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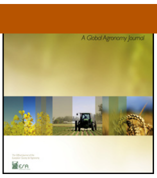

Strategic double cropping on Vertisols: A viable rainfed cropping option in the Indian SAT to increase productivity and reduce risk

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ABSTRACT

Our study suggests the possibility for transformational change in the productivity and risk profile of some of India's rainfed cropping systems. In the semi-arid regions of Southern India, farmers traditionally crop sorghum or chickpea on Vertisols during the post-rainy season, keeping the fields fallow during the rainy season. This practice avoids land management problems, but limits the potential for crop intensification to increase systems productivity. A long-term (15 year) experiment at ICRISAT demonstrated that cropping during the rainy season is technically feasible, and that grain productivity of double cropped sorghum + chickpea (SCP–SCP) and mung bean + sorghum (MS–MS) sequential systems were higher than their conventional counterparts with rainy season fallow, i.e. fallow + post-rainy sorghum (FS–FS) and fallow + post-rainy chickpea (FS–FCP). Without N application, mean grain yield of post-rainy sorghum in the MS–MS system was significantly greater (2520 kg ha^{-1} per two-year rotation) than in the FS–FS system (1940 kg ha^{-1} per two-year rotation), with the added benefit of the mung bean grain yield (1000 kg ha^{-1} per two-year rotation) from the MS–MS system. In the SCP–SCP system the additional grain yield of rainy sorghum (3400 kg ha^{-1} per two-year rotation) ensured that the total productivity of this system was greater than all other systems. Double cropping MS–MS and SCP–SCP sequential systems had significantly higher crop N uptake compared to traditional fallow systems at all rates of applied nitrogen (N).

The intensified MS–MS and SCP–SCP sequential systems without any N fertilizer applied recorded a much higher median gross profit of Rs. 20,600 (US $ 375) and Rs. 15,930 (US $ 290) ha^{-1} yr^{-1}, respectively, compared to Rs. 1560 (US $ 28) ha^{-1} yr^{-1}) with the FS–FS system. Applying 120 kg of N ha^{-1} considerably increased the profitability of all systems, lifting median gross profits of the sorghum + chickpea system over Rs. 60,000 (US $ 1091) ha^{-1} yr^{-1} and the conventional system to Rs. 20,570 (US $ 374) ha^{-1} yr^{-1}. The gross profit margin analysis showed that nitrogen is a key input for improving productivity, particularly for the double cropping systems. However, traditional systems are unviable and risky without N application in the variable climates of the semi-arid tropics. Together, our results show that on Vertisols in semi-arid India, double cropping systems increase systems' productivity, and are financially more profitability and less risky than traditional fallow post-rainy systems while further benefits can be achieved through fertilizer application.

1. Introduction

Rainfed crop lands occupy 1.223 billion ha (FAOSTAT, 2005), produce 70% of the staple food and support nearly 40% of the world's population. The importance of rainfed agriculture varies regionally, ranging from 93% across sub-Saharan Africa to 57% in South Asia (Alexandratos and Bruinsma, 2012). In India, rainfed agriculture comprises >50% of agricultural land, contributing 44% of the total food grain production and supports 40% of India's population (Census India, 2011). It is estimated that in India even after

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achieving full irrigation potential, nearly 50% of the net cultivated area will remain dependent on rainfall (Sharma, 2011). The status of rainfed agriculture in India is precarious, with productivity being hampered by low cropping intensity which results from risk-averse crop management decisions associated with high incidence of poverty among small-holder farmers.

Variability in the onset and distribution of monsoonal rains in June-July is a key risk for crop production, limiting opportunities for crop intensification on Vertisols. Rainfed fields are usually left fallow during the South-West monsoon (June-September) rainy season and cropped with either sorghum or chickpea during the post-rainy season on stored soil moisture. The area of rainy season fallows in India was estimated to be 26.2 M ha in the 1970s (Malone, 1974). A more recent report from the Directorate of Economics and Statistics (2007–2008) estimated that the total fallow area in India has not greatly changed (25.1 M ha), though the area under rainy season fallows on Vertisols has increased to 14.8 M ha. Major crops grown on these Vertisol fallows in Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, and Karnataka in Central and Southern India are post-rainy season sorghum and chickpea.

Vertisols occupy extensive areas (267 M ha) across all continents (Dudal and Eswaran, 1988), and constitute approximately 22% of the total geographical area of India (Murthy, 1988). Traditionally, farmers leave Vertisols fallow during the rainy season and crop them during the post-rainy season on stored soil moisture. Growing crops in the rainy season on Vertisols is considered risky, because (a) shrinking, cracking and hardening of soils on drying prior to the monsoon, and swelling and stickiness of soil on wetting after monsoon rains, make land preparation and sowing unviable; (b) poor drainage and water logging under heavy rains due to the high clay contents of the soil (Virmani et al., 1982a), and (c) unreliable rainfall in June–July may result in poor crop establishment.

Rainy season fallowing leads to low land productivity even in better rainfall seasons, and also results in leaching of nutrients (particularly N), and soil erosion (Rego et al., 1982). Hydrological studies of traditional systems on the ICRISAT farm showed that just 41% of the potentially available rainfall was actually used for evapotranspiration by a post-rainy season sorghum crop (Pathak et al., 1985). Soil loss through erosion was estimated at 10 to 43 t ha^{-1} yr^{-1} and an estimated 80% of soil erosion could be reduced by cropping the fallows. This aggravates the fact that Vertisols in this part of the world are generally low in N and phosphorus (P). Response to N fertilization is much greater than with any other nutrient, and the response is greater in the rainy season than in the post-rainy season (Finck and Venkateswarlu, 1982; Katyal, 1988).

Legume-based systems have been particularly successful in providing N inputs to companion or sequential crops and attractive to farmers as legumes provide valuable grain and fodder as part of the crop production system. Legume root material and nodules remaining in the soil have positive residual effects on the subsequent cereal crops, estimated to be equivalent to 30 to 40 kg N ha^{-1} (Kumar Rao et al., 1983). Vertisols with soil depth up to 185 cm usually have water holding capacity in the range of 230 to 300 mm (Virmani et al., 1982a), providing an opportunity for double cropping to better use soil water in both seasons. Hence, early research at ICRISAT concentrated on maize and soybean based cropping systems in higher rainfall (long-term average >750–950 mm) areas (El-Swaify et al., 1985). However there are substantial areas of Vertisols in India that receive less rainfall (i.e., $\leq$750 mm under traditional fallow systems that have potential for intensification through double cropping).

Farmers' decisions to adopt an alternative cropping system depend not only on improvements in mean productivity but also on their understanding of the fluctuations in profits and risks associated with the new strategy. Despite of this, economic analyses and risk assessments of cropping systems are rarely included in the assessments of cropping systems productivity. The majority of farmers in rainfed regions of India are either small or medium holder farmers, who have varying degrees of willingness and ability to bear risks; hence we realized the need to evaluate risk-return trade-offs for different rates of N application to traditional and improved cropping systems.

In this study, our overall objective was to assess whether crop intensification options through sequential double cropping and N application can lead to improved productivity of Vertisols. This could be seen as a transformational change to the management of cropping systems across India's SAT, analogous to the introduction of transformational technologies such as irrigation or hybrid seed. The specific objectives of our study were (1) to assess whether double cropping options with different N rates sustain the improved productivity compared to traditional cropping systems, (2) to compare system N uptake in response to applied N and legume N contributions in traditional and improved systems, (3) to determine the system profitability and variability of financial risks with double crop systems and traditional fallow post-rainy season systems in response to different rates of applied N.

2. Materials and methods

2.1. Location climate and soils

A long-term experiment was conducted with 10 different cropping system rotations on a Vertisol at the ICRISAT Centre (lat. 17.5°N, long. 78.2°E), Patancheru, India. The climate is semi-arid tropical with a rainy season (Southwest monsoon) between June and September months for 60 to 130 d. Rainfall varies from 750 mm to 1200 mm, with 70% probability of mean rainfall in June (116 mm) and July (185 mm) (Virmani et al., 1982b). Of the mean annual rainfall (860 mm), 80 to 90% is received during the monsoon season, which ranges between 30 and 75% of the potential evapotranspiration during that period. The soils are Vertisols, Kasireddipally series, a Typic Pellustert. The Physical properties of these soils are detailed in Table 1. In the top soil (0–15 cm) layer, soil total N was 550 mg kg^{-1}, organic carbon was moderate at 0.61%, pH varied from 8.1 in the top layer to 8.5 in the lower layers, EC varied from 0.10 in the top layer to 0.30 mmho cm^{-1}, and CEC varied from 34.9 in the top layer to 43.6 meq 100 g^{-1} in the lower layers of the soil.

2.2. Experimental design and cropping systems rotations

The experiment was established in 1983 and continued until 1997, a total of 15 years on the same Vertisol watershed site. Long-term effects of grain legumes on succeeding rainy-season sorghum productivity in rainfed cropping systems on Vertisols have been published from this experiment (Rego and Nageswara Rao, 2000). In this paper we analyse the effects of four cropping systems described in Table 2 (FS–FCP is a mirror image treatment) to understand the rationale behind traditional fallowing and cropping during the post-rainy season. The experimental design was a split-plot with cropping systems as main plots and four rates of N fertilizer application as subplots. Two of the four cropping systems were double crop sequential systems. Mung bean (*Vigna radiata* (L.) Wilczek) sown in the rainy season followed by post-rainy sorghum (*sorghum bicolor* (L.) Moench) constituted the mung bean and sorghum (MS–MS) sequential system. Rainy season sorghum followed by chickpea (*Cicer arietinum* L.) rotated annually constituted the sorghum and chickpea (SCP–SCP) sequential system. The other two systems were traditional systems whereby a rainy-season fallow preceded a post-rainy season crop; either annual repetition of sorghum after a fallow (FS–FS), or chickpea after a fallow on one year and sorghum after a fallow in the other (FS–FCP), i.e., a two-year rotation. This

Table 1
Major characteristics of a Vertisol (Kasireddipalli soil series, a Typic Pellustert) measured to soil depth of 0–155 cm during 1983 at the experimental site in ICRISAT, Patancheru, AP, India.

Physical properties							
Horizon	Soil depth	Distribution (%) of <2 mm particles				Water holding capacity (gravimetric %)	
		Coarse sand (2–0.2)	Fine sand (0.2–0.02)	Silt (0.02–0.002)	Clay (<0.002)	1/3-bar	15-bar
AP	0–15	18.3	25.3	16.3	40.1	32.5	18.7
B12	16–57	17.6	15.6	17.3	49.5	34.9	20.5
B13	58–118	8.9	10.0	20.4	60.7	33.4	20.5
B14	118–155	9.9	10.4	19.4	60.3	35.8	21.3

Extracted from El-Swaify et al. (1985).

Table 2
Cropping system rotations as main plots in a long-term cropping systems study at ICRISAT, Patancheru, India during 1983–1997. $N = 3$.

First year	Second year	Rotation abbreviation
Rainy + post-rainy	Rainy + post-rainy	
Fallow (F) + Sorghum (S)	Fallow + sorghum	FS–FS
Mung bean (M) + Sorghum	Mung bean + sorghum	MS–MS
Fallow + Sorghum	Fallow + chickpea	FS–FCP*
Fallow + Chickpea	Fallow + sorghum	FCP–FS*
Sorghum + Chickpea (CP)	Sorghum + chickpea	SCP–SCP

* Mirror image treatments.

rotation had a mirror image (FCP–FS) treatment, so that in any given year both sorghum and chickpea were grown in order to account for the effect of seasonal variability annually. The productivity of these four systems was assessed in two-year rotations to represent them uniformly. Main plot size was 12 × 12 m with eight sets of broad bed and furrows (described in Section 2.3). Each plot was divided into four subplots receiving 0, 40, 80, or 120 kg N ha^{-1} applied as urea to each non-legume crop. Note that this entailed that the MS–MS, FS–FS and SCP–SCP systems therefore received these fertilizer applications annually, while FS–FCP received them once every two years.

2.3. Land management for dry seeding on Vertisols

This experiment was conducted within an operational scale Vertisol watershed (BW3) at ICRISAT Centre. We adopted an improved land management system of Broad-Bed (100 cm) and Furrow (50 cm) (BBF), which was developed by ICRISAT as an improved land management practice for these Vertisols (Kampen et al., 1981). The BBF of 150-cm-width were prepared across the major slope (0.6%) graded contour and are separated by furrows formed along the minor slope to drain water through grassed waterways to facilitate controlled draining of runoff water. They reduce runoff under both fallow and cropped conditions and greatly reduce soil erosion in comparison with ungraded fallow soils (Binswanger et al., 1980). The seed bed was formed after mould board ploughing twice on the beds immediately after the harvest of the preceding post-rainy season crop, under receding soil moisture conditions. Further land preparation included cultivation in the first fortnight of May after pre-monsoon showers, and shaping the beds with a bed-former while cleaning furrows with ridges on both sides.

2.4. Dry seeding and crop management

Rainy season crops were dry seeded at a depth of 5 to 7 cm in June before the onset of the monsoon; the basal dose of fertilizer was applied simultaneously in a band 5 cm to the side and 5 cm below the seed furrow. However, row spacing and numbers of rows varied depending on the cropping treatments in order to maintain the optimal plant population. In the rainy season, the sorghum plant population was maintained at 180,000 plants ha^{-1}, and the mung bean population at 330,000 plants ha^{-1}, the generally recommended optimum crop stands in this region. Post-rainy season crops were planted as soon as the rainy season crop was harvested or in fallows at the equivalent time. In the post-rainy season, the plant population maintained for sorghum was 120,000 plants ha^{-1}, and the plant population for chickpea was 330,000 plants ha^{-1}. Weeding and intercultivation was carried out twice during the rainy season cropping and once during the post-rainy season (including fallow treatments). Crops and varieties of each crop were kept the same over the years with the exception of sorghum varieties during the post-rainy season. The hybrid CSH 8R was replaced by SPV-421 (with similar phenology) after eight years of experimentation due to non-availability of CSH 8R seed. Other varieties used were rainy season sorghum CSH-6, mungbean variety PS-16; and chickpea variety Annigiri.

2.5. Fertilizer application

Phosphorus (P) in the form of single superphosphate (16% P_2O_5) was band-placed as a basal dressing at 20 kg P ha^{-1} for both the crops in sequential rotation. Zinc sulphate was broadcast at 50 kg $ZnSO_4$ ha^{-1} once every three years. During the rainy season 20 kg N ha^{-1} was band-placed in all N treatments (i.e., the above-mentioned 40, 80 and 120 kg N ha^{-1}) as a basal application and the remainder was band-placed as a top dressing 21–28 d after crop emergence, approximately synchronizing with the primordial initiation stage of sorghum based on rainfall and soil moisture. In the post-rainy season the entire application of N was band-placed at the time of sowing due to uncertainty of top dressing opportunity.

2.6. Estimation of crop yield, gross profit margins

Crop harvest samples were collected in an area of 12 m^2 from each subplot at full crop maturity. Fresh weights of stems/stalks, panicles or pods were recorded and then sub-sampled oven-dried at 65 °C for 48 h before measuring their dry weights. Panicles or pods were threshed to extract grain. All data are expressed as dry weights per ha. To compare rotations of different lengths, we present data as totals per two year rotation.

We used the minimum support price (MSP) for crop grain (http://agricoop.nic.in/) for 2012–2013 to calculate gross profit margins. When we expressed gross profits as US $ in parenthesis, we used an exchange rate of Rs. 55 per dollar. We estimated cost of cultivation in two parts: (1) Costs applied across all cropping systems which included land lease per year, summer land preparation for fallows, sowing, two intercultivation operations with the Tropicultor in the rainy season, fertilizer P and $ZnSO_4$ and their application costs, cost of two hand-weedings in the rainy season and one hand-weeding in the post-rainy season. (2) Costs unique to each cropping system including costs of: fertilizer N, seeds, pesticides, harvesting and threshing. MSP of grain per 100 kg for various crops were: mung bean, Rs. 4400 (US $ 80); chickpea grain, Rs. 2800 (US $ 51); and hybrid sorghum grain, Rs. 1500 (US $ 27). We estimated sorghum fodder value at Rs. 1400 (US $ 26) per ton. Mung bean haulms have no value since haulms from the rainy season crop are not generally useful as fodder because it spoils quickly due to its high moisture content. Gross profit was estimated by subtracting gross expenditure (total cost of cultivation) from gross returns, a sum value of all marketable components (i.e. grain and stalk if stalk is useful as fodder) of single or double crops yields of a cropping system, obtainable from the sale proceeds. The gross profit margin was calculated as the gross profit divided by the gross returns, represented as a percentage.

$$\text{Gross profit} = \text{Gross returns} - \text{Gross expenditure} \tag{1}$$

$$\text{Gross profit margin} = \frac{\text{Gross profit for the system}}{\text{Gross returns}} \times 100 \tag{2}$$

2.7. Stochastic dominance approach for risk analysis of cropping systems

Stochastic dominance (SD) analysis a is simple and relevant way to compare cumulative distributions of gross profits of two or more management strategies in relation to human behaviour on decision making for an uncertain and risky or certain outcome (Hadar and Russell, 1969; Hanoch and Levy, 1969). We employed the stochastic dominance approach used by Lowenberg-Deboer and Aghib (1999) to evaluate the economics of management options. The first degree stochastic dominance (FDSD) condition is satisfied when the cumulative density function (CDF) F of a random variable stochastically dominates another CDF G of another random variable, with the inequality strictly holding over the entire domain of x (Hirshleifer and Riley, 1992); in other words: the two CDFs never intersect

$$F(x) \geq G(x) \quad \text{for all } x \tag{3}$$

FDSD assumes decision makers prefer that more is better than less, and an alternative is preferred over others, if it provides a higher outcome (stochastically larger) at every level of probability. FDSD behaviour is preferred by risk neutral decision-makers.

If cumulative density functions F and G intersect at some point ‘z’ at one time, this is called single-crossing, and then the second degree stochastic dominance (SDSD) is considered useful as the FDSD rule cannot rank them when the CDFs of two choices cross. A sufficient condition for SDSD is with the inequality strictly holding for some domain of y (Hirshleifer and Riley, 1992).

$$\int_{-\infty}^{y} F(x)\,dx \leq \int_{-\infty}^{y} G(y)\,dy, \quad \text{for all } y \tag{4}$$

Second degree stochastic dominance (SDSD) assumes that the decision-maker (i) prefers more wealth to less, and (ii) is risk-averse (concavity). That means a decision maker may prefer a cropping system even with a lower mean gross profit, if the variance in profits is lower compared with the cropping systems with a greater gross profit associated with higher variance in profits and risk. The trade-off function of variance reduction versus yield is likely to differ between individual decision makers.

The cumulative distributions of gross profits for each of the four rates of nitrogen for five cropping systems were estimated in a spreadsheet following an empirical approach with probability of each observation being $1/N$, where N is the sample size, 15 observations in this case. Points were connected with straight lines to construct plots of empirical CDFs. Two CDFs compared are significantly different, only if, the maximum vertical distance between them exceeds the confidence interval, and at all levels of probability the FDSD curve is to the right of all other CDFs.

We used the empirical cumulative distribution function (eCDF) in R, version 3.0 (R Core Team, 2013) to calculate the stochastic dominance and the eCDF function in the package Hmisc (Harrell, 2013) and areas under distribution are calculated for each system. We evaluated the second degree stochastic dominance for pairs of cropping systems when their CDFs cross over (FS–FS; FS–FCP; FCP–FS; MS–MS and SCP–SCP) by calculating the mean difference in areas after bootstrap sampling the data 10,000 iterations with replacements.

2.8. Chemical analysis for plant nutrient uptake

Stover (including chaff from the panicle) and grain samples were oven-dried at 65 °C for 48 h to attain <12% moisture content, then ground to pass a 0.5-mm sieve. Stover and grain samples were digested by sulfuric acid–Se digestion (Sahrawat et al., 2002) and N concentration determined using an auto-analyzer, P concentration by the phosphovanadomolybdate colorimetric procedure, and K using an atomic absorption spectrophotometer. Dry matter production and grain yield are expressed as kg ha^{-1} on a dry weight basis. N, P, and K concentrations in stalk and grain of all crops were determined treatment-wise in all years from 1983 to 1997, which enabled calculation of total plant uptake of N, P, and K. Rotational effects are measured when a monoculture system is compared with a cropping system rotation having one component crop as in monoculture at the same level of external inputs. One method of quantifying the N contributions of legumes is the estimation of fertilizer replacement value (FRV) (Iragavarapu et al., 1997). Hesterman (1988) defined FRV as the amount of inorganic N fertilizer required to produce yields in a non-rotated crop, equivalent to that obtained in the same but non-fertilized crop following a legume in the rotation.

2.9. Statistical analysis

The SAS PROC GLM procedure (SAS Institute, 2009) was used to analyse the individual crop yields across systems (ex. Post-rainy sorghum yields from three systems), and system-wide total uptake of N in this experiment, as it was a balanced split-plot design, with cropping system and N rates as fixed effects. Annual measurements were made from the same sub-plot treatments in two seasons of a year, continuously for 15 years; hence a repeated measures approach was used. The sphericity of data was not assumed; hence we used corrected univariate p values, which are detailed under the Greenhouse-Guisser and Huynh-Feldt Epsilon results. The annual treatment (year) was a repeated measurement factor. ANOVA tables for repeated measures analyses are provided as supplementaries to this paper. To test the hypothesis that there are treatment differences and interactions between cropping systems, nitrogen and year, Multivariate Analysis (manova) tests (Pillai's trace, Wilk's lambda, Hotelling-Lawley trace and Roy's greatest root) were also performed.

3. Results

3.1. Crop yields and system productivity

Overall our results show that the double cropping systems resulted in higher sorghum and total system yields but this advantage declined with increasing level of N fertilizer. Prior to a more detailed explanation of these findings we first clarify the basic way in which results are presented. We report the system productivity

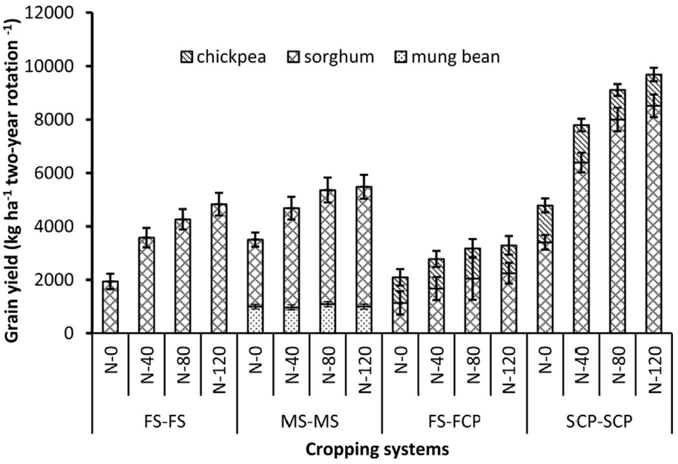

Fig. 1. Grain yield of rainfed cropping systems (Table 2) with increasing rates of nitrogen application, averaged over 15 years. Bars represent SE ± for each crop type.

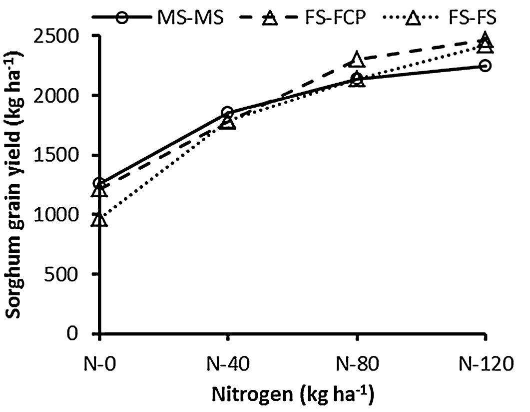

Fig. 3. Mean grain yield of post-rainy season sorghum in response to applied N with different cropping systems.

(Fig. 1) as mean yield of two crops combined for double crop systems or a single crop yield after fallow for traditional systems; and similarly mean of crop total uptake of N as the system N uptake (Fig. 2) in a two-year rotation. Although three systems were annual rotations, because FCP–FS and FS–FCP systems were two-year rotations; we presented system productivity and total uptake of N for all systems as two-year rotations to standardize comparisons. FS–FCP and FCP–FS were mirror image treatments of a cropping system and there were no differences between these two treatment observations in long-term analysis, thus we pooled the data of these two treatments except for the variable 'gross profits' where they were considered separately to reflect annual variability in profits.

The total productivity of the MS–MS system, as mean grain yield of post-rainy season sorghum (2510 kg ha^{-1} per two-year rotation) plus mung bean mean grain yield (1000 kg ha^{-1} per two-year rotation) was greater than the mean grain yield in the continuous fallow-sorghum system (1940 kg ha^{-1} per two-year rotation) without N application in both systems (Fig. 1). As the applied N rates increased to 40, and 80 kg ha^{-1} for post-rainy season sorghum, the benefit of MS–MS system on sorghum yield was reduced compared to sorghum yield in FS–FS or FS–FCP, and at 120 kg N ha^{-1} sorghum grain yield in MS–MS converged with traditional systems, indicating diminishing marginal returns at the highest level of N in the MS–MS system (Fig. 3). The MS–MS system annual grain productivity (including mung bean yield) (Fig. 4, upper panel) was significantly higher than that of the FS–FS or FS–FCP systems (Fig. 5) when compared at the same level of applied N. Higher rates of applied N increased sorghum grain median yield from 1180 to 2600 kg ha^{-1} in the traditional FS–FS systems (Fig. 5, right panel). Post-rainy sorghum responded to 120 kg N applied ha^{-1} in 11 out of 15 years (Fig. 6) in the receding soil moisture conditions generally prevalent during the post-rainy season.

We analysed post-rainy season sorghum grain yield from three cropping systems, and chickpea grain yield from two cropping systems as main plots with four N rates as subplots. Proc GLM repeated measures analysis was used to assess annual change, with years as the "time" factor. Rainy season sorghum in SCP–SCP and mung bean in MS–MS systems were available in one main treatment and these crops' responses cannot be compared with any other main treatment, hence these treatments were analysed for N rate responses only annually using Proc GLM repeated measures analysis. There were no cropping systems (FS–FS, FS–FCP, MS–MS) main effects ($P = 0.306$) on post-rainy sorghum grain yield except in 1985 and 1991, but post-rainy sorghum grain yield response to N application was significant ($P < 0.001$) across all systems except in the year 1985 (Table A.1 and A.3). In this year, early matured sorghum

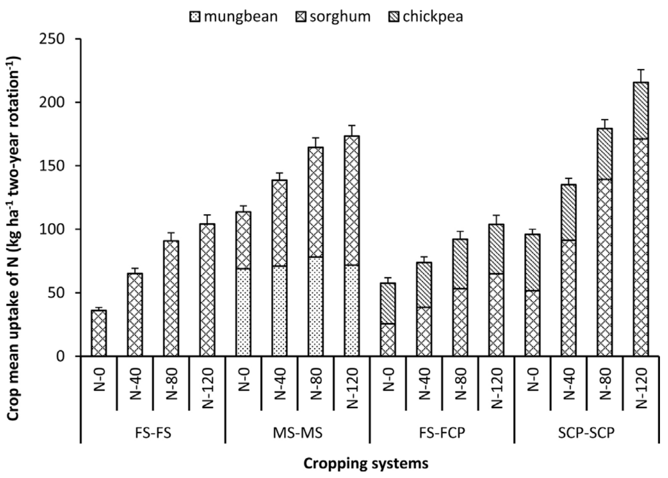

Fig. 2. Crop mean uptake of nitrogen (kg ha^{-1}) at different rates of applied nitrogen in a two-year cropping system rotation.

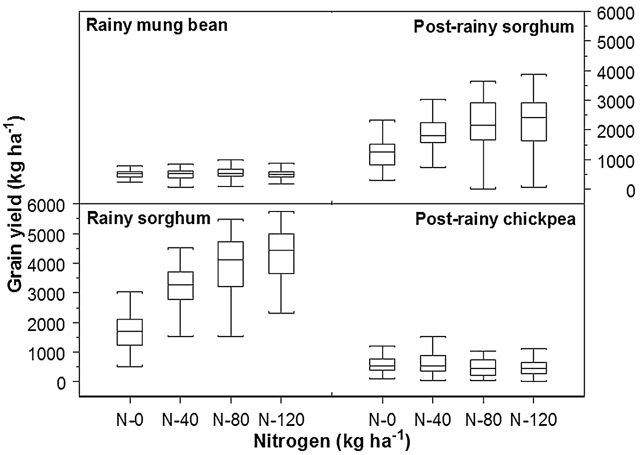

Fig. 4. Annual grain yields of mung bean and post-rainy sorghum (upper panel) in MS–MS, and annual grain yields of sorghum and chickpea (lower panel) in SCP–SCP double cropping systems during 1983–1997. *Note*: Whiskers denote the nearest value not beyond the standard span of the box plot, which is 1.5 times the inter-quartile range. Data points fall beyond the whiskers are either in the top 10 percentile or in the bottom 10 percentile of the data range. These points are considered as outliers and are not drawn in the graph. The line in the centre of the box indicates the median value of the data (50th percentile). Bottom of the lower quartile indicates the 25th percentile and top of the upper quartile indicates the 75th percentile.

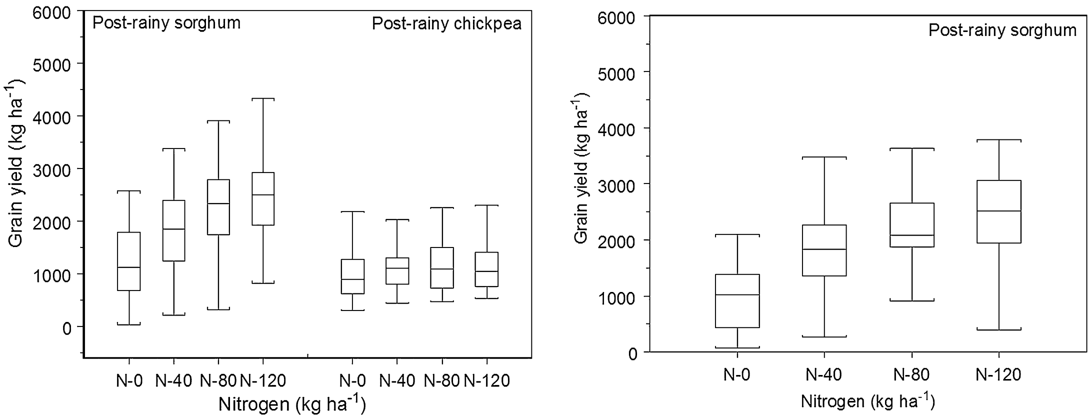

Fig. 5. Grain yields of post-rainy sorghum and chickpea in alternate years with the FS–FCP system (left) in a two-year rotation and grain yield of post-rainy sorghum in the FS–FS system (right) in an annual rotation, during 1983–1997.

panicles in the 80 and 120 kg N ha^{-1} treatments were damaged by birds, resulting in lower grain yield. GLM repeated measures analysis indicates that there were significant interactions of cropping systems and N application ($P = 0.0269$) however, univariate analysis of individual years revealed that there were no interactions in any of the years except 1984, 1987and 1992 (Table A.3). These CS × N interactions were associated with: very low yields in the FS–FS system without N application in 1984; a severe effect of leaf spot (*Helminthosporium sorghicola* Lefebvre & Sherwin) on post-rainy sorghum in 1987; and water stress resulting in lower yield of sorghum for the 120 kg N ha^{-1} treatment compared to the 80 kg N ha^{-1} treatment in 1992. Each of the four multivariate tests i.e. Pillai's trace, Wilk's lambda, Hotelling-Lawley trace and Roy's greatest root were significant and Wilks' Lambda at <0001 either for cropping systems or for N levels without "time" effect (Table A.1). Post-rainy sorghum grain yield analysis showed a significant time effect on cropping systems as well as N rates but there was no interaction of time, cropping systems and N rates (Table A.2). Greenhouse-Guisser and Huynh-Feldt adjusted *F* probability values were in agreement with *F* probability values of the univariate analysis.

Chickpea grain yield in the SCP–SCP system (Fig. 4, lower panel) was less than chickpea yield in the FS–FCP systems (Fig. 5, left panel) confirmed by the significant ($P = 0.023$) cropping systems main effect (Table A.4), although the chickpeas did not receive any N in either system. This effect however depended on the level of N

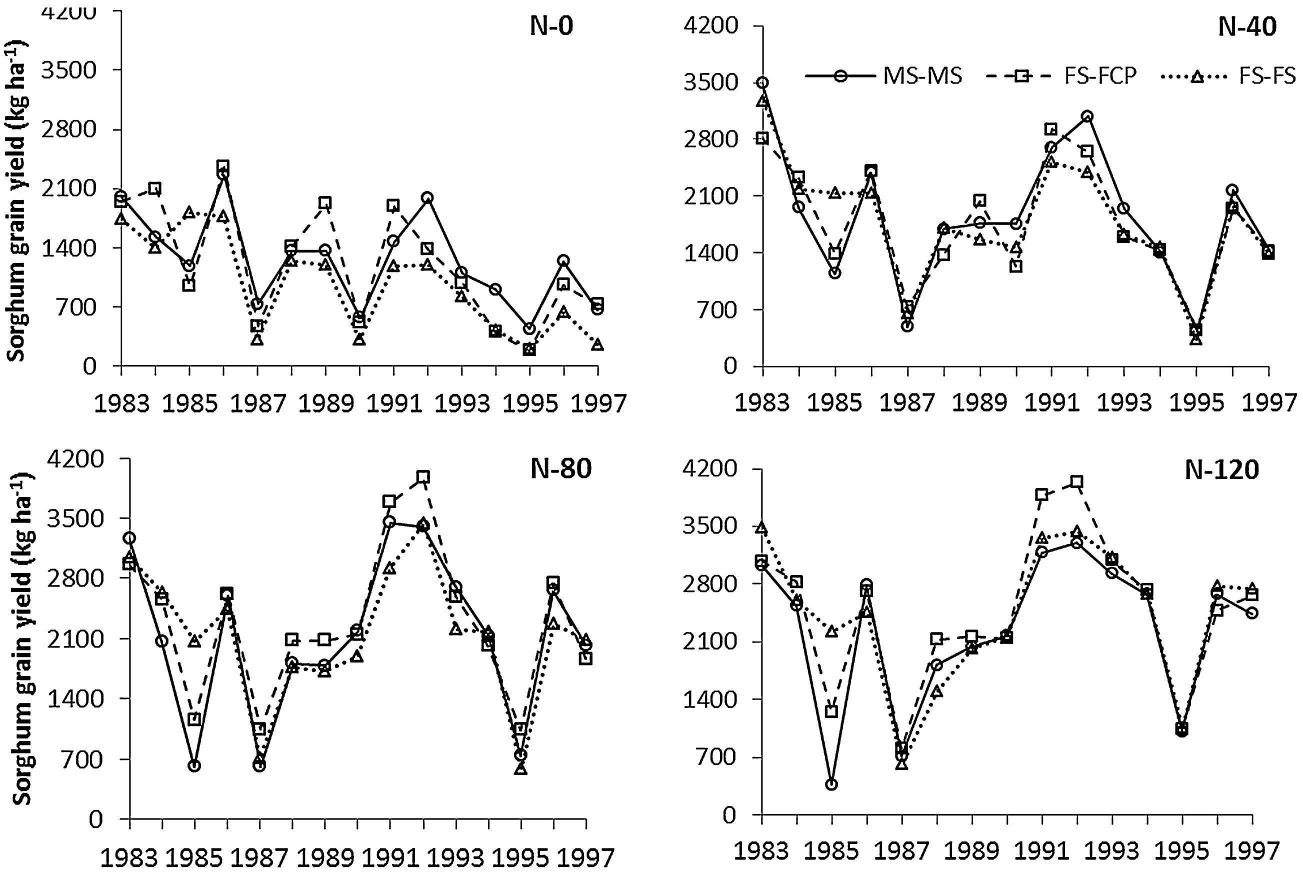

Fig. 6. Sorghum grain yield response to N application in different cropping systems annually during 1983–1997.

Table 3
Residual N effect and legume contributions to the total productivity of different dry land cropping systems at ICRISAT, Patancheru, India during 1983–1997.

Cropping system		Rotational benefits			
	N-0	N-40	N-80	N-120	
MS–MS	Sorghum additional grain (kg ha^{-1} yr^{-1})	290	70	05	−170
	Residual N uptake by sorghum (kg N ha^{-1} yr^{-1})	4.4	1.2	−2.2	−1.3
	Mung bean N uptake (kg N ha^{-1} yr^{-1})	34.5	35.5	39	35.9
FCP–FS	Sorghumadditional grain (kg ha^{-1} once in two years)	170	120	−80	−170
	Residual N uptake (kg N ha^{-1} once in two years)	7.5	4.1	−8.0	−12.8
	Chickpea N uptake (kg ha^{-1} once in two years)	32	35.2	38.8	38.8

application to non-legumes in the systems, as reflected in the significant cropping system * N interactions ($P = 0.0378$) (Table A.4). The seasonal variability in available soil moisture would have affected the cropping systems × N rate interaction. Greenhouse-Guisser and Huynh-Feldt adjusted F probabilities are in agreement with F probabilities of the univariate analysis.

Rainy sorghum mean grain yield in the SCP–SCP system (3400 kg ha^{-1} per two-year rotation; Fig. 1) was additional yield compared with the traditional fallow system single crop yield (FCP–FS), ensuring that the total productivity of the SCP–SCP system was greater than the traditional system, even without N application. Rainy season sorghum grain yield in the SCP–SCP system increased significantly ($P \leq 0.0001$) with increased rates of applied N (40, 80, 120 kg N ha^{-1}) in the rainy season, and seasonal effects on N rates were also significant ($P \leq 0.0001$) in all years (data not presented), i. e. grain yield response to N rates was not similar across all seasons. Rainy season mung bean grain yield in the MS–MS system did not respond to N ($P = 0.5102$), in various seasons as there was no effect ($P \leq 0.3044$) on grain yield response to N rates.

Overall, the productivity of the sequential double cropped systems (MS–MS or SCP–SCP) was higher than any of the fallow plus post-rainy crop systems compared at the same rates of N.

3.2. *Rotation effects and legume contributions*

In our study, we observed rotational effects of legumes in the MS–MS and FCP–FS systems, when compared to the FS–FS monoculture. The residual effect or FRV of mung bean on sorghum is the difference in N uptake of sorghum between the MS–MS and FS–FS systems at each N rate. The FRV of mung bean was ≈9 kg ha^{-1} per two-year rotation without N application to sorghum. The residual effect of chickpea on sorghum in FCP–FS systems was almost 7.5 kg ha^{-1} once in two years without N application to sorghum (Table 3). The FRV of MS–MS and FCP–FS decreased at higher rates of N where sorghum yield in these systems converged with sorghum yield in FS–FS

Legumes were included in the rotations to fix atmospheric N and make more N available to following crops in the system. Mung bean, through crop N uptake (≈35 kg ha^{-1} yr^{-1}) and through residual N (4.5 kg ha^{-1} yr^{-1}) to sorghum contributed almost 40 kg N ha^{-1} yr^{-1} in the double cropping MS–MS system without N application.

3.3. *N uptake by the systems*

N is the major nutrient which determines crop yield on dryland Vertisols in India (Katyal, 1988).

We calculated mean total uptake of N in the above ground biomass (grain and stalk) for the four cropping system (FS–FS, FS–FCP, MS–MS, SCP–SCP) in response to different N rates (0, 40, 80,120 kg N ha^{-1}) applied to non-legume crops, and presented crop-wise N uptake of a cropping system in a two year rotation (Fig. 2). There was a significant difference ($P < 0.01$) in N uptake between cropping systems except in 1997 (Table A.9). Within cropping systems, the differences in N uptake at the system-level in response to N application were significant ($P \leq 0.0001$) for all years. There were interactions of cropping systems × N application ($P \leq 0.0002$), but only in two years (1984 and 1997) of the 15 years. Each of the four multivariate tests were statistically significant at Wilks' Lambda ≤0001 for no year effect between cropping systems. System-wise total N uptake analysis showed significant time effect on 'within subjects' cropping systems and N rates as well as interaction of time, cropping systems and N rates.

Annually the system N uptake was the lowest in the FS–FS system followed by FCP–FS (Fig. 7) across all N fertilization treatments. Without applied N, the total N uptake by both crops of the MS–MS system was almost three-fold higher (113.7 kg N ha^{-1} per two-year rotation) than the total uptake of N by sorghum (35.4 kg N ha^{-1} per two-year rotation) in the FS–FS system. This difference shifted to 171.4 vs 108.3 kg N uptake ha^{-1} under the 120 kg N ha^{-1} fertilization treatment. Total uptake of N of the SCP–SCP system was higher (94.8 kg N ha^{-1} per two-year rotation) than the FCP–FS system (56.9 kg N ha^{-1} per two-year rotation) when no N was applied in either system. Similarly, with 120 kg N ha^{-1} application in both systems, total uptake of N in the SCP–SCP system was higher (202.2 kg N ha^{-1} per two-year rotation) than the FS–FCP system (88.8 kg ha^{-1} per two-year rotation). The trends were similar with 40 kg or 80 kg N ha^{-1} applied to the cropping systems. The rainy season crops, mung bean in the MS–MS system and sorghum in the SCP–SCP system, took up 70 kg and 25 kg N uptake ha^{-1} two year rotation^{-1}, respectively, from the soil, which would otherwise be lost from the soil. Although chickpea in the FS–FCP system contributes considerably to N uptake of the system, it is only cropped once in two years in the rotation.

3.4. *System-wide gross returns and gross profit margins*

Gross returns were calculated for five systems, including separate presentation of FS–FCP and FCP–FS to detail annual variability. When no N fertilizer was added the double cropping MS–MS sequential system had greater mean gross returns Rs. 44,020 (US $ 819) ha^{-1} yr^{-1} than the traditional FS–FS system at Rs. 17,000 (US $ 316) ha^{-1} yr^{-1} (Fig. 8). Under these same conditions, SCP–SCP system had greater mean gross returns (Rs. 48,830, US $ 908, ha^{-1} yr^{-1}) than the mean gross returns of either the FCP–FS (Rs. 29,960, US $ 557, ha^{-1} yr^{-1}) or the FS–FCP system (Rs. 25,180, US $ 468, ha^{-1} yr^{-1}). The gross returns increased as the N rates increased, and at 120 kg N ha^{-1}, gross returns were Rs. 41,900 (US $ 779) ha^{-1} yr^{-1} with FS–FCP and Rs. 87,440 (US $ 1626) ha^{-1} yr^{-1} with the SCP–SCP double crop system (Fig. 8). Mean gross returns from component crops of double cropping and traditional cropping systems are provided in a supplementary table (Table B.1).

We also calculated gross profit and profit margins (%) by estimating the cost of cultivation, including the cost of leasing land. Without N application, a mean gross profit of Rs. 20,990 (US $ 391) ha^{-1} yr^{-1} and profit margin of 46% was achieved in the MS–MS

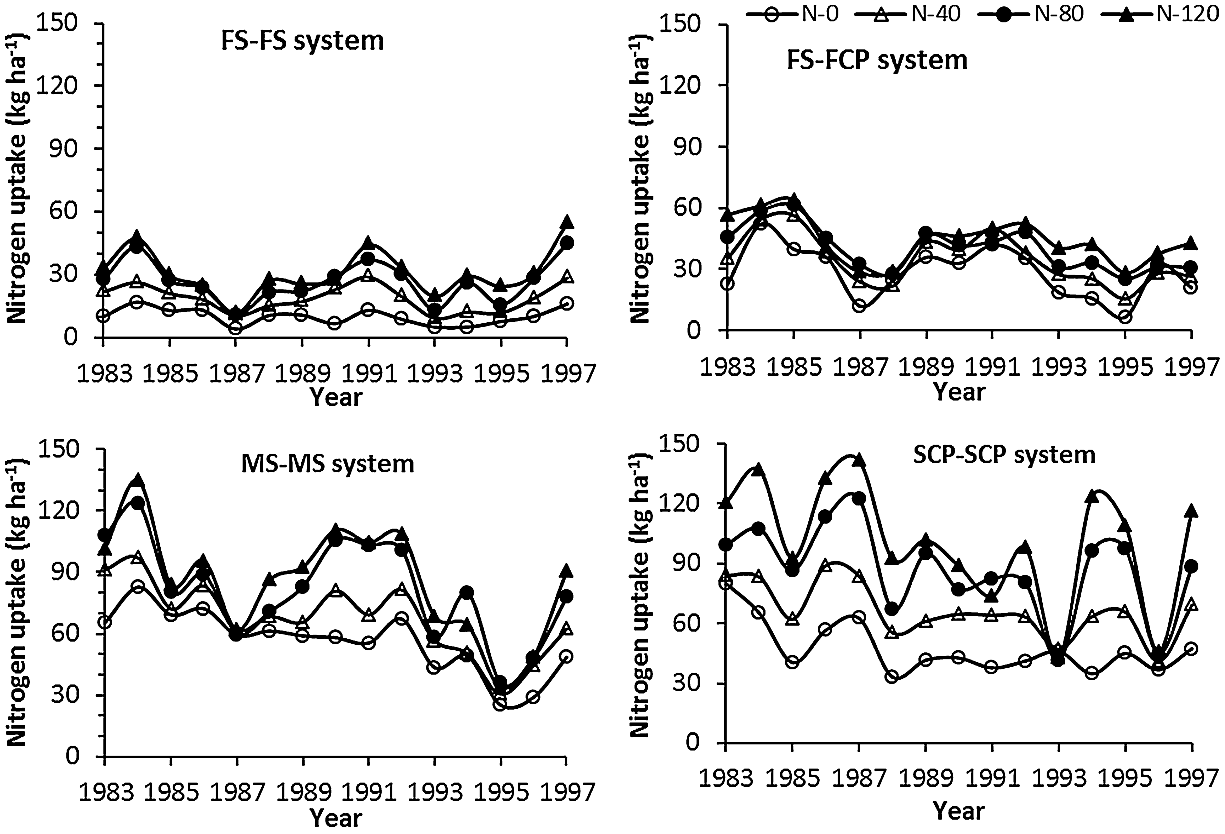

Fig. 7. Nitrogen uptake by cropping systems annually in response to nitrogen application over 15 years.

system. In the SCP–SCP system, a mean gross profit of Rs. 21,820 (US $ 406) ha^{-1} year^{-1} and profit margin of 39% was achieved, and this system was profitable in all years except 1995. Conversely, at this same N treatment, gross losses were estimated in seven, five and six out of 15 years in the FS–FS, FS–FCP and FCP–FS systems, respectively (Fig. 9), indicating that without application of fertilizer the fallow systems had highly unreliable returns on investment. Application of 40 kg N ha^{-1} to post-rainy sorghum improved profits, resulting in Rs. 30,410 (US $ 553; 54% margin) and Rs. 45,270 (US $ 823; 59% margin) in MS–MS and SCP–SCP systems, respectively. A further increase in N application to 80 kg N ha^{-1} resulted in Rs. 37,240 (US $ 677) ha^{-1} yr^{-1} (57% margin), but a further in N application to 120 kg N ha^{-1} did not increase profits beyond this level. In all years, MS–MS systems achieved gross profits with all four rates of N. For the SCP–SCP system, N applications of 80 and 120 kg N ha^{-1} resulted in increases in profit to Rs. 53,190 (US $ 967) ha^{-1} yr^{-1} and Rs. 57,260 (US $ 1041) ha^{-1} yr^{-1}, respectively. Thus, at N applications of 40–120 kg N ha^{-1} the SCP–SCP system provided the larger gross profits of all systems in all years, but recorded a loss without N application in 1995. To summarize, we also provided median gross profits and median profit margins at each rate of nitrogen for the five cropping systems (Table 4).

3.5. *Risk assessment of cropping systems*

By assessing empirical cumulative distribution functions (eCDF) of gross profits in response to four rates of N for cropping systems, it is possible to segregate the choice of cropping systems and N rates (Fig. 10) for different risk groups of farmers. First degree stochastic dominance (FDSD) and second degree stochastic dominance (SDSD) are used to determine sensible options (in terms of economic returns and likely risks) for decision-makers. The eCDF of FS–FS is to the left of all other curves of N-0 (plot N-0 in Fig. 10) hence the FS–FS system is not the best choice for any decision-maker, because all other systems are First Degree Stochastic Dominant to the FS–FS system. The eCDFs of FS–FCP and FCP–FS cross each other but both are at left to the eCDFs of MS–MS and SCP–SCP double cropping systems; hence the double crop systems exhibited FDSD by having consistently higher profits at all probabilities compared to the three traditional systems. Between the double cropping systems, the eCDF of MS–MS crosses the eCDF of SCP–SCP once, indicating a lack of FDSD when differences between two eCDF are not conspicuous. As an alternative we therefore calculated the area under the curve to decide second-degree stochastic dominance (SSD) which provides weaker but more selective discrimination by comparing the probabilities of the eCDFs. The results

Table 4
Medians of gross profit and profit margin (%) recorded with four rates of nitrogen in each cropping systems from 1983 to 1997.

Cropping systems	N-0		N-40		N-80		N-120	
	Gross profit	Margin (%)	Gross profit	Margin (%)	Gross profit	Margin (%)	Gross profit	Margin (%)
FS–FS	1560	7	9650	68	18,660	47	20,570	49
MS–MS	20,600	47	31,040	56	37,020	60	36,870	58
FS–FCP	6680	24	11,060	35	12,400	36	13,520	38
FCP–FCP	4410	21	8360	27	16,050	42	14,410	40
SCP–SCP	15,929	37	44,550	60	56,780	65	60,200	66

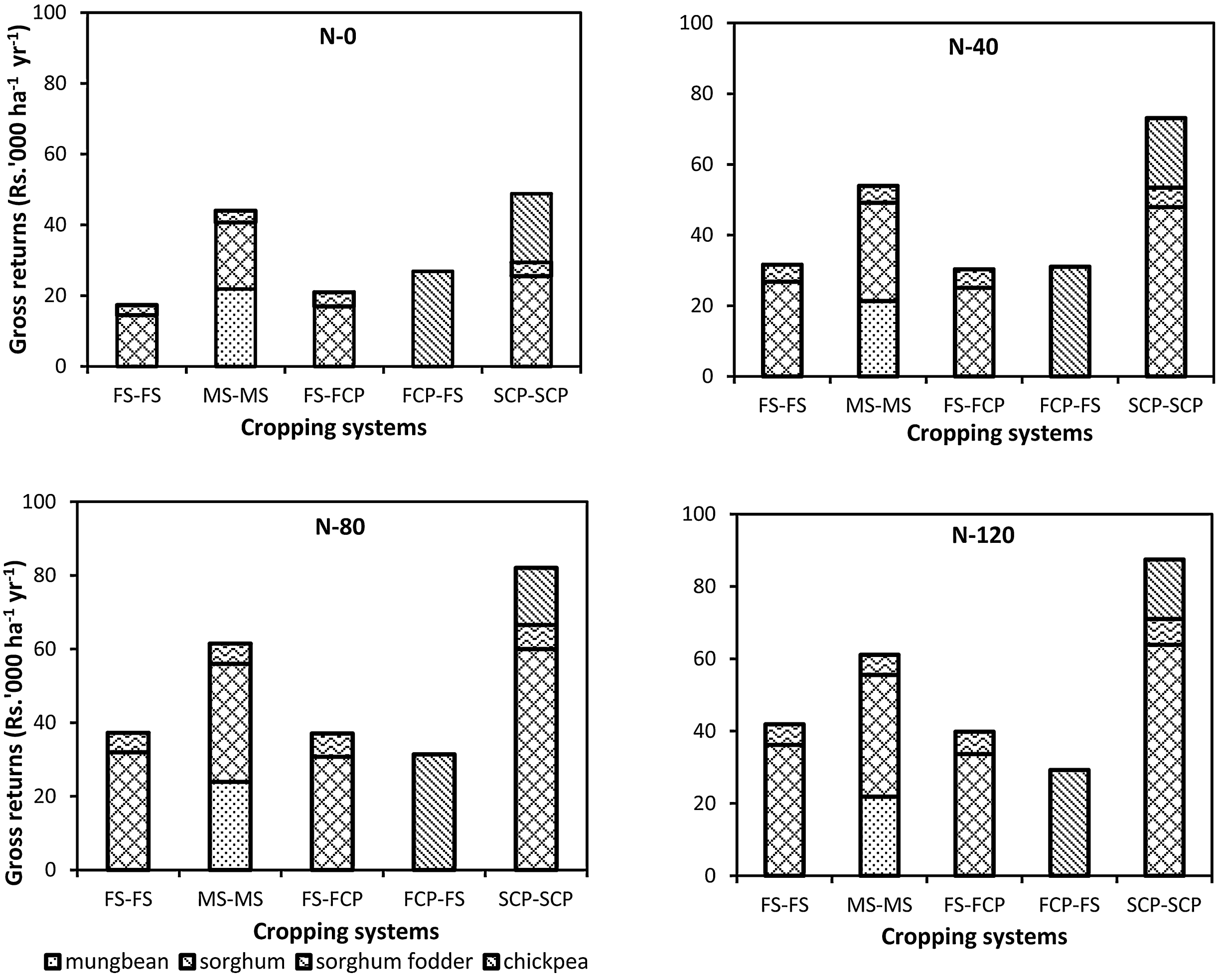

Fig. 8. Mean gross annual returns from components of traditional and improved cropping systems with different rates (0, 40, 80, 120 kg N ha^{-1}) of added nitrogen, averaged over 15 years.

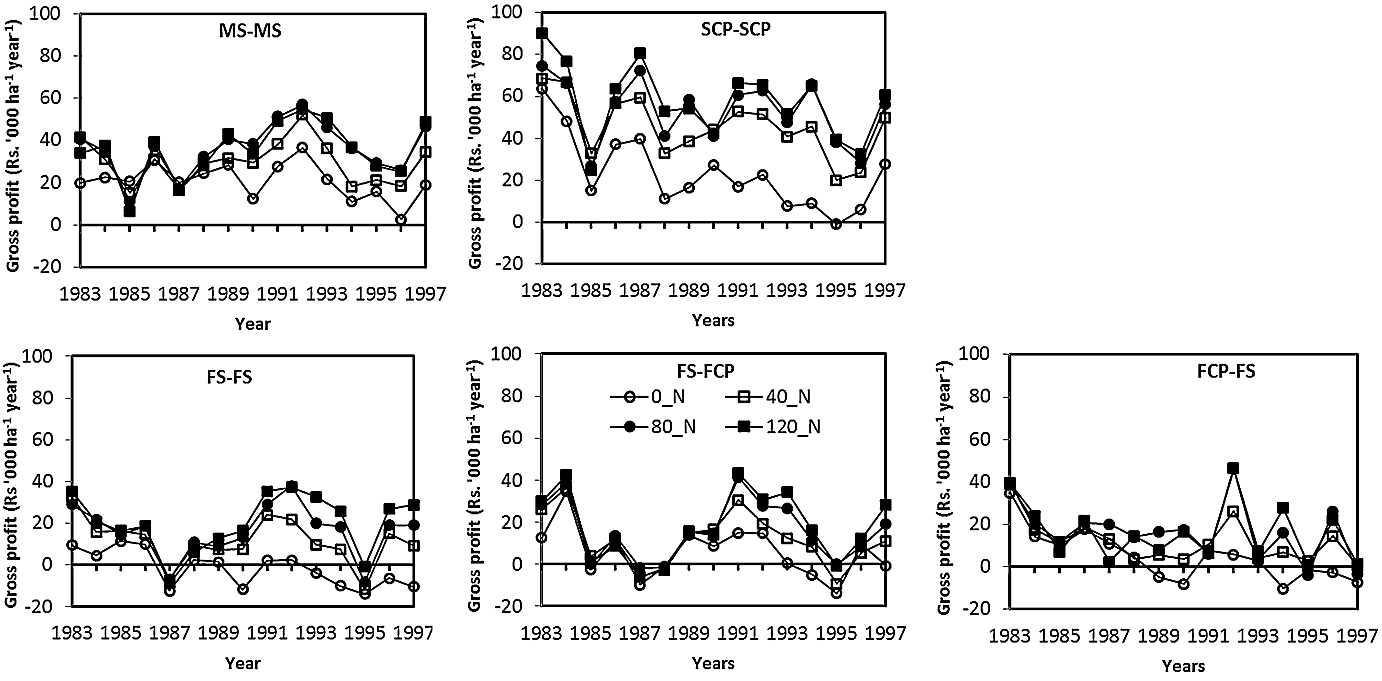

Fig. 9. Gross annual profits for four rates of applied nitrogen with improved rainfed double cropping systems and traditional rainy season fallow single crop systems during 1983–1997.

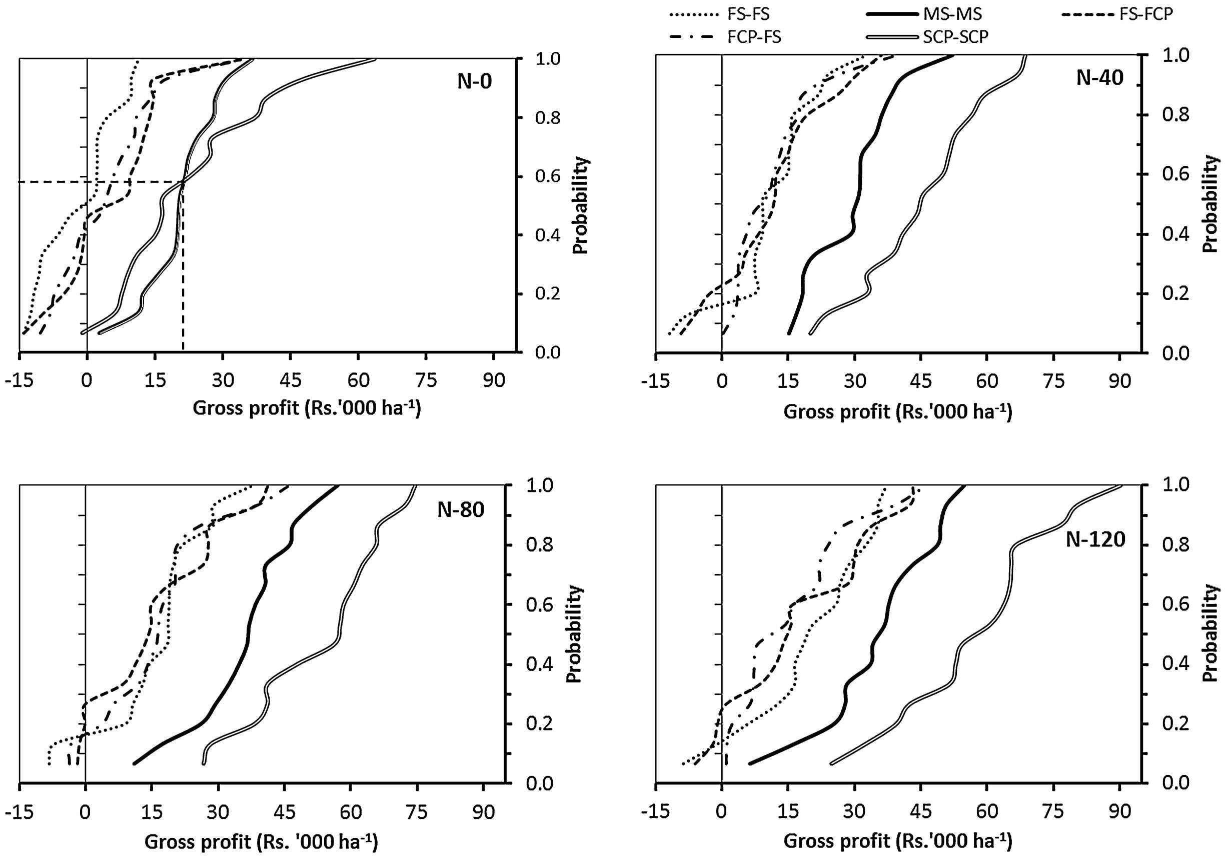

Fig. 10. Cumulative distribution of gross profits for four rates of nitrogen in five cropping systems, showing first-degree stochastic dominance (FDSD) and second-degree stochastic dominance (SDSD) for decision options.

indicate that the mean probability of gross profit is 62%, closest to neutral (50%) and the confidence interval (CI) at 95% probability is between 58% and 65% of the mean (Table B.2) and does not include 50%, hence MS–MS is SDSD over SCP–SCP; it would be the system of choice for risk-averse decision-makers without N application. Both double cropping systems (MS–MS and SCP–SCP) at higher (40, 80, 120 kg N ha^{-1}) rates of N exhibit first degree stochastic dominance compared to all the three fallow post-rainy cropping systems as the probability for greater gross profits exists with double crop systems (plots of N-40, N-80, N-120 in Fig. 10) at all probabilities. Between double crop systems, SCP–SCP has FDSD over MS–MS with N-40 and higher N rates. The eCDFs for FS–FS, FS–FCP and FCP–FS cross each other at higher rates of N, however, FS–FS with 40 and 120 kg applied N ha^{-1}, dominates FCP–FS and FS–FCP, and all three are neutral at 80 kg N ha^{-1} indicating that the FS–FS system with higher rates of applied nitrogen would be a choice of risk-neutral (FDSD) decision-makers among traditional systems.

4. Discussion

In our study, double cropping sequential systems (SCP–SCP and MS–MS) resulted in greater grain and stover yields than the traditional fallow systems. Availability of residual N from the legume crop in the system played a key role in enhancing the productivity of sorghum in the rainy and post-rainy seasons in these double cropped systems. During high rainfall years, erosion, runoff, percolation losses and NH_3 volatilization loss from top soil (Kanwar and Rego, 1983) are considerable. When large rainfall events occurs (generally during Southwest monsoon from July to September), benefits of fallowing is severely limited as fallow systems result in considerable resource use inefficiencies (e.g. land and/or N) when water is no longer the limiting resource. On the other hand, depletion of soil water by the rainy season crop can negatively impact post-rainy season crops in some seasons, as was observed by Prihar et al. (1981) in rainfed wheat. Fallowing is an age-old strategy in the Indian Semi-Arid Tropics to conserve moisture and fertility; Katyal et al. (1987) and Katyal (1988) confirmed that the benefits of fallowing to a post-rainy season crop were evident when rainfall during the rainy season was either normal or low. In the semi-arid regions of India, post-rainy season crops often suffer from water and nutrient limitations under receding soil moisture conditions in several seasons as seen from this long-term experiment. Intensified double cropping systems had greater annual yields, mainly due to additional yields coming either from the sorghum or mung bean grown during the rainy season which resulted in a better utilization of available water and nutrients.

In our study, mung bean N uptake was 35 kg N ha^{-1} without N application in the MS–MS system. Shah et al. (2003) reported that N uptake by mung bean was in the range of 55 to 86 kg N ha^{-1}, of which 54% to almost 82% of N was derived from the atmosphere (% Ndfa). In their study, stover and the grain yield of mung bean were 520–1120 kg ha^{-1} in a summer crop. Mung bean grain yields observed in our study were in the same range, but N uptake rates were 10 to 20 kg ha^{-1} lower. This difference is probably because N uptake estimates in their study included N in the below-ground root biomass. In our study mung bean N uptake estimates were similar to the 30–40 kg N per ton of legume whole plant biomass reported in a review by Peoples et al. (2008) that examined the factors contributing to the observed benefits of legumes in crop rotations. Residual N effects of mung bean on the succeeding sorghum was equivalent to about 4.5 kg N ha^{-1} yr^{-1}, which might be coming from biologically fixed N, in the form of nodules, plant roots and stubbles which remained in the soil. Mung bean residual N contribution would have been much higher if plant residues were incorporated after mung bean threshing. Sidhu et al. (2003) reported that mung bean residue incorporation increased subsequent maize crop yield by 39%. However, farmers in India do not incorporate legume stalk after threshing in rainfed systems as most farmers use it as cattle fodder; hence in our study the legume stalk was not incorporated.

In the SCP–SCP double cropping system, rainy season sorghum, a C4 plant with high vegetative growth in the rainy season could effectively use mineralized N to produce greater biomass, thus utilizing the mineralized N which otherwise would be lost in a fallow due to leaching when higher rainfall occurs in the monsoon period. Nitrogen leaching losses are an important environmental consideration in the light textured Alfisols but not in the Vertisols as evidenced in field studies with ^{15}N-labelled fertilizers in Australia (Craswell and Martin, 1975), in the United States (Kissel et al., 1976) and at ICRISAT in India (Moraghan et al., 1984) as most of the fertilizer N was accounted for in the soil–plant systems in these studies. In this long-term experiment, N rates applied as urea were in two split doses band-placed below the soil surface. The highest dose of applied N was 120 kg N ha^{-1}, less than the 150 kg N ha^{-1} optimal requirement for improved cultivars of sorghum during the rainy season in India (Pal et al., 1982). Furthermore, the low permeability of these Vertisols for water and N, and low (<750 mm) mean annual rainfall in the region were reasons for not considering the risk of N leaching losses. Although rainy season sorghum responded significantly with higher grain yield for high rates of applied N, the post-rainy season chickpea grain yields in the SCP–SCP system were significantly lower than the chickpea yields in the FS–FCP systems. The residual N from the previous post-rainy sorghum crop in the FS–FCP system had a positive effect on the grain yield of chickpea. But, surprisingly, N application to rainy season sorghum in SCP–SCP caused a corresponding decrease in chickpea yield. The causes of this phenomenon are unclear and need to be further investigated. N uptake by double cropping systems was higher compared to traditional systems at all rates of applied N, resulting in higher productivity. This was mostly because double cropping entails a longer crop season than traditional systems and thus a better utilization of available resources, e.g., through prevention of N leaching and water runoff, and the inclusion of N-binding legumes. However, temporal variation in annual N uptake of a given cropping system was primarily due to variation in the seasonal length. Together these results clearly emphasize the importance of using the full length of the crop growing period through well designed sequential double cropping with appropriate rates of N application.

Gross profit margin analysis of the five systems showed that the three traditional systems incurred losses in 5–7 of the 15 years without N application, and in 2–3 years with higher rates of N application. This indicates that the traditional system of rainy season fallowing is financially very risky, particularly when combined with low fertilizer application. On the other hand, on average over the 15 years the MS–MS intensified N-0 systems recorded 46% higher mean gross profit margin and SCP–SCP recorded 39% higher mean gross profit margin than the traditional systems. In addition, SCP–SCP systems resulted in financial losses in only one out of fifteen years, and MS–MS never made a loss. This indicates that these double cropping systems are on average more profitable and less risky than their traditional fallow counterparts. With increased N, intensified double cropping systems gave higher gross profit margins in the range of 54% to 63%, which is an indication of higher potential for economic viability and maximize efficiency of investment in these systems. By contrast, traditional systems without N application made losses in 5 to 7 out of 15 years, which were in the range of −4 to −16% of the total costs of cultivation. Thus, traditional dryland systems are much riskier without N application, and N is a key input for productivity and profitability of these systems.

Risk analysis through the eCDFs of gross profits revealed that for any given level of probability, the gross profit of the MS–MS system is not larger than that of the SCP–SCP system without N application, and the FDSD doesn't exists when differences between two eCDF are small. This entails that if decision-makers are risk neutral, they can choose the SCP–SCP if it offers higher income for a given probability. Conversely, if decision-makers are risk-averse (DeVuyst and Halvorson, 2004), the obvious choice would be the MS–MS system without N application as this system is second degree stochastically dominant offering lower risks albeit at lower mean profits. Stochastic dominance analysis clarifies the dominance of double cropping systems profits compared to traditional fallow systems at all rates N applied. Proper risk analysis requires adequate number of observation across years for cropping systems (Dillon, 2003) to capture the variability for stochastic dominance risk analysis. Our experiment was assessed under rainfed conditions, and the variability in yields between years was largely a consequence of inter-annual rainfall variability. Hence, this risk analysis encompasses effects of inter-annual rainfall variability on rainfed cropping systems productivity and profitability. We provided ex-post analysis of yields over 15 years and MSP of crop yields and fodder in a recent year (2012) to show risk scenarios of cropping systems at different N levels that are relevant for the present.

Crop yields, total productivity and economic returns were greater with double cropped sequential systems compared to traditional fallow and post-rainy season single cropped rotations. Furthermore, sorghum and legume-based systems have become more popular with farmers in recent years as sorghum grain prices have doubled; and the alternative uses of sorghum grain as poultry feed and industrial demand for grain-based alcohol is also increased (Parthasarathy Rao et al., 2010). Sorghum-based systems are relevant today as these are easily adoptable by dryland small holder farmers on Vertisols in the regions with a mean rainfall around 750 mm. However, there were significant year-to-year yield variations in crop yields due to seasonal weather conditions, suggesting the need for identifying suitable systems options for different ENSO analogue years (Nageswara Rao et al., 2007; Piara Singh et al., 2008) to inform farmers on decision-making to minimise the risk of climate variability and to sustain productivity.

5. Conclusions

Grain productivity of double cropping SCP–SCP and MS–MS sequential systems was significantly greater than rainy season fallow FS–FCP or FS–FS systems with N application rates of 40, 80, or 120 kg N applied ha^{-1}; however yield of post-rainy season crops in double crop systems converged with traditional systems at 120 kg N ha^{-1} in some years. Mung bean residual N contribution or fertilizer replacement value to subsequent sorghum was equivalent to ≈9 kg ha^{-1} per two-year rotation in the MS–MS system and chickpea residual N contribution to a subsequent sorghum crop was 7.5 kg ha^{-1} per two-year rotation. Analyses of cropping systems for their economic efficiency in terms of gross profit margin indicate that traditional rainy season fallow systems without N application is an unviable and risky option in the highly variable climate of the semi-arid tropics. Gross profits increased with N application in intensified double cropping systems on Vertisols in this region. Risk analysis indicates double cropping systems at different rates of N provide options for decision makers based on their willingness for risk, to minimise the economic risks or to maximize system productivity compared to traditional fallow systems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eja.2014.09.003.

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