Productive Efficiency of Traditional Multiple Cropping Systems Compared to Monocultures of Seven Crop Species: A Benchmark Study

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Introduction

Despite the global trend of agricultural modernization, which promotes crop intensification and upscaling of monocultures of high yielding crop varieties (HYVs), traditional multiple cropping (MC) systems are still in vogue in numerous traditional farms in the global South, primarily maintained by a section of small and medium farmers (IAASTD 2009; La Via Campesina 2010; Panneerselvam et al. 2011; Singh et al. 2002). Traditional MC systems are common in countries with high amounts of subsistence agriculture and low amounts of agricultural mechanization, and is the most suitable for peasant farmers practising low-input farming on small parcels of land (Ngwira et al., 2012; Brooker et al. 2015). These small peasant farms, most of which are family farms, are replete with a wide diversity of crop species (including cereals, fruit trees, tuber plants, vines, herbs, and shrubs in some places), and a legion of vertebrate and invertebrate fauna, constitute an enormously complex ecosystem, and are good examples of agroecology to ensure food security of the poor (Singh et al. 2002; Deb 2020). Multiple cropping is a major component of the practice of agroecology, fostering a rich diversity of crops, both in terms of species and landraces.

MC systems are of two broad types, namely, mixed cropping and intercropping. **Mixed cropping** refers to a system where two or more crops are cultivated in the same piece of land simultaneously. This technique is practised to reduce the risk of total crop failure because of less rainfall or adverse climatic conditions. Most traditional farmers mix the seeds of multiple crops, and sow them in a randomly mixed pattern in rainfed farms.

Intercropping is a technique in which two or more crops are cultivated simultaneously in the same piece of land adhering to a specific row pattern in order to increase the productivity of the crops. Intercropping designs include **row cropping**, in which the component crops are sown in alternate rows, **alley cropping**, where crops are grown in between rows of trees, and **strip cropping**, in which a strip (composed of multiple rows), of one crop are alternated with multiple rows of another crop. **Relay intercropping** is a technique of growing different crops with overlapping life cycles, in which a second crop is planted before the first crop matures. MC also includes **rotational cropping**, in which different crops are cultivated serially, one batch after another.

In most MC systems, a legume cover crop is grown either simultaneously or rotationally with the principal crop species. The cover crop consists of one or more leguminous species, which include pulses for human consumption and species for livestock fodder. Leguminous crops enhance nitrogen availability to plants through root rhizobial activity, and contribute to improving the quality of diet of animals, and enhancing yield and persistence of grasses. The system of multiple cropping, which breaks down the monoculture structure, can provide pest control benefits, weed control advantages, reduced wind erosion, improved water infiltration, and enhance crop productivity (Francis and Porter 2017; Malézieux et al. 2009; Vandermeer 1989).

A major importance of MC systems is that in the event of any environmental vagaries such as too much rain, too late rain or too scanty rain, or a pest outbreak, at least a few of the multiple crops would survive and yield, thereby ensuring food security for the farmer household. That multiple crops in a complex agroecosystem tend to provide greater food security is not obvious in the mainstream discipline of agricultural science, nor does it find a place in agriculture policy, which emphasizes intensive monocultures as the best means of greater food production. This contrasting understanding of traditional agroecology practitioners and academic agronomists was described by Devon Sampson (2018: 45):

> *When I told a friend who runs a diverse, sloping garden on the UC Santa Cruz campus that I was carrying out a study designed to test the hypothesis that households with more diverse gardens were more likely to be food secure, he stared at me for a minute. "How much time and money did you spend on that?" he asked. Farmer friends in California and Yucatan often responded the same way, either slightly confused or incredulous that such an obvious question needed investigation. He finally conceded, "Well, I guess sometimes you have to prove things scientifically."*

While the diversity-productivity link is so obvious to *milpa* farmers of South America and the women home gardeners in South Asia, there is paucity of scientifically validated statistical evidence that agrobiodiversity is associated with greater food security. Of course, there is adequate literature to show that diverse diets are associated with greater food security (Hoddinott and Yohannes 2002) and improved nutrition (Arimond and Ruel 2004; Savy et al. 2005). Multiple cropping systems have been shown to provide multiple ecosystem services (Gaba et al. 2015; Francis and Porter. 2017), especially for superior resource use efficiency (Chen et al. 2017; Liu et al. 2018; Vandermeer 1989) and eliminating crop pest and disease problems (Vendermeer 1989; Chen et al. 2019). The diversity of crop as well as non-crop plants in an agroecosystem influences the composition and abundance of the associated pest complex, their natural enemies, soil invertebrates, and microorganisms, and at the same time is a proven means to reduce crop damage from pest and disease incidences (Francis and Porter 2017; Prasanna et al. 2012; Deb 2020).

A general agroecological understanding of superior productivity potential of MC systems notwithstanding (Altieri 2016; Gliessman 2015; Huang et al. 2015; Liu et al. 2018; Raza et al. 2019), there exist very few published studies to examine crop productivity in multiple cropping systems compared to monocultures of the same crops in the tropics (e.g. Runkulatile 1998; Morales-Rosales and Franco-Mora 2009; Hamzei and Seyedi 2015), and none of these studies examined MC systems involving more than 2 crops. In particular, no study in this respect is available from South Asia. The present study is an attempt to fill this lacuna. The principal objective of this study is to examine the agronomic performance of traditional MC farms growing 7 crops, compared to monocultures of the same crop species, planted in the same edapho-climatic condition within the same geographic location.

Methods and Materials

Study Sites

Five farms in the village of Berdangpadar and five in the village of Lelingpadar, both in Bissamcuttack Block, Rayagada District of southern Odisha were selected for study in the kharif season of 2019. Owing to failure of compliance to the experimental design, data from one farm from each village were not considered, leaving the data from a total of 8 farms, which constitute 8 replications of the experiment. All these farms are owned by indigenous farmers, who use to grow a large number of crop species on their farms every season, unlike the modern farmers in the same area adopting monocrop cultivation of cereals and vegetables.

The experimental set up was pivoted on the crops usually cultivated in the traditional farms, following indigenous agroecological practice, involving $S > 5$ crop species and application of farmyard manure, leaf mulch, mixed compost, and zero synthetic agrochemical input. A total of 7 crop species were selected for this experiment, in addition to a legume cover crop traditionally 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 a plot of monoculture of each of these 7 species grown in a separate plot of the farm land. Thus, in each farm, there were a large test plot for multiple cropping (MC) and 7 smaller plots for a single crop species (SC) grown separately.

It is desirable to have all the species combinations for mixtures of 7 species; however, we are usually not interested in the effects of diversity in communities of large number of species, yet we will never have enough resources to include all possible species combinations for so many species; for $S = 7$ we would have 21 possible two - species combinations, 35 three - species combinations, 35 four- species combinations, and so on. Usually, we are not even able to cover all possible richness values, so we select just 3 of them, and for each of them, select some species combinations as benchmarks.

Monocrop or Sole-Crop (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 monoculture plots were of the same size, and the crop plants were planted at a uniform spacing, with a planting density of
6.25/sq.m. for brinjal saplings (40 cm x 40 cm), and
16/ sq.m for all other crops (25 cm x 25 cm).
A legume crop (cowpea) was planted on the margins of each plot.

Multiple Cropping (MC) Plot Designs:

A total of 7 crop species were chosen for the multiple cropping (MC) farms. The crop species chosen for growing in the MC plots are:

Fruit crops: Brinjal (BR), Okra (OK).
Leaf crop: White Amaranth (A1) and Red Amaranth (A2).
Cereal crops: Finger millet (FM), Little millet (LM), Rice (RC).

The test plot in each farm was divided into 3 subplots (designated A, B, and C), each composed of 21 x 21 cells, as shown in **Fig. 1** below.

Crop plants in design *A* was planted to all 7 species identically arranged in 7 successive rows, repeated 3 times over. Thus, this design actually is a row intercropping system.

Design *B* was non-random mixed cropping, where 7 crop species were planted 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 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

Fig. 1A: The Planting Design A for 7 Crop Species in a 21 x 21 Grid Plot. Numbers in the first column denote respective rows, and the numbers in the top row denote respective columns.

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

Fig. 1B: The Planting Design B for 7 Crop Species in a 21 x 21 Grid Plot. Numbers in the first column denote respective rows, and the numbers in the top row denote respective columns.

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. 1C: The Planting Design C for 7 Crop Species in a 21 x 21 Grid Plot. Numbers in the first column denote respective rows, and the numbers in the top row denote respective columns. [*Legend*: BR: Brinjal, A1: Green Amaranth, A2: Red amaranth, FM: Finger millet, LM: Little millet, OK: Okra, RC: Rice.]

Design C was a different design of non-random mixed cropping. The order of crops was different from that of design *B*, yet each cell repeated the crops diagonally matching the previous row and column, repeating the arrangement 3 times over in both dimensions.

A row of leguminous vine, cowpea was planted in single rows all around the three replicated plots, as a cover crop, to supply nitrogen to the soil.

Quantification of Crop Production:

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 weight of the produce from the monoculture (SC) farms were harvested and weighed together, whereas the produce from the crops from each row and column 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. Similarly, the biomass of the millets harvested on different days were successively added to record the total biomass from each row and column in the plot.

Per-Plant Yield estimation

The distance between crop plants was 25 cm on all sides, except for brinjal, for which the distance was 40 cm. to each plant on all sides. The total area of the sole crop plots was thus uniformly 240 cm (7 rows) x 520 cm (14 columns) for brinjal, and 150 cm x 325 cm for all other crops. On each SC plot, the number of crop plants was 98, uniformly.

The total area of each MC plot was also estimated accordingly at ca. 28 m^2. The total number of crop plants in each MC farm was 441, but the density of each crop was 63/441 or 0.143, uniformly. Thus, the area under each crop in each MC farm was 0.143 x (Total Plot Area).

However, a variable number of plants in each plot died, owing to pest attack. A few saplings also withered because of deficient irrigation after transplanting. Plant mortality was the highest in SC plots. Thus, the area under each crop species according to plant density was not uniform for the crops and in different farm plots. Therefore, instead of measuring the proportionate area under each crop, we counted the number of plants of each crop species in each farm plot, and estimated the per-plant productivity as:

$$Y_{ij} = P_{ij}/N_i \qquad \text{(eq. 1)}$$

where N_i is the number of crop i = 1,2,3, ... 7 and P_{ij} is the total edible biomass output of crop i from the plot j.

Statistical Analyses:

The standard estimation of yield efficiency was measured by Land Equivalent Ratio (LER), following Gliessman (2015):

$$LER = \sum_{i=1}^{7} (Y_{iMC}/Y_{iSC}) \qquad \text{(eq. 2)}$$

where Y_{iMC} is the per-plant yield (in kg) of the i^{th} crop in the multiple cropping system (see eq. 1), and Y_{iSC} is the yield of the same crop in monoculture or sole crop plots. The total number of crops grown in the poly-crop farm plots, $\Sigma i = 7$

The confidence interval of the LER estimates was measured at p = 95%, and estimated as:

$$\text{C.I.} = (\text{M} - z|_{95\%,\, N-1}\, s/\sqrt{R},\ \text{M} + z|_{95\%,\, N-1}\, s/\sqrt{R}) \qquad \text{(eq. 3)}$$

where R = No. of replications, M = mean of replications, s = standard deviation, and z is the critical value for the confidence limit and degree of freedom (= $R - 1$).

Student's t test was performed to estimate the significance of difference between means.

Results and Discussion

The overall edible biomass yield per unit of crop land area from the sole crop (SC) farms is given in **Table 1**, and **Fig. 2** shows the mean yield of the crops and the standard deviation of the means of all the SC farms.

Crop yield was variable in the 8 replicates of monoculture farms, owing to different environmental factors. Rice yield in all the plots was somewhat lower than the average production of the same rice variety, owing to delayed rain and scanty rainfall in the initial weeks. Severe fruit borer attack was responsible for a total yield loss of brinjal fruits in the farm plots A-2 andA-8.

Table 1: Food Production per Plant in Monocrop Farms (Uniform Density).

Productivity (kg/Plant)	Farm Replications: Sole Crop Plots							
Crop	**SC-1**	**SC-2**	**SC-3**	**SC-4**	**SC-5**	**SC-6**	**SC-7**	**SC-8**
Brinjal	1.34	1.521	1.801	0.446	0.389	0.955	0.318	0.243
Okra	0.521	0.463	0.454	0.060	0.228	0.335	0.315	0.223
Finger Millet	0.819	0.802	0.809	0.9005	0.767	0.832	1.032	0.604
Rice	0.086	0.036	0.160	0.079	0.203	0.101	0.155	0.101
Little Millet	0.102	0.030	0.103	0.050	0.099	0.156	0.192	0.122
Green Amaranth	0.286	0.503	0.505	0.167	0.199	0.228	0.548	0.369
Red Amaranth	0.257	0.639	0.316	0.203	0.262	0.300	0.301	0.422

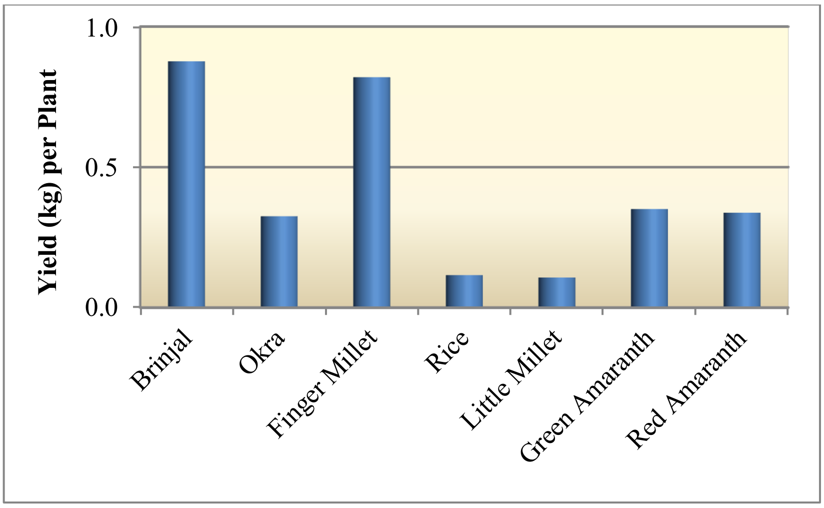

Fig. 2: Mean Yield of Crops in SC Farms. Vertical bars show the standard deviations of the mean.

Table **2** shows crop yields in MC plots as line or strip cropping (design *A*). Among the strip cropped multi-crop plots, two of the plots, namely, A2 and A8, brinjal fruit biomass was entirely lost due to severe pest attack. However, all other plots yielded considerable edible biomass, albeit the quantity was variable. The mean yield estimates are shown in Fig. **3**.

Table 2: Food Production in Multi-Crop Farms, Design *A* (Row Cropping).

Productivity (kg/Plant)	**Farm Replications, Design *A***							
Crop	**A-1**	**A-2**	**A-3**	**A-4**	**A-5**	**A-6**	**A-7**	**A-8**
Brinjal	0.569	0.000	0.964	0.305	0.115	0.262	0.162	0.000
Okra	0.311	0.230	0.282	0.017	0.060	0.167	0.106	0.116
Finger Millet	0.009	0.013	0.027	0.011	0.019	0.014	0.020	0.040
Rice	0.017	0.010	0.037	0.006	0.008	0.004	0.010	0.010
Little Millet	0.007	0.006	0.015	0.006	0.008	0.005	0.006	0.004
Green Amaranth	0.033	0.011	0.038	0.024	0.026	0.012	0.022	0.012
Red Amaranth	0.024	0.012	0.032	0.027	0.029	0.009	0.013	0.013

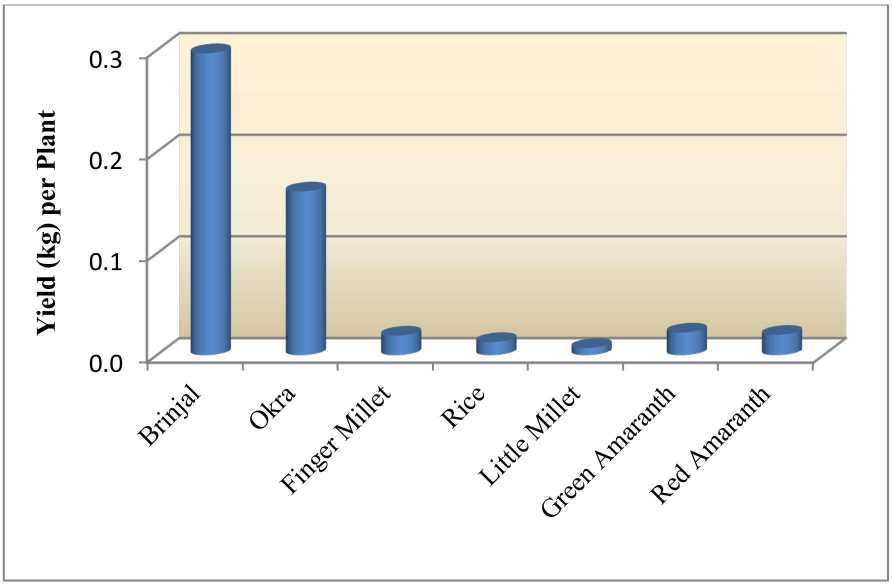

Fig. 3: Mean Yield of Crops in Row Cropped Farms. Vertical bars show the standard deviations of the mean.

Table 3: Food Production in Mixed Crop Farms, Design *B*

Productivity (kg/Plant)	**Farm Replications, Design *B***							
Crop	**B-1**	**B-2**	**B-3**	**B-4**	**B-5**	**B-6**	**B-7**	**B-8**
Brinjal	0.702	0.593	0.779	0.446	0.067	0.276	0.213	0.174
Okra	0.348	0.310	0.225	0.024	0.069	0.225	0.209	0.154
Finger Millet	0.413	0.732	0.883	0.408	0.590	0.722	1.006	0.210
Rice	0.053	0.023	0.111	0.055	0.301	0.093	0.143	0.112
Little Millet	0.067	0.027	0.076	0.049	0.062	0.153	0.168	0.059
Green Amaranth	0.227	0.312	0.314	0.178	0.322	0.214	0.330	0.140
Red Amaranth	0.244	0.360	0.344	0.195	0.313	0.230	0.231	0.144

Table **3** shows the yields in MC farm replications in design *B*, in which each row and column has a different combination, yet the arrangement of the neighbouring crops is the same on both rows and columns. It appears that the productivity per plant is improved in this design, compare to the row cropping system in design *A* (Fig. **4**).

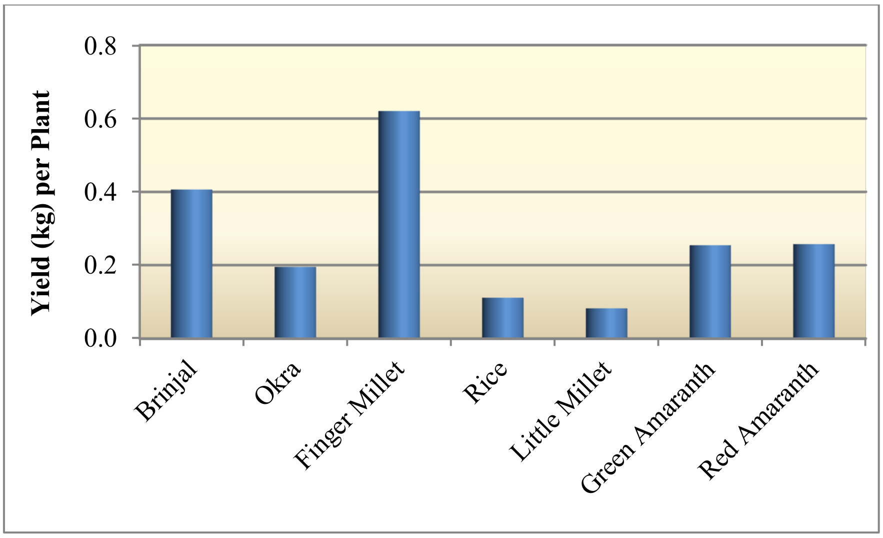

Fig. 4: Mean Yield of Crops in Mixed Crop Farms of Design *B*. Vertical bars show the standard deviations of the mean.

Table 4: Food Production in Mixed Crop Farms, Design *C*.

Productivity (kg/Plant)	**Farm Replications, Design *C***							
Crop	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Brinjal	0.719	0.554	0.901	0.295	0.238	0.175	0.294	0.066
Okra	0.405	0.306	0.251	0.020	0.319	0.156	0.282	0.054
Finger Millet	1.007	1.011	0.713	0.390	0.610	0.325	0.957	0.231
Rice	0.080	0.032	0.105	0.062	0.131	0.145	0.140	0.095
Little Millet	0.098	0.035	0.110	0.071	0.100	0.122	0.163	0.141
Green Amaranth	0.298	0.370	0.381	0.224	0.164	0.320	0.311	0.205
Red Amaranth	0.300	0.312	0.325	0.209	0.206	0.351	0.251	0.148

Table 4 shows the per-plant productivity of crops in mixed crop system replications in design *C*, in which each crop species is surrounded by different other crops. It appears that productivity of the crops has significantly (p <0.01) improved, compared to the row cropped system in design *A*.

The similitude of the crop arrangement between design *B* and design *C* is borne out in the similar pattern of crop yields and in the proximity of the productivity estimates in these two designs (Fig. **4** and Fig. **5**).

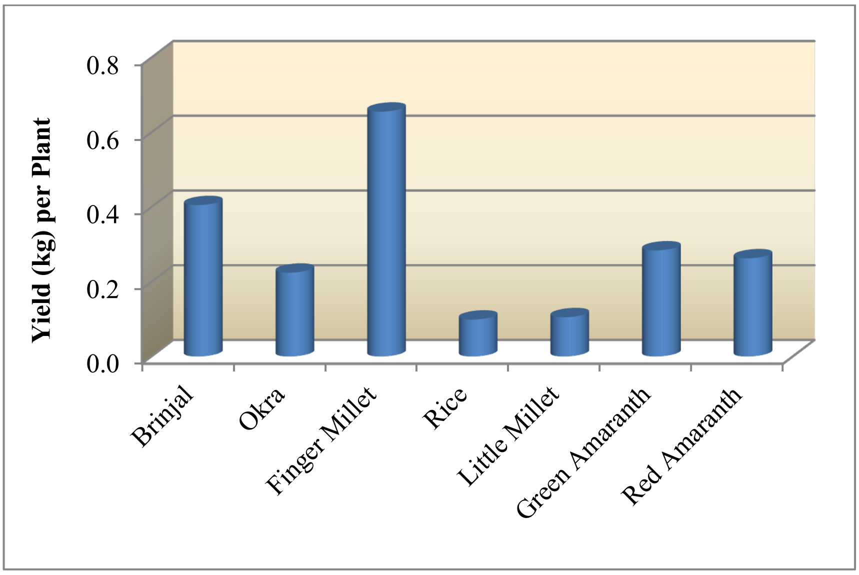

Fig. 5: Mean Yield of Crops in Mixed Crop Farms of Design *C*. Vertical bars show the standard deviations of the mean.

Data contained in Tables 1 to 4 indicate that the crop output per plant of each of the 7 crops in MC farms is less than that cultivated in the monocrop fields. However, the LER analyses of the replicated MC farms draw a different picture. It appears that monoculture of a crop species, whether in the entire farm or in a given row, is likely to yield considerably less than when each crop is flanked by different other crop species on all sides. When the crop species are planted in alternate rows (design *A*), the combined yield of the 7 crops is marginally less in MC farms A-5, A-6 and A-8, while the LER marginally exceeds 1 for all other replications of design *A*, implying no significant difference in yield efficiency from monocultures of the same crops (**Table 5**). The mean LER for all MC farms in design *A* is 1.18, with the 95% confidence interval (0.9, 1.46).

It is noteworthy that the species count in each column (*alpha diversity*) of all the farms in design *A* is no more than 1, although the overall species count of the farms (*beta diversity*) is 7. Thus, the *alpha diversity* in the MC farm of design *A* is extremely low and identical to monoculture farms. In contrast, the *alpha* and the *beta diversity* in design *B* are both 7. Because mixed cropping incorporates greater alpha diversity and complexity than row cropping systems, design *B* and *C* are likely to significantly enhance the synergistic effect on crop productivity.

Table 5. LER Values of Multiple Crops Planted in Design *A* (Row Cropping).
(Values corresponding to each crop is its Partial LER in each replicate)

Productivity (kg/Plant)	**Farm Replications, Design *A***							
Crop	**A-1**	**A-2**	**A-3**	**A-4**	**A-5**	**A-6**	**A-7**	**A-8**
Brinjal	0.42	0.00	0.53	0.68	0.29	0.27	0.51	0.00
Okra	0.60	0.50	0.62	0.28	0.26	0.50	0.34	0.52
Finger Millet	0.01	0.02	0.03	0.01	0.02	0.02	0.02	0.07
Rice	0.19	0.28	0.23	0.08	0.04	0.04	0.07	0.10
Little Millet	0.06	0.21	0.15	0.13	0.08	0.03	0.03	0.03
Green Amaranth	0.12	0.02	0.08	0.14	0.13	0.05	0.04	0.03
Red Amaranth	0.09	0.02	0.10	0.14	0.11	0.03	0.04	0.03
LER	**1.50**	**1.04**	**1.74**	**1.46**	**0.94**	**0.95**	**1.05**	**0.78**

The LER for the 8 MC farms planted in design *B* range from 4.07 to 6.16 (**Table 6**), with a mean of 5.15, with a 95% confidence interval of (4.6, 5.7), implying that the mean productivity per unit area of the 7 crops, when planted in design *B*, is about five times that of the same crops grown in monocultures. In other words, the crop species would require more than five times land area in monoculture to equal the mean productivity of the same crops in the mixed crop farms.

Table 6. LER Values of Mixed Crop Farms Planted in Design *B*.
(Values corresponding to each crop is its Partial LER in each replicate)

Productivity (kg/Plant)	**Farm Replications, Design *B***							
Crop	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**
Brinjal	0.52	0.39	0.43	1.00	0.17	0.29	0.67	0.71
Okra	0.67	0.67	0.50	0.39	0.30	0.67	0.66	0.69
Finger Millet	0.50	0.91	1.09	0.45	0.77	0.87	0.98	0.35
Rice	0.61	0.65	0.69	0.69	1.48	0.92	0.93	1.11
Little Millet	0.66	0.90	0.73	0.98	0.62	0.98	0.87	0.48
Green Amaranth	0.79	0.62	0.62	1.07	1.62	0.94	0.60	0.38
Red Amaranth	0.95	0.56	1.09	0.96	1.19	0.77	0.77	0.34
LER	**4.71**	**4.70**	**5.15**	**5.54**	**6.16**	**5.44**	**5.47**	**4.07**

The degree of heterogeneity in the design *B*, with each row and each column incorporating 8 species, is obviously greater than in design *A*. The LER of the more heterogeneous cropping is correspondingly enhanced. This is also borne out in the MC farms of design *C*, as shown in **Table 7**.

Table 7. LER Values of Mixed Crop Farms Planted in Design *C*.
(Values corresponding to each crop is its Partial LER in each replicate)

Productivity (kg/Plant)	**Farm Replications, Design *C***							
Crop	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Brinjal	0.54	0.36	0.50	0.66	0.61	0.18	0.92	0.27
Okra	0.78	0.66	0.55	0.33	1.40	0.47	0.90	0.24
Finger Millet	1.23	1.26	0.88	0.43	0.80	0.39	0.93	0.38
Rice	0.93	0.89	0.66	0.79	0.65	1.43	0.90	0.95
Little Millet	0.96	1.17	1.07	1.41	1.01	0.79	0.85	1.15
Green Amaranth	1.04	0.74	0.75	1.34	0.82	1.40	0.57	0.55
Red Amaranth	1.17	0.49	1.03	1.03	0.78	1.17	0.83	0.35
LER	**6.64**	**5.57**	**5.44**	**5.99**	**6.07**	**5.83**	**5.90**	**3.90**

The species heterogeneity of each row and column in design *B* and design *C* is identical, and both are more complex than design *A*. However, the different planting orders of the crops in the two designs entail varying degrees of the "neighbor effect" on at least a few crop species. As a result, the LER for the 8 MC farms in design C ranges from 3.9 to 6.64. The mean LER for this design is 5.67, with the 95% confidence interval of (5.0, 6.3). The agroecological implication is that these crop species would require 5.67 times land area in monocultures to equal the mean productivity of the same crops in the MC farms, planted in design *C*.

Conclusion

The results of this study is in conformity with previous, albeit limited, number of experimental productivity studies with mixed and multiple cropping systems. In natural ecological systems, it has been shown that biomass production can be elevated with increasing biodiversity (Flombaum and Sala 2008; Fridley 2002). For example, Tilman *et al.* (2001) showed that biomass production from experimental fields in which 16 grass species were grown in a mixture was increased by 2.7 times compared to those in which single species were grown alone. Similar biomass output is likely to be significantly greater in MC systems than in monocultures, and a larger the number of crop species is likely to increase this biomass enhancing effect. However, there is a paucity of experimental field studies in the Indian subcontinent, to examine these effects in traditional MC systems incorporating 5 or more crop species. This study provides a reliable experimental evidence of agronomic yield benefits from traditional MC system over monocultures.

In a recent study in China, Li et al. (2009) tested intercropping of tobacco, maize, sugarcane, potato, wheat and broad bean – either by relay cropping or by mixing crop species based on differences in their heights, and practiced these patterns on 15,302 hectares in ten counties in Yunnan Province, China. They showed that some specific crop combinations increased crop yields for the same season between 33.2 and 84.7% and reached a land equivalent ratio (LER) of between 1.31 and 1.84. In our study, we tested LER for 7 crops in different planting designs, for which the value ranged between 1.88 and 2.69. This study is the first empirical validation of traditional MC systems with combination of 7 crop species commonly cultivated in indigenous farms of southern Odisha. We have examined the effect of different planting designs of the same 7 crops in the same edapho-climatic condition in the same season, and identified the best cropping design to significantly enhance productivity.

The salient findings of this study may be described under three rubrics.

A. *Firstly*, this study corroborates the agoecological understanding that MC farms are generally more productive than monocultures. The results of our study suggests that the much-discussed "scale effect" of yield, associated with monocultures in modern agriculture may not be ubiquitously applicable. Rather, small MC farms may be considerably more productive than large monocultures – a fact that corroborates the emerging understanding that small indigenous farmers can ensure food security better than monocultures (GRAIN 2014). However, the degree of yield enhancement compared to monocultures varies with the combination of crops in the MC farm.

B. This leads to a *second* important finding: not all MC farms are equally productive; rather, their productivity significantly depends on the specific crop combination and planting design. Multiple cropping can incorporate row cropping (design *A* in our experiment), in which each row or column consists of a line of a single crop species, so that each row or column is a monoculture, although the overall farm is sown to multiple crops. In this case, the *alpha diversity* of each line of crop is just 1, just as in a monoculture plantation. Considering the severe crop damage in two replications of the row cropped farms (Design *A*), we eliminated brinjal and recalculated the LER, which showed no appreciable difference between the two means ($t = 0.42$, $p > 0.1$). This indicates that whether 6 or 7 crops are grown in row cropping, the overall crop productivity scarcely exceeds that of monocultures, and therefore, LER is not appreciably greater than 1.

In contrast, a randomly, semi-randomly, or uniformly heterogenous plantation of multiple crops in each row and column is obviously more diverse in composition, and hence the impact of diversity on productivity is likely to be more pronounced. This is exactly evidenced in our results of MC farms of design *B* and *C*. As Fig. 6 shows, the difference between the mean LER of farms of design *A* is prominently different from that of both either of the mixed cropping design *B* and design *C* (p <0.01).

C. MC farms of both design *B* and design *C* are equally rich in *alpha* and *beta* diversity, and there is no significant difference between the mean values of LER of the two designs (t = 1.43, df = 14, p = 0.174). **Fig. 6** summarizes this finding, and also indicates that the values of LER are significantly different from each other. The difference indicates a different dimension of complexity, beyond the species count. This constitutes a *third* important finding of this study: the specific physiological interactions between neighbouring crop species may entail different degree of productivity of the adjacent crops.

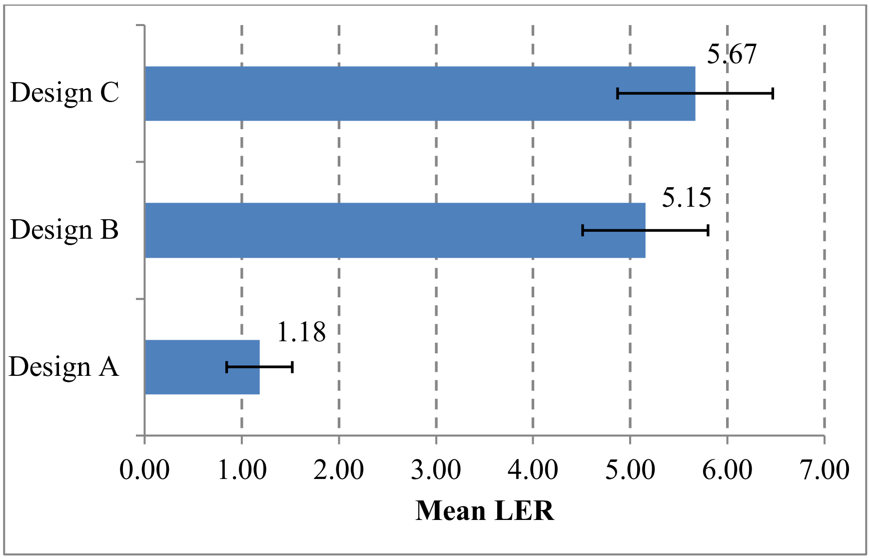

Fig. 6: Mean Values of LER for Different Designs of Crop Planting in Multiple Cropping Farms. Horizontal bars represent ±1 SD.

Table 8: Crop-Wise Mean Partial LER Values for 3 Planting Designs of MC Farms.

Crop	Crop-wise Partial LER		
	Design A	**Design *B***	**Design *C***
Brinjal	0.297	0.406	0.405
Okra	0.161	0.195	0.224
Finger Millet	0.019	0.621	0.656
Rice	0.013	0.111	0.099
Little Millet	0.007	0.083	0.105
Green Amaranth	0.022	0.255	0.284
Red Amaranth	0.020	0.258	0.263

In mixed cropping, "neighbour effects" including allelopathy, root competition, and mutually beneficial interactions between the neighbouring species are often observed. Crop species of the same taxonomic family often tend to have competitive interaction. Specifically, cereals (belonging to family Poaceae) tend to have allelopathic effects, and may suppress each other's productivity. In order to avoid or minimize negative neighbor effects, the thumb rule is not to plant crops of the same family next to each other. In our experiment, design *B* farms planted rice next to finger millet uniformly, whereas in design C farms had rice and little millet as neighbors. Nevertheless, the data in Tables 3 and 4 indicate that the mean yields of the crops in the two designs of mixed cropping are not statistically significant. Table 8 indicates that while the mean partial LERs each crop in design *A* is different ($p < 0.05$) from the corresponding values of both design *B* and design *C*, there is no perceptible difference between the latter two designs of mixed cropping.

This study strongly suggests that mixed cropping incorporating a crop combination similar to either design *B* or design *C* is likely to significantly improve productivity compared to not only monocultures, but also to row MC of design *A* (row cropping). This recommendation to farmers warrants consolidation from further multi-location trials, based on the findings of our benchmark study. Further combinations of the same crops may also elucidate the appropriate crop associations and may also detect certain "neighbor effects" which are not evident in this study.

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