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Assessing long term impact of nutrient management and rainfall variability on the agroecological resilience of maize (*Zea mays*)- wheat (*Triticum aestivum*) system in NW India

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ABSTRACT

A long-term (2000-2010) field experiment was carried out in the lower Shiwalik foothills of Punjab to study the carry over effect of organic manures and fertilizers on the productivity of maize (*Zea mays* L.)- wheat (*Triticum aestivum* L.) cropping system for efficient N management and resource use under rainfed conditions and to develop predictive models describing relationship between yields and seasonal rainfall. N management strategies involving combined application of 15 kg N/ha either through compost or leucaena loppings along with 20 kg N/ha through inorganic fertilizer for maize-wheat cropping sequence utilized growth resources most efficiently and maintained stable yield performance culminating in significantly higher system productivity, better resource use efficiencies and sustainable yield index, suggesting partial N substitution through compost or locally available plant material. The regression models developed to predict the effects of N sources on crop yields using monthly rainfall would be of interest to estimate the yield at a given level of rainfall with the likely fluctuation (as error) particularly under rainfed conditions.

Key words: Maize-wheat, Nitrogen, Prediction model, Rainfall, Sustainability

Worldwide 82% of the cultivated land represents rainfed ecosystem (Laux *et al.* 2010). Covering 58% of the net sown area and contributing 40% in national food basket, rainfed farming forms an important component of Indian agriculture (Srinivasa Rao *et al.* 2014). The diverse challenges and biophysical constraints, viz. erratic and undependable rainfall, excess and deficit moisture within the same season, erosion prone poor fertility soils, deep ground water table, harsh thermal regime, constricted input use and low technology adoption often limits crop productivity to a larger extent under dry farming conditions (Sheoran *et al.* 2008, Sharma *et al.* 2010).

Intensive cultivation, inadequate and imbalanced crop nutrition often leads to the impoverishment of soil fertility/ quality, and decline in crop productivity (Van Eerd *et al.* 2014). Increasing fertilizer costs, unstable crop production particularly under rainfed conditions coupled with environmental concerns augment the need to manage fertilizer N more judiciously enabling maximum energy conservation and profitability (Hirel *et al.* 2007). Synchronizing N application with crop demand and improving its supplying capacity are aimed to enhance the nutrient use efficiency (Fischer 1998). All these subsequently call for substituting part of chemical fertilizers by locally available low input cost organic materials so as to maintain soil health and sustain crop production with minimum soil and environmental pollution and degradation (Lelei *et al.* 2009). However, total dependence on organic fertilization as a whole can sustain only one-fourth of the nutrient needs by utilizing all the available organic resources, is still a question mark. Thereby, it is necessary to develop an integrated production system targeting maximum productivity and sustainable soil health (Kannan *et al.* 2013).

Nitrogen (N) is important plant nutrient for crop growth and development. The current fertilizer N recommendations are based on individual crop ignoring the carry over effect of manures/fertilizers on the succeeding crops. Therefore, there is a need to follow holistic approach considering cropping system as a whole for efficient utilization of residual and cumulative soil nutrient balance along with added fertilizers. Recommendations of fertilizer N requirement of individual crops have been made but database for cropping system as a whole in Indian context is still not adequate enough to recommend nutrient requirements for crops based on system approach. Hence,

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an attempt was made to develop a suitable integrated nutrient supply system for the prominent maize (*Zea mays* L.)-bread wheat (*Triticum aestivum* L.) cropping system in dry sub-humid zone of north-western India and similar environments.

MATERIALS AND METHODS

The experimental site is located at RRSKA, Ballowal Saunkhari, SBS Nagar (31°6'5" N latitude, 76°27'26" E longitude) in lower Shiwalik foothills of Punjab, India. The average annual rainfall is around 1,130 mm of which nearly 80% is received during a short time span of July to mid-September associated with high relative humidity and comparatively lower solar radiation. Winter and spring seasons, remains dry and receive few showers of cyclic rains. A long term field experiment (2000-2010) with eight treatments replicated thrice in randomized block design (RBD) in fixed plots was carried out with maize and wheat as the test crops except in 2007-08. The treatments were; T_1=control, T_2=40 kg N/ha through inorganic source, T_3=25 kg N/ha through compost, T_4=15 kg N/ha through compost + 10 kg N/ha through inorganic source, T_5=15 kg N/ha through compost + 20 kg N/ha through inorganic source, T_6=15 kg N/ha through *leucaena* loppings + 10 kg N/ha through inorganic source, T_7=15 kg N/ha through *leucaena* loppings + 20 kg N/ha through inorganic source and T_8=15 kg N/ha through compost + 10 kg N/ha through *leucaena* loppings. The soil of the experimental site was typical *fluventiv ustochrept* with sandy loam texture, low in organic carbon (0.21±0.03%) and available N (152.6±12.8 kg/ha $KMnO_4$-N), medium in available P (15.1±1.8 kg/ha Olsen-P), high in available K (364.2±20.2 kg/ha NH_4OAC-K) and slightly alkaline (8.2±0.04). A uniform dose of 20 kg P_2O_5/ha in both crops was applied at sowing in all the treatment plots. Inorganic N (urea, 46% N) as per treatments was applied in two splits, i.e. half at sowing time of each crop and the remaining half at knee high stage in maize and with the receipt of winter rains (December/early January) in wheat. Nitrogen application through organic source (soil incorporation of compost/green leaf loppings of *leucaena*) on dry weight basis was done about 15-20 days prior to sowing. The mean moisture content of the compost ranged between 55.7-62.3% while N, P and K contents (on oven dry weight basis) varied from 0.62-0.72, 0.28-0.35 and 0.69-0.81%, respectively. The details of agronomic practices and sowing and harvesting schedule along with seasonal rainfall pattern are presented in Table 1 and 2. Total crop growth period (CGP), considered as the period from emergence to physiological maturity of maize crop ranged between 83 to 93 days (mean of 88 days) over the study period with coefficient of variation (CV) of 3.7%. In wheat, the total CGP ranged from 142 to 159 days (mean of 149 days) with CV of 4.0%.

To assess the effect of rainfall on crop yields, treatment-specific linear regression models were developed using grain yields and total monthly rainfall (RF) received (Draper and Smith 1998). The expressions of linear regression model for both maize and wheat are given as:

Table 1 An account of agronomic practices followed for both crops

Crop season	*Kharif* (July-October)	*Rabi* (October/ November-April)
Crop/variety	Maize/Megha	Wheat/PBW 175
Sowing method	Dibbling	Pora
Seed rate	20 kg/ha	100 kg/ha
Spacing	45 × 22.5 cm	30 cm
Weed management	Atrazine @ 1.0 kg a.i./ha PE	2,4-D @ 0.5 kg a.i./ha as PoE

†The SSP, single super phosphate, $Ca(H_2OP_4)_2.H_2O$, containing 16% P_2O_5 was applied to both crops at the time of sowing.

Maize: $\Upsilon = \pm\,\alpha \pm \beta_1$(Jun RF) $\pm\,\beta_2$(Jul RF) $\pm\,\beta_3$(Aug RF) $\pm\,\beta_4$(Sep RF) (1)

Wheat: $\Upsilon = \pm\,\alpha \pm \beta_1$(Oct RF) $\pm\,\beta_2$(Nov RF) $\pm\,\beta_3$(Dec RF) $\pm\,\beta_4$(Jan RF) $\pm\,\beta_5$(Feb RF) $\pm\,\beta_6$ (Mar RF) (2)

where, α is intercept and βs are the slopes or regression coefficients measuring the change in yield for a unit change in the rainfall.

The sustainability yield index (SYI) 'η' of a treatment 't' over a period of 'n' years was derived to identify the sustainable N management practice for each crop individually as well as for the system as per Vittal *et al.* (2003).

$$\eta_t = (Y_t - \sigma)/Y_{max}$$

where, Y=estimated mean yield of t; s=estimate of error based on regression of yield with rainfall; Y_{max}=observed maximum yield in the experiment over the years.

Production efficiency (Patil *et al.* 1995) and rainwater use efficiency (Rockstrom *et al.* 2003) were determined for each treatment using crop seasonal rainfall, maturity duration and grain production. Individual parameters were subjected to one-way analysis of variance (ANOVA) technique according to the randomized block design using statistical programme SAS (Version 9.2, SAS Institute Inc., Cary, NC, USA) and OPSTAT (www.hau.ernet.in/opstat.html). Treatment means were compared using Duncan's Multiple Range Test (DMRT) at significance level of $P<0.05$.

RESULTS AND DISCUSSION

Rainfall pattern and crop yields

Under rainfed farming situations, total precipitation received during crop growing season is critical to decide the fate of crop production. Crop seasonal rainfall received over the study period (2000-10) remained below normal in 7 out of 9 crop years in both seasons with the exception of 2000 and 2008 in *kharif* season and 2004-05 and 2006-07 in *rabi* season (Table 2). The actual precipitation at the experimental site ranged between 516 mm (2009) to 1061 mm (2008) with coefficient of variation (CV) of 28.7% in maize (*kharif* season, June-September) while it varied from 71 mm (2009-10) to 410 mm (2004-05) with 70.7% CV in

Table 2 Sowing and harvesting schedule, crop growth period and temporal distribution of rainfall during the study period (2000-01 to 2009-10)

Parameter	2000-01	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07	2008-09	2009-10	Mean	CV (%)
Maize											
Sowing date	6 Jul	4 Jul	4 Jul	5 Jul	7 Jul	4 Jul	15 Jul	14 Jul	22 Jul	9 Jul	
Harvesting date	1 Oct	30 Sep	3 Oct	27 Sep	28 Sep	4 Oct	6 Oct	10 Oct	16 Oct	4 Oct	
Crop growth period (days)	87	89	92	85	84	93	84	89	87	88 (±3.3)	3.7
Total rainfall (mm)¥	1050	852	711	616	585	567	600	1061	516	729 (±209.3)	28.7
Crop seasonal rainfall (mm)‡	841	586	512	369	539	481	398	577	356	517 (±148.8)	28.7
Seasonal variability (%)†	16.4	–5.5	–21.2	–31.7	–35.2	–37.1	–33.5	17.6	–42.8		
Grain yield (kg/ha)	1788	2331	2557	2260	2055	3126	2256	3006	2654	2448(±433.4)	19.1
RWUE (kg/ha/mm)	2.1	4.0	5.0	6.1	3.8	6.5	5.7	5.2	7.5	4.7 (±1.61)	33.9
PE (kg/ha/mm)	20.6	26.2	27.8	26.6	24.5	31.6	26.9	33.8	30.5	27.8 (±4.27)	15.3
Wheat											
Sowing date	14 Nov	17 Nov	8 Nov	14 Nov	7 Nov	6 Nov	27 Nov	5 Nov	17 Nov	13 Nov	
Harvesting date	5 Apr	10 Apr	14 Apr	6 Apr	14 Apr	3 Apr	21 Apr	4 Apr	9 Apr	10 Apr	
Crop growth period (days)	142	145	158	145	158	149	146	150	144	149 (±5.9)	4.0
Total rainfall (mm)§	111	73	155	154	410	100	292	96	71	162 (±114.8)	70.7
Crop seasonal rainfall (mm)‡	43	67	112	139	173	96	239	72	30	108 (±66.8)	61.9
Seasonal variability (%)†	–41.6	–61.4	–18.7	–19.8	–115.7	–47.5	53.8	–49.6	–62.5		
Grain yield (kg/ha)	636	1705	1965	1800	2107	698	2333	1753	1592	1621(±585.3)	36.1
RWUE (kg/ha/mm)	14.8	25.4	17.5	13.0	12.2	7.3	9.8	24.3	53.1	15.0 (±6.54)	92.8
PE (kg/ha/mm)	4.5	111.8	12.4	12.4	13.3	4.7	16.0	11.7	11.1	10.9 (±3.83)	35.2

Values in parentheses indicate ±standard deviation; CV-coefficient of variation; ¥total rainfall received during June to September months; §total rainfall received during October to March months; ‡actual rainfall received from sowing to harvesting time in a particular season (*kharif/rabi*), †seasonal rainfall deviation from long-term normal rainfall of 25 years.

wheat (*rabi* season, October-April). The rainfall data presented in Table 1 indicated -42.8 to 17.6% variability in *kharif* season and -62.5 to 115.7% in *rabi* season as against the anticipated normal (25 years) seasonal rainfall of 902 and 190 mm in the respective seasons. However, the spatio-temporal distribution of rainfall from sowing to harvesting indicated -29.2 to +44.0% (with mean value of 729 mm) and -56.1 to +152.3% (with mean value of 162 mm) variability in *kharif* and *rabi* seasons, respectively. Within cropping seasons, mean maximum rainfall of 226 mm was received in August (CV 40.6%) month with 32.7% contribution to the total rainfall followed by July (215 mm, CV 60.7%) during *kharif* season while, November was observed to be the least rainfall contributing (0.9%) month during *rabi* season.

Higher variation in total rainfall across seasons (Table 2) reflected in greater yield fluctuations across different treatments in both crops (Table 3). Maize grain yield varied significantly over the years following decreasing trend of rainfall 2005>2008>2009>2002>2001>2003>2006>2004>2000 (Table 2). Continuous heavy downpour immediately after sowing (SWM 28-30) in 2000 and long dry spell at the terminal stage (SMW 35-39) coinciding reproductive phase in 2004 were the main reasons for lower maize yields. In contrast, better spatio-temporal distribution of rainfall ensuring better germination and desired crop stand followed by good quantum of rainfall during seed filling periods (upto 38th SMW) justified comparatively higher maize yields in 2005, 2008 and 2009. The wheat yields obtained were relatively poor in 2000-01 and 2004-05. Early cessation of rains in 2000-01 (36th SMW) and 2005-06 (38th SWM) during *kharif* season might have culminated in very low residual soil profile moisture for sowing of succeeding wheat crop resulting in its poor seed germination and plant stand. Thereafter, the crop could not be further sustained due to long dry spell up to 52nd SMW resulting in poor growth and development and ultimately resulting in significantly lower crop yields of wheat. Contrarily, late monsoonal rains extended even up to third week of October in 2006-07 (43rd SWM), mid-October in 2004-05 (41st SMW), 2002-03 (41st SMW), 2008-09 (41st MW) and last week of September in 2003-04 (39th SMW39) *rabi* seasons offered relatively better residual soil profile moisture for sowing, proper germination and better crop stand of succeeding wheat crop. Furthermore, the receipt of winter showers in December-mid January (in different cropping seasons) proved beneficial in efficient utilization of second dose of N (top dressed) for better nutrient availability and subsequent utilization for plant growth and development. Favourable weather conditions in terms of rainfall availability coinciding grain filling periods particularly in February-March might have contributed towards more assimilation of metabolites and subsequently paved way for their efficient translocation from vegetative plant parts to reproductive organs (better source: sink ratio) resulting in better expressions of yield components and improvement in wheat yields following the order of 2006-07>2004-05>2002-

03>2003-04>2008-09>2001-02>2009-10>2005-06>2000-01 (Table 2).

Effect of manuring

Maize

Application of 40 kg N/ha through inorganic source (T_2) registered the highest mean grain yield (2805 kg/ha with CV of 20.9%) indicating 65.3% yield superiority in comparison to unfertilized control (Table 3). This treatment was at par with treatments receiving 15 kg N/ha through compost (2758 kg/ha, CV 16.9%) or *leucaena* (2698 kg/ha, CV 16.7%) supplemented with 20 kg N/ha in the form of inorganic source (T_5/T_7). Substantial yield gains (13.1%) in *kharif* maize could be realized with partial substitution through inorganic source such as urea (T_4) compared to sole application of compost (T_3). Nitrogen supply through inorganic source (T_2) and organic (compost/*leucaena*) source either individually (T_3 and T_8) or in combination (T_4, T_5, T_6, T_7) resulted in significantly higher straw yield (10.1-30.6%), harvest index (3.2-4.3%) and resource use efficiencies (34.0-58.1%) when compared with control (T_1). Integrated application of 15 kg N/ha through compost with 10-20 kg N/ha through inorganic source/urea (T_4 and T_5) resulted in statistically better expressions of growth (plant height, cob girth and length) and yield components (grains per cob and 1000-grain weight) as compared to sole N supplied through inorganic source i.e. urea (T_2) and/or compost/*leucaena* either independently or their integrated application with inorganic source/urea (T_3, T_6, T_7, T_8).

Wheat

All the N management practices (dose/source) proved significantly superior (*P<0.05*) to unfertilized control (T_1) with yield improvement ranging between 21.6-44.4% (Table 3). Application of 25 kg N/ha solely through compost (T_3) resulted in 1521 kg/ha yield with CV of 37.4% and was at par with the treatment receiving 25 kg N/ha through *leucaena* (T_8). Substantial gain in yield was noticed when part of the N supply through compost was substituted with inorganic fertilizer. Yield improvement to the tune of 12.8% was recorded with application of 15 kg N/ha through compost in combination with 10 kg N/ha through inorganic source/urea (T_4) in comparison to the application of 25 kg N/ha entirely through compost (1717 kg/ha, CV 39.5%). Integrated application of 15 kg N/ha through *leucaena* +10 kg N/ha through urea (T_5) enhanced wheat yield (1808 kg/ha, CV 37.6%) by 7.4% compared to 25 kg N/ha entirely

Table 3 Effect of dose and source of N application on the growth and yield of maize and wheat under rainfed conditions (pooled data)

Parameter	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	Mean	P-value
Maize										
Grain yield (kg/ha)	1697 ^{d}	2805 ^{a}	2276 ^{c}	2574 ^{b}	2758 ^{a}	2470 ^{b}	2698 ^{a}	2305 ^{c}	2448 (±361.8)	<0.0001
Straw yield (kg/ha)	7170 ^{d}	8619 ^{abc}	7895 ^{c}	9082 ^{ab}	9346 ^{a}	8401 ^{bc}	9362 ^{a}	8007 ^{c}	8485 (±774.4)	<0.0001
Harvest index (%)	20.5 ^{b}	23.8 ^{a}	24.1 ^{a}	24.7 ^{a}	23.7 ^{a}	24.8 ^{a}	23.7 ^{a}	23.7 ^{a}	23.6 (±1.34)	<0.0001
RWUE (kg/ha/mm)	3.53 ^{d}	5.38 ^{ab}	4.73 ^{c}	5.60 ^{a}	5.58 ^{a}	5.23 ^{b}	5.57 ^{a}	4.80 ^{c}	5.05 (±0.70)	<0.0001
PE (kg/ha/day)	19.29 ^{d}	29.45 ^{ab}	25.84 ^{c}	30.50 ^{a}	30.50 ^{a}	28.37 ^{b}	30.38 ^{a}	26.18 ^{c}	27.56 (±3.83)	<0.0001
Plant height (cm)	173.5 ^{b}	181.1 ^{a}	180.8 ^{a}	181.2 ^{a}	185.5 ^{a}	179.7 ^{a}	183.9 ^{a}	179.9 ^{a}	180.7 (±3.53)	<0.0001
Cob girth (cm)	11.4 ^{b}	12.0 ^{a}	11.9 ^{ab}	12.2 ^{a}	12.4 ^{a}	12.1 ^{a}	12.4 ^{a}	11.8 ^{ab}	12.0 (±0.33)	0.0023
Cob length (cm)	11.4 ^{d}	12.3 ^{abc}	12.1 ^{bcd}	12.9 ^{ab}	12.8 ^{ab}	12.3 ^{abc}	13.1 ^{a}	11.9 ^{dc}	12.4 (±0.57)	<0.0001
Grains/cob	324.1 ^{e}	355.5 ^{bcd}	343.5 ^{ed}	379.8 ^{ab}	372.5 ^{abc}	358.7 ^{bcd}	394.9 ^{a}	349.3 ^{dc}	359.8 (±22.24)	<0.0001
1000-grain weight (g)	140.0 ^{d}	152.9 ^{abc}	147.9 ^{c}	154.5 ^{abc}	155.6 ^{ab}	152.2 ^{abc}	158.6 ^{a}	148.7 ^{bc}	151.3 (±5.75)	<0.0001
Wheat										
Grain yield (kg/ha)	1252 ^{f}	1702 ^{bc}	1521 ^{e}	1717 ^{abc}	1808 ^{a}	1634 ^{cd}	1762 ^{ab}	1569 ^{de}	1621(±177.1)	<0.0001
Straw yield (kg/ha)	2405 ^{e}	3125 ^{bcd}	2894 ^{d}	3370 ^{ab}	3494 ^{a}	3221 ^{abc}	3360 ^{ab}	2969 ^{dc}	3105 (±349.2)	<0.0001
Harvest index (%)	33.9	34.5	34.8	33.9	34.6	34.5	35.1	35.5	34.6 (±0.55)	<0.0001
RWUE (kg/ha/mm)	15.66 ^{d}	20.70 ^{ab}	18.53 ^{c}	20.83 ^{a}	21.42 ^{a}	19.64 ^{bc}	21.07 ^{a}	18.99 ^{c}	19.60 (±1.90)	<0.0001
PE (kg/ha/day)	8.41 ^{d}	11.02 ^{b}	10.21 ^{c}	11.56 ^{ab}	12.05 ^{a}	10.96 ^{b}	11.82 ^{a}	10.51 ^{bc}	10.82 (± 1.16)	<0.0001
Plant height (cm)	71.7 ^{b}	76.0 ^{a}	75.2 ^{ab}	77.5 ^{a}	77.5 ^{a}	75.6 ^{a}	77.5 ^{a}	74.7 ^{ab}	75.7 (±1.97)	<0.0001
Spike length (cm)	8.99 ^{b}	9.59 ^{a}	9.45 ^{ab}	9.28 ^{ab}	9.61 ^{ab}	9.26 ^{a}	9.38 ^{ab}	9.51 ^{ab}	9.4 (±0.21)	<0.0001
Effective tillers/mrl	60.0 ^{c}	68.4 ^{ab}	63.2 ^{bc}	71.2 ^{a}	69.3 ^{a}	66.8 ^{ab}	69.6 ^{a}	67.4 ^{ab}	67.0 (±3.69)	<0.0001
Grains/spike	26.2 ^{b}	28.3 ^{ab}	27.5 ^{ab}	28.5 ^{ab}	29.2 ^{a}	29.0 ^{a}	29.2 ^{a}	28.3 ^{ab}	28.3 (±1.01)	0.0411
1000-grain weight (g)	42.0 ^{b}	42.8 ^{ab}	43.0 ^{ab}	43.3 ^{ab}	43.5 ^{ab}	42.4 ^{ab}	43.9 ^{a}	42.7 ^{ab}	43.0 (±0.61)	<0.0001

Values in parentheses indicate ±standard deviation; RWUE-Rain water use efficiency; PE-Production efficiency; Data followed by different lower-case letters differs significantly (Duncan's Multiple Range Test, *P<0.05*, with in row comparison). T_1=Control; T_2=40 kg N/ha through inorganic source; T_3=25 kg N ha^{-1} through compost; T_4=15 kg N/ha through compost + 10 kg N/ha through inorganic source; T_5=15 kg N/ha through compost + 20 kg N/ha through inorganic source; T_6=15 kg N/ha through *leucanea* loppings + 10 kg N/ha through inorganic source; T_7=15 kg N/ha through *leucanea* loppings + 20 kg N/ha through inorganic source; and T_8=15 kg N/ha through compost + 10 kg N/ha through *leucanea* loppings.

through compost (T_3) and by 5.3% over application of 15 kg N/ha through *leucaena* + 10 kg N/ha through urea (T_4). Highest wheat yield was obtained with T_5 treatment although it was statistically at par with T_7 and T_4 treatments. Differences among treatments for spike length, grains per spike and 1000-grain weight were found inconspicuous though improved with N application when compared with unfertilized control (Table 3).

System productivity, sustainability yield index (SYI) and efficiency indices

Irrespective of the dose, nitrogen application through inorganic (urea) and organic (compost/*Leucaena leucocephala*) source either individually or in combination resulted in significantly higher ($P<0.05$) maize equivalent yield (MEY) over unfertilized control under rainfed conditions in all the years of experimentation and in pooled analysis (Table 3). System productivity in terms of maize equivalent yield (MEY) ranged between 3199-4942 kg/ha with 28.4-54.5% yield superiority under different N management treatments over the control (Figure 1). Highest MEY (4942 kg/ha) with RWUE (8.36 kg MEY/ha/mm) and PE (20.87 kg MEY/ha/day) was recorded with 15 kg N/ha through compost + 20 kg N/ha through inorganic source/urea (T_5) though it was found to be at par with T_2 (MEY 4866 kg/ha; RWUE 8.25 kg MEY/ha/mm; PE 20.54 kg MEY/ha/day) and T_7 (MEY 4818 kg/ha; RWUE 8.16 kg MEY/ha/mm; PE 20.37 kg MEY/ha/day). Nitrogen applied solely either exclusively through organic source (T_3) or in combination (T_8) could not match with the either of treatments of integrated (T_4-T_7) approach. Combining application of organic and inorganic fertilizers increases synchrony and reduces losses by converting inorganic N into organic forms. Integrated N application might have resulted in continuous N supply along with other important mineral nutrients over an extended period of crop growth which in turn provided substantial boost to the growth and yield parameters culminating in better maize and wheat yields (Negassa *et al.* 2007, Sheoran *et al.* 2009). Application of compost and *leucaena* might have contributed to the N mineralization and higher enzymatic activities leading to increased transformation of nutrients in available form (Vidyavathi *et al.* 2011). Nitrogen fertilization solely through organic sources (T_3/T_7) resulted in comparatively lower SYI compared to integrated application (T_4, T_5, T_6, T_7) or exclusive inorganic N fertilization (T_2). Highest SYI (0.61) in maize was recorded with application of 15 kg N/ha through compost + 20 kg N/ha through urea (T_5) closely followed by T_7 and T_2 treatments (SYI 0.60). Similarly in wheat, treatment T_5 resulted in highest SYI (0.60) followed by T_4 (0.55) and T_2 (0.50) treatments.

Rainfall modeling and yield predictions

The regression model developed between the crop yields and monthly rainfall gave a non-significant yield predictability and higher prediction error for different treatments in maize, while it gave significantly higher yield predictability and lower prediction error in wheat (Table 4). In maize, the coefficient of determination (R^2) ranged from 0.40 for T_4 to 0.57 for T_7. The prediction error was in the range of 421.1 kg/ha for T_7 to 562.5 kg/ha for T_2. In wheat, R^2 ranged from 0.80 in T_1 to 0.97 in T_5 for yield prediction. Based on the model, prediction error ranged from 223.7 kg/ha for T_5 to 521.8 kg/ha for T_7. The predictability of yield was found to be significant for four treatments: T_5 (0.97), T_4 (0.96), T_2 (0.89) and T_6 (0.85).

The regression models developed through long-term field experimentation to predict crop yields under variable seasonal (*kharif*) rainfall indicated that rainfall events in the months of June, July and September played crucial role in increasing the maize yields (except for few treatments). Better spatio-temporal distribution of rainfall in July is the determining factor for preparatory tillage and seeding maize crop. Adequate rains during this month ensure timely sowing, optimum germination and desired crop stand. The anticipated negative impact of August rainfall could be ascribed to the water stagnation owing to occasional high rainfall events as the maize crop is highly sensitive to excessive moisture conditions. However, the positive influence of rains in September could well be attributed to the availability of moisture during reproductive (silking, pollination, tasseling, cob formation and grain formation) stages which is the most significant phase in the crop ontogeny (complete in a span of 15–20 days). Water stress

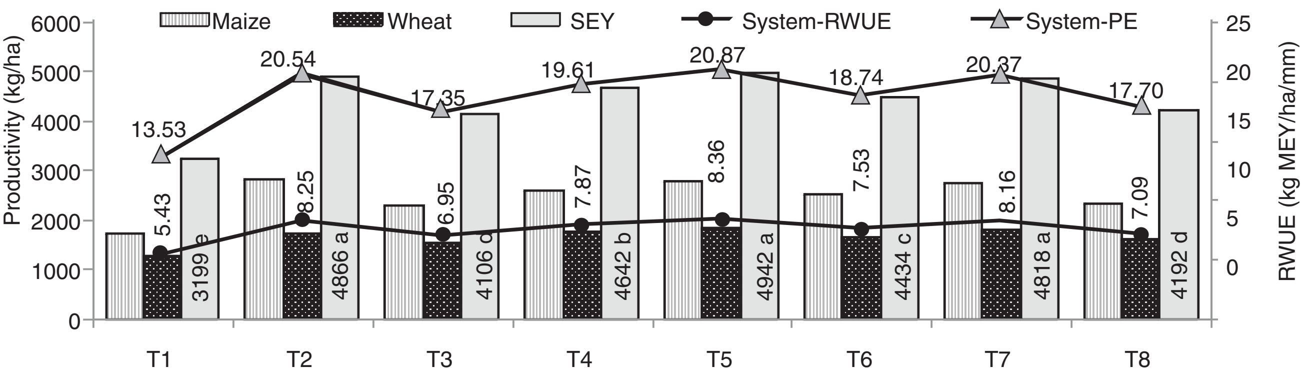

Fig 1 Crop productivity and resource use efficiencies in relation to nutrient management practices. Bars sharing the same lower case letter do not differ significantly (DMRT, P-value<0.0001, within treatment comparison).

Table 4 Effect of monthly rainfall on grain yield of maize and wheat under different treatments

Treatment	Regression model	R^2	Error	SYI
Maize				
T_1	Y = 2390** + 2.40 (Jun) – 1.11 (Jul) – 2.91 (Aug) + 0.94 (Sep)	0.48	438.8	0.32
T_2	Y = 2743* + 1.85 (Jun) + 2.63 (Jul) – 2.59 (Aug) + 0.24 (Sep)	0.54	562.5	0.50
T_3	Y = 2121* + 0.02 (Jun) + 1.73 (Jul) – 2.18 (Aug) – 0.14 (Sep)	0.41	455.1	0.39
T_4	Y = 2695** + 1.88 (Jun) + 1.92 (Jul) – 2.72 (Aug) – 2.06 (Sep)	0.40	518.5	0.55
T_5	Y = 2819** + 1.12 (Jun) + 2.23 (Jul) – 2.65 (Aug) + 1.10 (Sep)	0.47	481.0	0.60
T_6	Y = 2622** + 1.65 (Jun) +1.85 (Jul) – 3.15 (Aug) + 2.31 (Sep)	0.42	501.0	0.44
T_7	Y = 2796** + 1.87 (Jun) + 2.22 (Jul) – 3.18 (Aug) + 2.13 (Sep)	0.57	421.1	0.47
T_8	Y = 2308* + 1.31 (Jun) + 2.05 (Jul) – 2.81 (Aug) – 0.84 (Sep)	0.49	474.2	0.42
Wheat				
T_1	Y = 970* – 1.43 (Oct) – 42.69 (Nov) – 4.41 (Dec) + 2.03** (Jan) + 17.16** (Feb) – 4.17 (Mar)	0.80	415.6	0.45
T_2	Y = 1223** – 3.35 (Oct) – 141.80 (Nov) – 9.42* (Dec) + 6.22** (Jan) + 28.52** (Feb) – 9.86 (Mar)	0.89**	392.6	0.69
T_3	Y = 1046* + 0.23 (Oct) + 2.74 (Nov) – 4.47 (Dec) + 1.49** (Jan) + 18.14* (Feb) – 6.07 (Mar)	0.82	484.3	0.60
T_4	Y = 1169* – 3.39 (Oct) – 97.61 (Nov) – 11.68* (Dec) + 4.70** (Jan) + 31.45* (Feb) – 10.6 (Mar)	0.96*	278.3	0.67
T_5	Y = 1111** – 3.83 (Oct) – 125.04 (Nov) – 10.84* (Dec) + 9.76** (Jan) + 32.31* (Feb) –9.55 (Mar)	0.97**	223.7	0.71
T_6	Y = 1101* + 0.29 (Oct) – 21.64 (Nov) – 7.27* (Dec) + 1.80** (Jan) + 18.97* (Feb) – 3.27 (Mar)	0.85*	471.5	0.64
T_7	Y = 1121** – 1.25 (Oct) – 42.08 (Nov) – 6.36* (Dec) + 5.16** (Jan) + 22.38* (Feb) – 4.21 (Mar)	0.83	521.8	0.69
T_8	Y = 1050* – 0.89 (Oct) – 57.11 (Nov) – 6.40 (Dec) + 2.80** (Jan) + 22.21* (Feb) – 5.69 (Mar)	0.84	471.4	0.62

*, ** Significant at P<0.05 and P<0.01 level, respectively; R^2: Coefficient of determination; SYI: Sustainability yield index.

at this stage could be quite dramatic in drastically reducing the maize yield (Rashid and Rasul 2012). It has been observed that rainwater stored in the soil profile during September ensures moisture availability up to physiological maturity. In *rabi* season, the regression model indicated that the precipitation received in late December/January (with N top dressing) and February (reproductive phase-booting, heading) months due to western disturbances is vital for better expressions of growth and yield parameters for higher wheat yield. Recharging of soil profile with rains received in February may take care of crop moisture requirements up to mid March. The moisture stress at anthesis may result in poor pollination resulting in higher pollen sterility, shriveled grains and lower test weight and reduced crop yields (Ashraf 1998).

The present long-term study indicates that balanced N fertilization achieved through partial N substitution with compost or *leuceana* provides a prescription for sustainable agricultural production. Application of 15 kg N/ha either through compost/*leucenea* loppings along with 20 kg N/ha as inorganic fertilizer proved beneficial to harvest optimum yields from maize-wheat cropping sequence under rainfed conditions. The suggested regression models thus developed can be used to predict the treatment effects on crop yields using monthly rainfall data with likely fluctuations (errors).

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