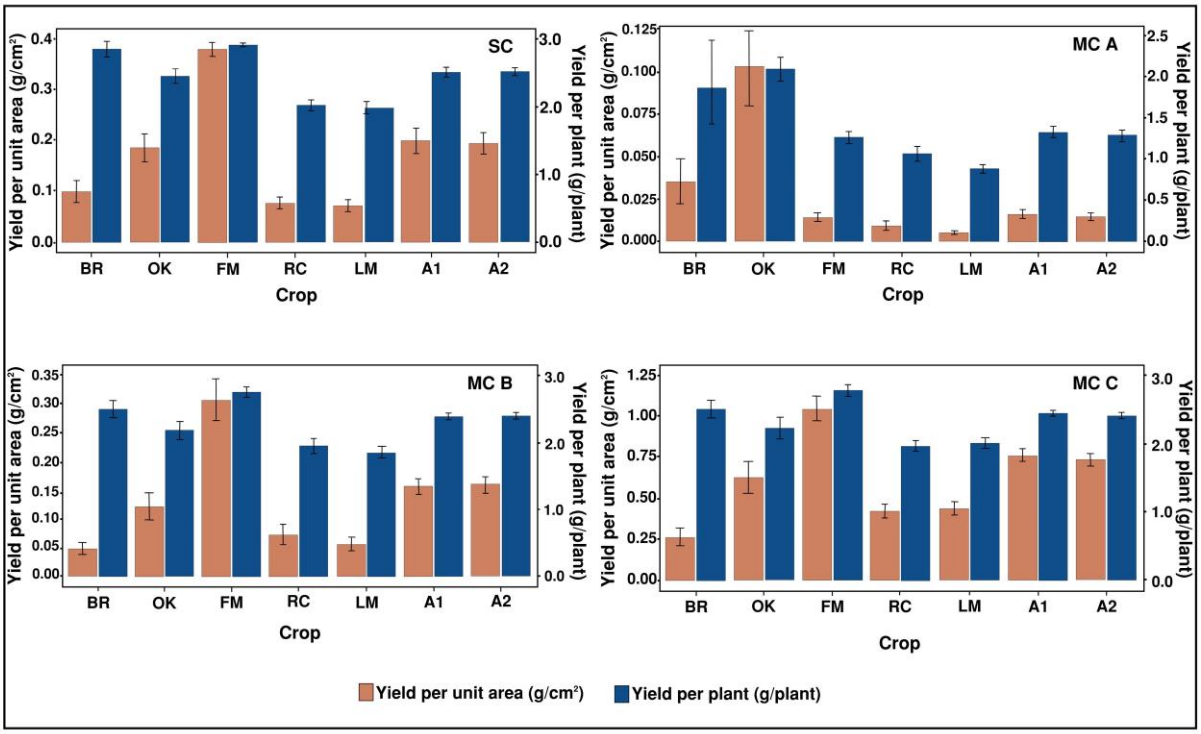


Fig. 2: Mean yield of crops in SC and MC farm plots. Vertical bars show standrd deviations.

Here we focus our analysis to estimations of yield and yield advantage indicators, and highlight that although the values of $Y_{ir}[p]$ and $Y_{ir}[a]$ are widely different, the values of LER using both $Y_{ir}[p]$ and $Y_{ir}[a]$ are identical (Table **1**). While corroborating and expandig upon the findings of a large number of previous studies of MC systems compared to SC systems (e.g. citations given in Sec. 1, Introduction), our findings demonstrate for the first time that the value of LER remains invariant for both biomass per plant and biomass per unit area estimations. In fact, when A_i is identical in all replicate plots ($r = 1,2,3...8$), and the number of crop plants N_i in all replicate plots is identical ($N_i = N_{ir}$), $Y_i\,[a]$ and $Y_i\,[p]$ are mutually derivable:

$$Y_i\,[p] = (A_i/N_i)\,Y_i\,[a] \qquad \text{(Eq. 8a)}$$

$$\text{or, } Y_i\,[a] = \frac{1}{(A_i/N_i)}\,Y_i\,[p] \qquad \text{(Eq. 8b)}$$

We denote the area per plant (A_i/N_i) as the determining constant in the estimation of yield, so long as the intra- and inter-specific spacings are kept invariant across all planting designs. Table 1 shows that LER remains invariant when calculated using both Y[a] and Y[p]. As a corollary, the values of ATER and LUE are also identical in both cases. **Fig. 3** illustrates the mean LER, ATER and LUE for all three MC designs.

Table 1: Land equivalent ratio (LER), Area time equivalent ratio (ATER) and Land use efficiency (LUE) of MC Farms with 7 Crop Species, Planted in 3 Different Designs.

Planting Design	**Mean Yield per Unit Area Estimate**			**Mean Yield per Plant Estimate**		
	LER	ATER	LUE	LER	ATER	LUE
A	1.17	0.74	0.96	1.17	0.74	0.96
B	5.15	3.21	4.18	5.15	3.21	4.18
C	5.65	3.54	4.59	5.65	3.54	4.59

Because LER estimated using Y_i [a] is no different from LER estimated using Y_i [p], the value of ATER and that of LUE also remain invariant for both Y[a] and Y[p], as shown in **Table 1** and **Fig. 3**.

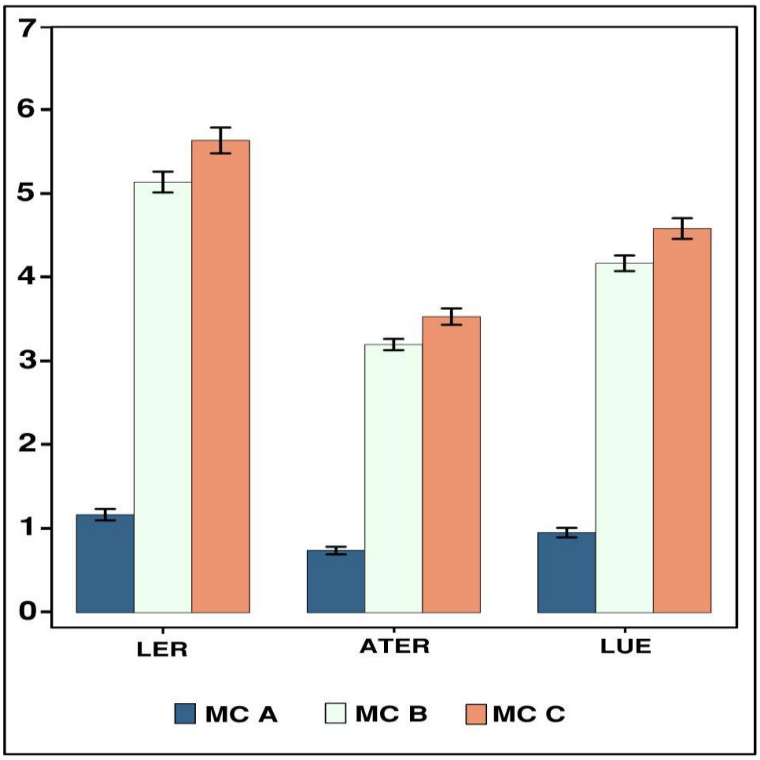


Fig. 3: Mean LER, ATER and LUE, invariant with Y[p] and Y[a] calculations of MC plots with design A, B and C. Vertical bars indicate standard deviations.

4 Conclusion

The primary results of this study are in conformity with previous, albeit limited, number of experimental productivity studies with mixed and polyculture systems, demonstrating that
(a) overall crop yields of MC farms are decidedly superior to that of SC farms; and that
(b) MC with row intercropping is scarcely more productive than monocultures (Deb 2021). This study also demonstrates that LER is a robust indicator of yield advantages, as it remains invariant whether estimated in terms of land area or the number of plants. ATER and LUE, derived from LER, are also robust, and truthfully depict the yield advantage of MC over SC systems.

Estimation of exact land area under a crop species in the MC farm plots is often a rigorous exercise, especially with complex crop planting designs with variable spacings between crop plants. Moreover, there is some scope of confusion in estimation of area, as some authors prefer to calculate the total land area in the MC plot, instead of the "occupied area" (e.g. Liu, X. et al. 2018). In real life situations, where indigenous farmers often randomly sow the seeds of diverse crop species with variable inter-crop spacings in their MC farms, estimation of the land area is a tedious exercise. In such cases of difficulty in measuring yield per unit area (Y_{ir}[a]), yield per-plant (Y_{ir}[p]) estimation is much easier. Thus, LER, ATER and LUE may safely be calculated using Y_{ir}[p], without compromising the exactitude of their values, as demonstrated in Table 3.

Supplementary Material S1: Calculation of crop area in MC plots and derivation of Eq. S4.
Supplementary Tables A1-A4: The area and edible biomass yield per unit of land area (Y[a]) under each crop species from all plots.

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Conflict of Interests

Authors declare that there is no conflict of interest.

Data Availability

All data are freely available on request.

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