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Sustainable intensification opportunities for Alfisols and Vertisols landscape of the semi-arid tropics

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ABSTRACT

Land and water management interventions are key to achieving sustainable intensification in the drylands. This study explores opportunities for doing so in Vertisols and Alfisols using 34-year (1976–2009) long-term experimental data. Four cropping systems were evaluated in each soil types with two land form management interventions, i.e., raised beds and flat beds. Surface runoff generated and soil water content in each system were monitored along with crop yields. In Vertisols, maize-chickpea sequential cropping and sorghum+pigeon pea intercropping on raised beds representing an improved practice was followed for 34 years (1976–2009). Sole chickpea and sole sorghum were grown on flat beds as a traditional system during the same period. In Alfisols, groundnut/pigeon pea intercrop and sole sorghum were grown for 5 years (2002–2006) and sorghum/pigeon pea intercrop and sole castor were grown for 3 years (2007–2009) under raised bed and flat bed conditions, respectively. The use of improved practices in Vertisols produced 3–5 times higher yield compared to traditional practices with net returns estimated at US$ 800–1300/ha/year compared to US$ 90–350/ha/year under the traditional practice. Despite growing an additional crop, chickpea yield under the improved practice was close to the yield obtained from the traditional practice. In Alfisols, raised beds improved crop yields by 15–20% compared to the flat bed method, leading to an additional net return of US$ 80–100/ha/year. Sorghum/pigeon pea intercrop was found to be superior followed by sole castor, groundnut/pigeon pea intercrop and sole sorghum in Alfisols. Hydrological monitoring revealed opportunities to harvest surface runoff, especially in Alfisols, by building low-cost rainwater harvesting structures that can provide life-saving irrigation during dry spells. An interpretive machine learning (IML) approach was used to estimate four response variables (Sorghum equivalent yield; Net Income; Technical Water Productivity, and Economic Water Productivity) using five different predictor variables (i.e., cropping systems, land form, soil order, effective rainfall (R_{eff}= rainfall-runoff), and water regimes (dry, wet, and normal). Results showed that cropping system is the highest mean feature importance for all the productivity parameters followed by effective rainfall. This paper also discusses soil water dynamics, production functions and technical and economic water productivity which could aid in resource optimization and in developing strategies for land, water and crop management interventions with the aim of bridging yield gaps in the semi-arid tropics.

1. Introduction

Rainfed agriculture contributes to 60% of the global food production from 80% of arable land (Herrero et al., 2017). The livelihoods and food security of nearly 70% of the global population hinge on it (Mashnik et al., 2017). However, rainfed areas are characterized by poverty, malnutrition, land degradation, poor crop intensification and meagre agricultural productivity (van Ittersum et al., 2016; Pandey et al., 2016; Saco et al., 2018; Dhahri and Omri, 2020; de Araújo et al., 2021). Frequent floods and droughts are common (Wei et al., 2021), with climate change further exacerbating the risk of crop failure with increasing incidents of drought and flood (Aggarwal et al., 2010; Tibebu et al., 2018; Lakshmi et al., 2018; Huang et al., 2020; Soni and Syed, 2021). Current yields in rainfed systems range between 0.5 t/ha and 1.5

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t/ha, way below the achievable potential of 2–4 t/ha that is possible by introducing improved land-water-nutrient and agronomic practices (Rockström and Karlberg, 2009; Mueller et al., 2012; Hochman et al., 2012; Ray et al., 2013; van Ittersum et al., 2016; Zhang et al., 2020). There is increasing evidence of the huge untapped potential to bridge this yield gap (Anantha et al., 2021a). The adoption of Agricultural Water Management (AWM) interventions that ensures soil water availability for crop production by reducing non-productive evaporation and protecting soils from degradation is an opportunity waiting to be exploited (Rockström and Karlberg, 2009; Mueller et al., 2012; van Ittersum et al., 2016; Schils et al., 2018; Magombeyi et al., 2018; Monteiro et al., 2020; Anantha et al., 2021a; Anantha et al., 2021b; Anantha et al., 2021c).

Rainfed systems in the semi-arid tropics hold a great promise in their ability to feed growing population in these regions. With rainfall in the range of about 600–1100 mm, these areas allow the cultivation of at least two crops compared to a single crop (Rao et al., 2015; Wani et al., 2016; Flach et al., 2020). Currently, land and water use efficiency in rainfed systems stands at 30–40%, which could be enhanced through in-situ and *ex-situ* land and water conservation measures (Temesgen et al., 2009; Garg et al., 2012; Dile et al., 2014; Singh et al., 2014a; Garg et al., 2020). *In-situ* conservation practices such as field bunding, contour cultivation and terracing are known to improve residual soil water (Anantha et al., 2021a) while *ex-situ* interventions contribute surface runoff to local water bodies such as farm pond, check dams and community ponds (Garg et al., 2020; Singh et al., 2021; Anantha et al., 2022; Garg et al., 2022a; Garg et al., 2022b).

Semi-Arid Tropics (SAT) in Peninsular India are dominated by two contrasting soil types, i.e., Vertisols and Alfisols. Vertisols have high clay content, develop deep cracks after drying and are difficult to plough when wet (Pathak et al., 2016; Hidalgo et al., 2019). These soils occupy nearly 14% of the total arable land in the SAT (Swindale, 1981). Poor drainage is one of the critical challenges during the rainy season. Therefore, farmers prefer to keep their land fallow and raise crops using stored/residual soil water during the post-rainy season, because Vertisols have a relatively high water retention capacity (Selvaraju and Ramaswami, 1997; Srinivasarao et al., 2012; Pal et al., 2012). In contrast, Alfisols are characterized by high sand content and poor water retention capacity (Ahmad et al., 2019). These soils occupy about 20% of the SAT's arable land (Swindale, 1981). Soil crusting is a problem in Alfisols (Pathak et al., 2013). Supplemental irrigation is critical to sustain crops during dry spells (Mandal et al., 2007; Sarker et al., 2020) that are common during the rainy season in the SAT. Growing a second crop during the post-rainy season is only possible with the support of supplemental irrigation. Thus, farmers in both Alfisols and Vertisols systems usually grow only one crop in the rainy or post-rainy season (Kahinda et al., 2007; Sanfo et al., 2017; Vico et al., 2020). Such a challenges can be overcome through a range of land form management practices (Wang et al., 2018; Zhang et al., 2018; Fischer et al., 2019). However, a comprehensive analysis of the improved management of these soils is limited by the availability of sufficient hydrological, agronomic and economic data.

Long-term field experiments at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad have led to a large volume of meteorological, hydrological and agronomic data for different cropping systems and land form conditions for both Vertisols and Alfisols. With an overall objective to analyze such rich data, this study aims to (i) suggest suitable cropping systems in terms of crop yield, profitability and resource use efficiency; and ii) understand the impact of in-situ land form management interventions on crop yields under both Vertisols and Alfisols. We follow an interpretive machine learning (IML) approach (Padarian et al., 2020; Zhu et al., 2021; Jones et al., 2022) to examine how selected crop production factors influence crop yield and water productivity parameters in such typical rainfed systems of SATs.

2. Methods and materials

2.1. Study watersheds

The study was carried out at ICRISAT's research station (17.5192° N; 78.2784° E) in Hyderabad, India, where Alfisols and Vertisols occur naturally within the farm, making it a unique facility to undertake agricultural research covering both soil types. Two naturally drained watersheds of 2–5 ha representing Alfisols and Vertisols were monitored over a long period of time to generate data from the fields. Table 1, Table 2 and Fig. 1 provide details of the location, layout, duration, cropping system and land form management of the experiments.

2.2. Physical properties of Vertisols and Alfisols

Soil samples from 8 locations in Vertisols and 24 locations in Alfisols were collected to analyze their physical properties. Samples were collected at 15 cm depth interval to determine in-situ dry bulk density using the core cutter method (Cresswell and Hamilton, 2002). Soil textural fractions (sand, silt and clay content) were determined using the hydrometer method (Bouyoucos, 1962; Beverwijk, 1967). Organic carbon in these samples was analyzed using the Walkley-Black wet oxidation method (Nelson and Sommers, 1982). Soil water retention at − 0.3 MPa (field capacity) and − 15.0 MPa (permanent wilting point) were measured using pressure plate technique (Richards, 1948). Layer-wise soil texture and retention parameters for Vertisols and Alfisols are presented in Table 3. The sand content in Vertisols ranged between 15.4% and 28.7% and clay content between 51.8% and 61.8%. Clay content increased with increasing depth. Silt content was almost consistent (20.6–22.7%) across soil layers. The field capacity of Vertisols ranged from 0.28 to 0.40 (w/w) and permanent wilting point between 0.21 and 0.31 (w/w). Bulk density of the top layers of Vertisols was significantly lower (1.17 g/cm^3) compared to the deeper layers (1.33–1.36 g/cm^3) and organic carbon ranged between 0.16% and 0.27%. As expected, clay content plays a major role in Vertisols giving high moisture retention capacity that can be directly correlated with their clay content (>50%). The soil depth of the experimental site was 1.8 m, which can hold a maximum of 700 mm moisture and plant available water storage (FC-PWP) of 200 mm.

Alfisols are characterized by high sand content that ranges between 56.3% and 74.6%, clay content between 18.1% and 35.4% and silt between 7.0% and 8.4% in different soil layers (Table 3). Sand content decreased with increasing soil depth while clay content increased with soil depth. Field capacity and permanent wilting point were 0.11% and 0.06 (w/w) in the top layers of Alfisols compared to 0.13–0.17 and 0.07–0.10 (w/w), respectively, in the deeper layers. Bulk density of Alfisols was between 1.45 g/cm^3 and 1.53 g/cm^3 and organic carbon ranged from 0.45% to 0.57% in different soil layers. The soil depth of the experimental site was 1.0 m, which can hold 200 mm water at field capacity and with a plant available water storage of 80 mm.

2.3. Experimental details

2.3.1. Vertisol watersheds

Long-term studies were undertaken between 1976 and 2009 in paired micro-watersheds of almost similar size of 3.5 ha (Fig. 1). Of these, raised beds were prepared in one of the watersheds as an improved practice while the other watershed was left with traditional flat bed conditions. Raised beds with 1 m wide and 0.5 m furrow were developed using a tropicultor (Singh et al., 1999; Khambalkar et al., 2014), which function as mini bunds reducing the velocity of runoff and increasing water infiltration (Kampen and Krantz, 1976). Intercropping of cereals and pulses (sorghum/pigeon pea) or sequential cropping of cereals followed by pulses (maize-chickpea) were practiced in raised beds (Table 1). Sorghum/pigeon pea intercropping and maize-chickpea sequential cropping were followed in rotation for 34 years. Dry sowing

Table 1
Details of the experiments carried out on Vertisols between 1976 and 2009.

System	Improved practice				Traditional practice	
Experimental years	1976 – 2009				1976 – 2009	
Watershed area (ha)	3.48				3.41	
Land slope (%)	1.8–2.0				1.8–2.0	
Land form	Raised bed (plot 1 and plot 2)				Flat bed (plot 3 and plot 4)	
Cropping system	1. Sorghum/pigeon pea		2. Maize-chickpea		3. Fallow-sorghum	4. Fallow-chickpea
Experiment years	1976–2009 (Alternate)		1976–2009 (Alternate)		1976–2009	1976–2009
Duration of experiments (years)	34		34		34	34
Crops cultivated	Sorghum	Pigeon pea	Maize	Chickpea	Post-rainy sorghum	Chickpea
Sowing months	June	June	June	October	October	October
Harvesting months	October	February	October	March	March	March
Fertilizer application	60 kg N/ha 20 kg P/ha		60 kg N/ha 20 kg P/ha		10 t/ha of farmyard manure (FYM) (alternate year)	

Table 2
Details of the experiments carried out on Alfisols between 2002 and 2009.

Cropping system	Land form	1. Sole sorghum	2. Groundnut/pigeon pea intercrop		3. Sole castor	4. Sorghum/pigeon pea intercrop	
Experiment years		2002–2006	2002–2006		2007–2009	2007–2009	
Duration of experiments (years)		5	5		3	3	
Fertilizer application	Raised bed (plot 1 and 2)	40 kg N/ha; 40 kg P_2O_5/ha	20 kg N/ha; 40 kg P_2O_5/ha		40 kg N/ha; 40 kg P_2O_5/ha	40 kg N/ha; 40 kg P_2O_5/ha	
	Flat bed (plot 3 and 4)	FYM: 10 t/ha (every alternate year)					
Crops cultivated		Sorghum	Groundnut	Pigeon pea	Castor	Sorghum	Pigeon pea
Sowing months		June	June	June	June	June	June
Harvesting months		October	October	February	October	October	February

Land slope =1.6%

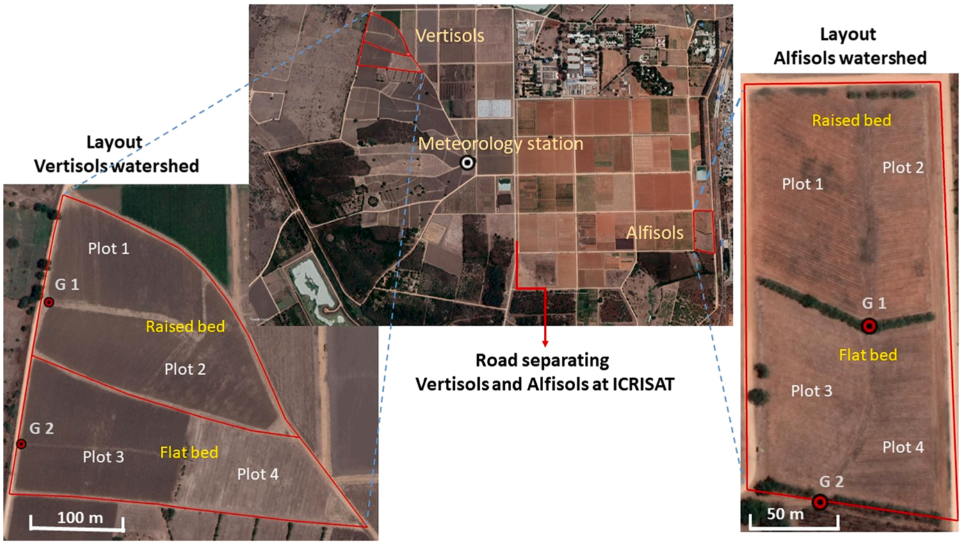

Fig. 1. Layout of the experimental watersheds on Vertisols and Alfisols.

was undertaken before the rainy season (2nd/3rd week of June) as Vertisols are difficult to manage under wet conditions and chickpea was sown in October. The recommended dose of fertilizers (60 kg N/ha and 20 kg P/ha) was applied to maintain soil fertility. Nitrogen was applied in split doses (50% as basal and the remaining at 30 days after sowing) and phosphorus fertilizer was applied as a basal dose. To represent farmers' practice under Vertisols, the land was kept fallow during the rainy season and a sole crop of sorghum and chickpea was sown in two separate plots on a flat bed during October. About 10 t/ha of farmyard manure (FYM) was applied every alternate year to represent the traditional practice. Data collected between 1976 and 2009 on sowing and harvesting dates are provided in Table 1. Crop cutting studies (Tek et al., 2016) were conducted during the harvesting stage to determine crop yields from different experimental plots.

2.3.2. *Alfisols watersheds*

The upstream side of the Alfisols watershed was treated with raised beds and its downstream side was retained with flat beds (Fig. 1). Two cropping systems were followed at a time in both the raised beds and flat beds, making it four treatments within a season. Sole sorghum and groundnut/pigeon pea intercrop were followed between 2002 and 2006. For the next 3 years (2007–2009), sole castor and sorghum/pigeon pea intercrop were adopted both in raised beds and flat beds. Table 2 shows the cropping system, fertilizer dosage applied and sowing and harvesting months in the Alfisols watershed. Crop cutting studies were undertaken during the harvesting stage to estimate crop yields from different

Table 3
Soil texture, moisture retention and bulk density at different soil depths in the Vertisols and Alfisols of experimental watersheds at ICRISAT, Hyderabad, Telangana.

Parameters	**Vertisols (n=8)**				**Alfisols (n=24)**			
Soil depth (cm)	0–15	15–30	30–60	60–90	0–15	15–30	30–60	60–90
Sand (%)	27.6 (3.6)[1]	28.7 (9.5)	20.8 (3.5)	15.4 (5.0)	74.6 (7.3)	67.3 (9.2)	61.0 (8.8)	56.3 (6.4)
Silt (%)	20.6 (0.8)	20.9 (3.7)	21.5 (2.0)	22.8 (1.3)	7.2 (1.1)	7.0 (0.9)	7.5 (1.1)	8.4 (1.4)
Clay (%)	51.8 (3.0)	50.4 (6.1)	57.7 (3.2)	61.8 (4.1)	18.1 (6.8)	25.6 (8.9)	31.5 (8.3)	35.4 (5.7)
Field capacity (w/w)	0.28 (0.02)	0.27 (0.02)	0.34 (0.04)	0.40 (0.06)	0.11 (0.02)	0.13 (0.03)	0.16 (0.02)	0.17 (0.02)
Permanent Wilting Point (w/w)	0.21 (0.02)	0.21 (0.02)	0.27 (0.03)	0.31 (0.04)	0.06 (0.015)	0.07 (0.016)	0.09 (0.013)	0.10 (0.011)
Bulk density (g/cm^3)	1.17 (0.08)	1.33 (0.06)	1.36 (0.08)	1.36 (0.03)	1.45 (0.05)	1.53 (0.04)	1.53 (0.05)	1.42 (0.04)
Organic Carbon (%)	0.27	0.17	0.16	0.16	0.53	0.52	0.57	0.45

Note: n = number of location where soil samples were collected

[1] Values in parentheses indicate standard deviation from the mean.

experimental plots.

2.4. Meteorological and hydrological monitoring

Daily data on rainfall, maximum and minimum temperatures, pan evaporation and solar radiation were collected from the meteorological observatory located within one kilometer of the experimental sites (Fig. 1). Rainfall data was analyzed between 1978 and 2019 (42 years) to understand rainfall characteristics. The analysis was done using the following classification: Dry year = rainfall < 20% of long-term average; normal year = ± 20% of long-term average; and wet year = rainfall > 20% of long-term average (Rao et al., 2013). Stage level recorders were installed in the paired watersheds to record surface runoff (represented by G1 and G2 in Alfisols and Vertisols watersheds in Fig. 1). A stilling well was placed at the outlet, which was hydraulically connected to the H-flume. The stage of the flowing water's depth was converted into water volume using a standard rating curve for different rainfall events (Chow, 1959; Kumar, 2011). These stages were converted to values representing discharge (runoff volume) using the rating curves, as detailed by Pathak et al., (2013, 2016) and Garg et al. (2022a).

To understand the water utilization pattern from the root zone, soil water content measurements were taken at bi-monthly intervals in Vertisol plots. A soil core of 5 cm diameter was collected manually at every 15 cm up to a depth of 180 cm to measure soil water content through gravimetric method. Samples are collected from all 4 plots in Vertisols during 2009. In Alfisols, tensiometers with pressure transducers (soil measure: SW-010; Hubbell and Sisson, 1998; Wang et al., 1998) were installed at 60–75 cm, 75–90 cm and 90–105 cm depths in all the plots for the bi-monthly measurement of matric potential head between 2003 and 2009.

2.5. Water productivity

Data collected from all the experimental fields were analyzed to assess the influence of land form management interventions on surface runoff based on effective rainfall (R_{eff}), which was estimated as the difference between measured rainfall (mm) and surface runoff (mm) values (Ali and Mubarak, 2017). As multiple crops were grown in four different fields, it was difficult to compare the produce. Therefore, crop yields and system level productivity for the entire year were analyzed by converting grain yield into sorghum equivalent yield (SEY) such that all cropping systems could be compared (Assefa et al., 2021):

$$SEY_i = Y_i \times \frac{P_i}{P_s} \tag{1}$$

where Y_i is the plot yield (t/ha) of i^{th} crop to be converted into its SEY (t/ha), P_i is the price of the crop (US\$/t), and P_s (US\$/t) is the price of sorghum. Similarly, net returns (NI_a; Assefa et al., 2021), technical water productivity (TWP; Ren et al., 2021), and economic water productivity (EWP; Wani et al., 2017) values were estimated as follows:

$$NI_a\left(\frac{US\$}{ha.year}\right) = \sum\nolimits_{i=1}^{n} Y_i \times P_i - COC_i \tag{2}$$

$$\mathrm{TWP}\left(\frac{kg}{m^3}\right) = \frac{\sum_{i=1}^{n} SEY_i \times 100}{R_{eff}} \tag{3}$$

$$\mathrm{EWP}\left(\frac{US\$}{m^3}\right) = \frac{\sum_{i=1}^{n} (Y_i \times P_i - COC_i)}{R_{eff} \times 10} \tag{4}$$

where COC_i is the cost of cultivation (US\$/ha) and n is the number of seasons.

2.6. Prediction of productivity parameters and interpretive machine learning

Both step-wise multiple linear regression (MLR) and random forest (RF) modeling (Breiman, 2001) approaches were employed to estimate four response variables (*SEY*, *NI*, *TWP*, and *EWP*) using five different predictor variables of cropping systems, land form, soil order, effective rainfall (R_{eff}= rainfall-runoff), and water regimes (dry, wet, and normal) based on the extent of rainfall. The RF is an ensemble machine learning algorithm based on decision trees for which single decision trees are fitted by partitioning the covariate values of the calibration dataset. Partitions are evaluated based on a splitting metric, and the partition providing the optimal value of the metric is selected. This procedure is repeated until a user-defined value of the node size is reached. The prediction value of a single tree is taken as the average prediction of all nodes at the terminal leaf. In RF, an additional procedure of bootstrapping and aggregating is introduced, where a user-defined number of trees are built from bootstrap samples of the calibration data. In each tree, a random perturbation is further introduced where only a subset of the covariates is used for fitting the tree. The final prediction from a RF model is the average of all the decision trees. We also implemented a step-wise MLR model, which predicts a response variable based on several predictor variables. Both models were trained using 70% of the dataset, and the remaining 30% was used to test their robustness. To tune the hyper parameters of the models a ten-fold cross-validation technique is used. The trained models were evaluated on the test data using coefficient of determination (R^2), root-mean-squared error (RMSE), and bias:

$$R^2 = 1 - \frac{\sum_{j=1}^{N} \left(y_j - \widehat{y}_j\right)^2}{\sum_{j=1}^{N} \left(y_j - \overline{y}\right)^2} \tag{5}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{j=1}^{N} \left(y_j - \widehat{y}_j\right)^2} \tag{6}$$

$$bias = \frac{\sum_{j=1}^{N} \left(\widehat{y}_j - y_j\right)}{N} \tag{7}$$

where N is the number of observations, y_j and $\widehat{y}_j$ are the observed and predicted productivity parameters for the j^{th} observation, respectively, and $\overline{y}_j$ is the mean of the observed parameter. After a predictive model was developed for a response variable, we used the Shapley additive explanation (SHAP) to quantify the influence of each predictor (feature) variable on a response variable (Lundberg and Lee, 2017). Recent studies have shown that SHAP values may be used for determining the effects of environmental covariates on soil properties (Wadoux et al., 2022; Padarian et al., 2020); similarly, Abramoff et al. (2023) used these values to interpret the effects of climate change on global crop yield. Generally, SHAP values are calculated for each observation in a training dataset; the sum of SHAP values provides a quantitative measure for the deviation of estimated response variables at each observation point from the average estimate. A positive SHAP value indicates that the predictor has a positive contribution on the corresponding response variable while the reverse is true for the negative values. Thus, SHAP values provide both the local model explanation and a quantitative measure of how each feature variable influences a response variable at every observation point. We used the *KernelSHAP* package (*ver.* 0.3.5) in the R software (R Core Team, 2023) to estimate SHAP values. This package uses the *KernelExplainer* function, which is an efficient and model-agnostic method for estimating SHAP values for any model. All the modeling and validation steps were carried out in RStudio 2023.03.0 (RStudio Team, 2023).

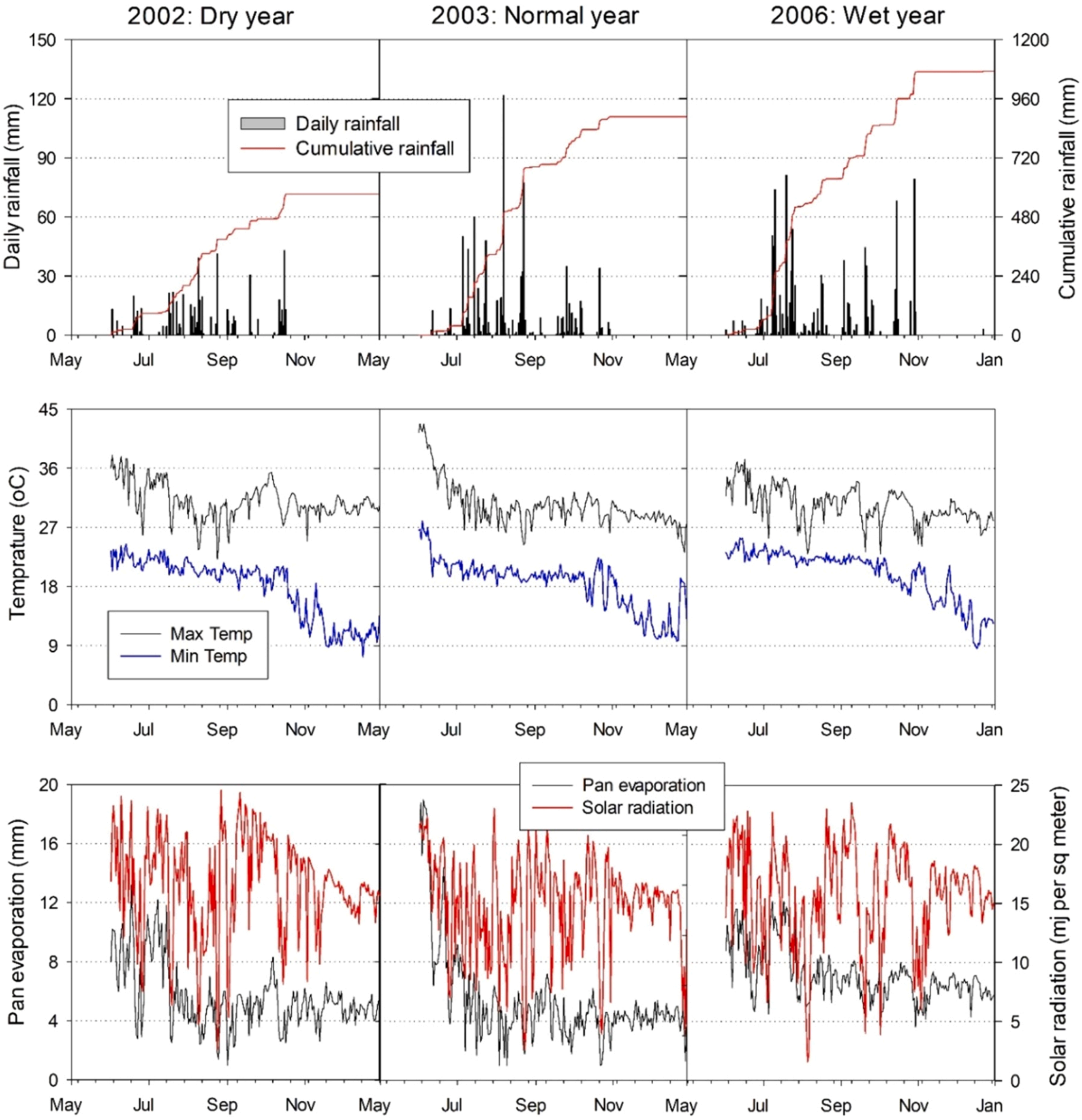

Fig. 2. Variation in daily rainfall, temperature (maximum and minimum), pan evaporation and solar radiation between June and December in select dry (2002), normal (2003) and wet (2006) years.

3. Results

3.1. Rainfall and other meteorological parameters

Annual rainfall at the study site ranged from 450 mm to 1500 mm with an average value of 860 mm. Nearly 85% of the annual rainfall was received between June and October, which is the main cropping season in this region. Fig. 2 shows the rainfall distribution pattern in a typical dry, normal and wet year. To illustrate the rainfall distribution and other meteorological parameters, three different years were shown as dry, normal and wet years. The year 2002 was categorized as a dry year with a total rainfall of 522 mm between June and December. Runoff recorded during this year was negligible (< 20 mm) in both Vertisols and Alfisols plots. While the highest rainfall event during 2002 was about 40 mm, its distribution was relatively uniform as the longest dry spell recorded during the year was less than 12 days. The year 2003 was a normal year with 887 mm of rainfall of which about 70% (~644 mm) was received during July to August. Further, from the last week of August to the third week of September (25 days), there was a long dry spell with the exception of one meagre rainfall event (<8 mm). Total runoff volumes generated in the Alfisols and Vertisols during 2003 were in the order of about 181–198 mm and 85–141 mm, respectively. The year 2005 was a wet year with a total rainfall of 1072 mm, which was well-distributed with a combination of high to low intensity showers throughout the season. Total runoff volumes for such a wet year were in the order of 258–275 mm in Alfisols and 224–344 mm in Vertisols. Daily maximum and minimum temperatures, solar radiation and pan evaporation values in selected dry (2002), normal (2003) and wet (2006) years are presented in Fig. 2, which show similar patterns across these water regimes. For instance, total pan evaporation between June and December was 1193 mm, 1128 mm and 1022 mm in 2002, 2003 and 2006, respectively. Average maximum and minimum temperatures in all three years between June and December were in the order of 30 °C and 18 °C, respectively. Average solar radiation in 2002, 2003 and 2006 was 17 MJ/m^2, 15 MJ/m^2 and 16 MJ/m^2, respectively.

3.2. Performance of improved and traditional practices

3.2.1. Vertisols

Fig. 3a shows the fluctuation in soil water contents and rainfall amounts during the year 2009 in the experimental Vertisol plots of sorghum/pigeon pea intercrop, maize-chickpea sequential cropping and fallow-chickpea. In the beginning of July, total depth of soil water in the top 180 cm soil profile was estimated to be 480–520 mm, which increased to about 600 mm by the end of October because of the monsoon rains. Soil water contents in fallow-chickpea plots were slightly higher compared to those in maize/chickpea or sorghum/pigeon pea plots. Soil wetness started declining after October in all the three cropping systems. By the end of December, the total depth of soil water again reduced to about 550 mm, 560 mm, and 500 mm in the sorghum/

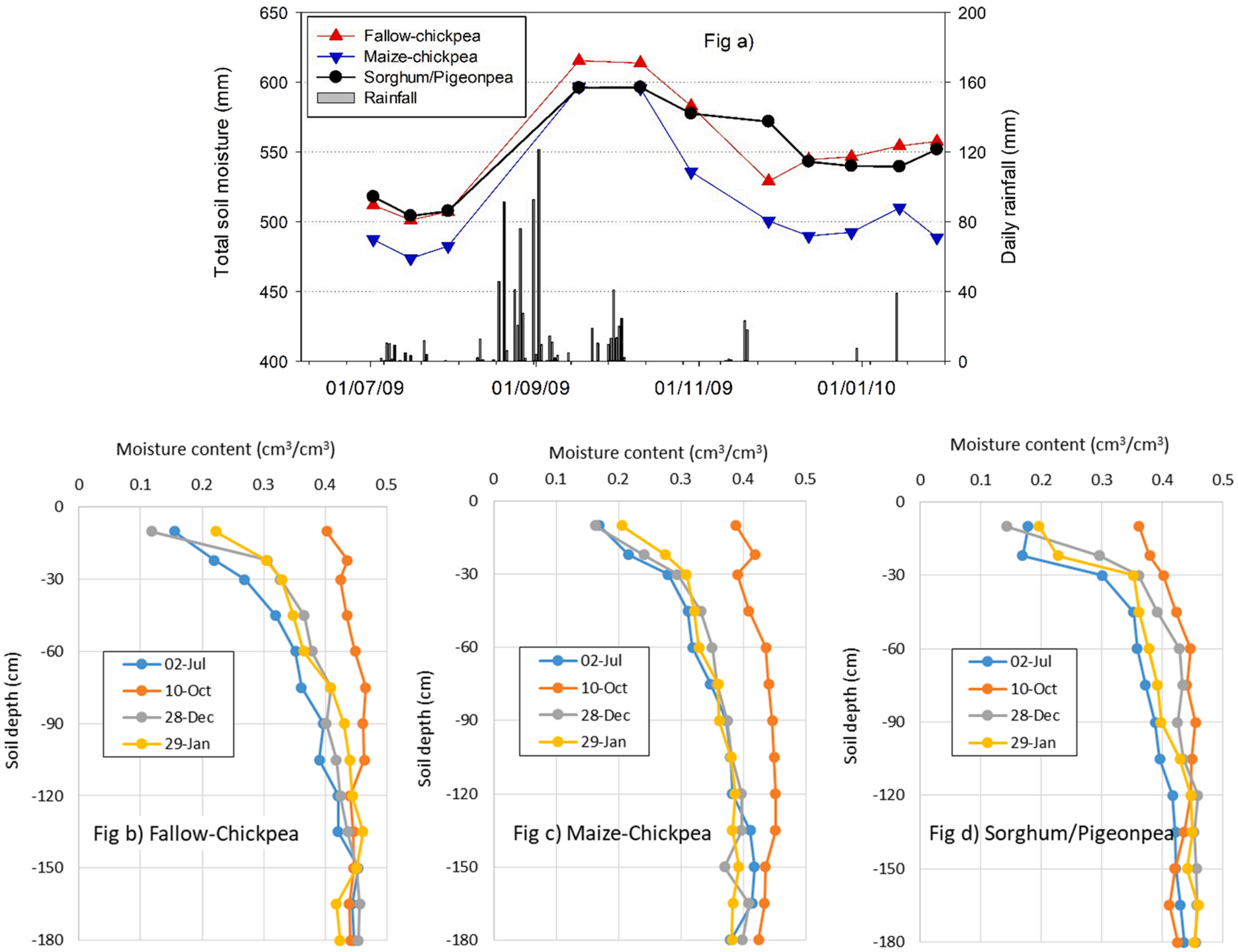

Fig. 3. a) Variation in soil water content at 0–180 cm depth during 2009 and layer-wise soil water content on different dates in (b) fallow-chickpea, (c) maize-chickpea and **(d)** sorghum/pigeon pea cropping systems in Vertisols.

pigeon pea, maize-chickpea and fallow-chickpea cropping systems.

Fig. 3b-d show the volumetric soil water contents at different depths at the beginning of the rainy season (2 Jul 2009); end of the rainy season (10 Oct 2009); middle of the post-rainy season (28 Dec 2010); and end of the post-rainy season (29 Jan 2010) in the study plots. Moisture depletion was highest in the upper soil layers. Soil water contents at 0–30 cm and 30–60 cm depths fluctuated from 0.10 to 0.45 cm^3/cm^3 and 0.3–0.45 cm^3/cm^3, respectively. Soil water contents exceeded 0.40 cm^3/cm^3 across soil depths by the end of the rainy season in all the experimental plots. Moisture was depleted during the post-rainy season due to water uptake by the crops (chickpea or pigeon pea) as residual moisture was the only source of water. Moisture depletion was prevalent up to a depth of 120 cm in fallow-chickpea and moisture level of 0.45 cm^3/cm^3 across the soil profile declined to 0.30–0.40 cm^3/cm^3 at 30–90 cm depth and to 0.2–0.3 cm^3/cm^3 at 0–30 cm depth by the end of the post-rainy season. In maize-chickpea, high moisture depletion up to 180 cm depth was recorded, indicating chickpea's deep rooting pattern (Fig. 3c). In sorghum/pigeon pea intercrop, moisture depletion was found up to 120 cm depth. Moisture level was higher than 0.40 cm^3/cm^3 below 120 cm and fluctuated to 0.30 cm^3/cm^3 between 30 and 120 cm and was 0.15 cm^3/cm^3 (lower than the permanent wilting point) in the top layers (0–30 cm).

Fig. 4 shows crop yields in raised beds and flat beds in the Vertisol experiments. In the flat beds, chickpea and sorghum which were cultivated in two different plots during the post-rainy season produced average yields of 1.2 t/ha and 1.1 t/ha, respectively. However, the yields ranged from 1.0 to 1.4 t/ha in chickpea and 0.6–1.6 t/ha in sorghum (within the interquartile range of the experimental data set). In the sorghum/pigeon pea intercrop, sorghum which was harvested first produced an average of 3.3 t/ha (interquartile range of 3.1–4.0 t/ha). Pigeon pea yield was about 1.1 t/ha. Similarly, maize-chickpea sequential cropping under raised beds yielded an average of 4.6 t/ha of maize (interquartile range of 3.8–4.9 t/ha) and 1.4 t/ha of chickpea (interquartile range of 1.2–1.7 t/ha).

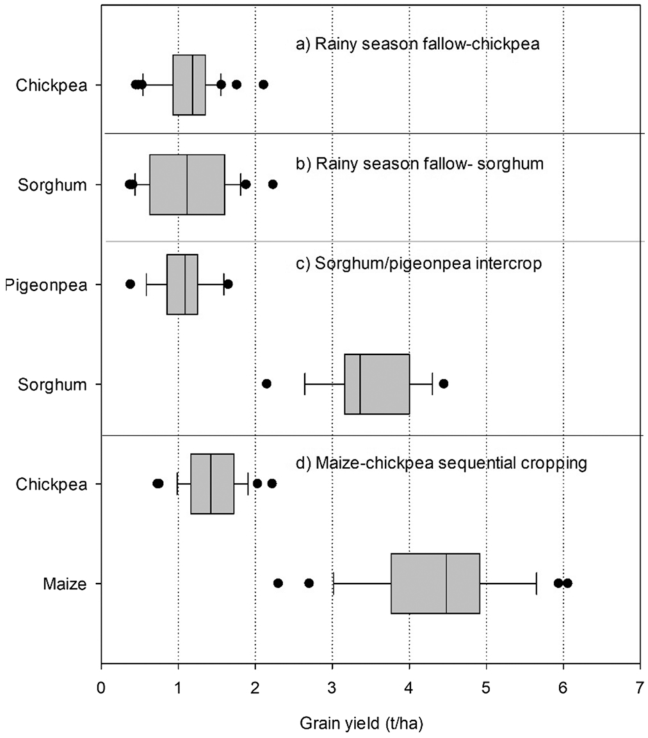

Fig. 4. Crop yields under different cropping systems in raised beds with two seasons of cropping and in flat beds with only post-rainy season cultivation in Vertisols.

A comparison of yields obtained from different cropping systems in Vertisols under dry, normal and wet years (Table 4) showed that out of the 34 years of field experiments, 20 years were normal with an average rainfall (June-October) of 750 mm, 9 were wet years with an average rainfall of 1100 mm and 5 years were dry with 530 mm rainfall. In sole sorghum grown under flat beds where only post-rainy crops are cultivated using residual soil water content, no significant difference in yield was observed between dry, normal and wet years. However, average yield during the normal year was marginally higher (1.16 t/ha) compared to 1.1 t/ha during dry years and 1.08 t/ha during wet years. In sole chickpea, average yield was 1.2 t/ha in normal years, 1.15 t/ha in dry years and 0.99 t/ha in wet years.

In sorghum/pigeon pea intercrop, average sorghum yield was the highest in dry years (3.9 t/ha), which declined with increasing rainfall (3.52 t/ha in normal years and 3.11 t/ha in wet years). As sorghum does not tolerate waterlogged conditions even for short periods (Pardales et al., 1991), crop yields were affected despite the raised beds that facilitate to dispose of excess runoff. The pigeon pea crop benefited from increasing rainfall owing to its deep root system (120 cm; refer Fig. 4d) that could tolerate waterlogging while also meeting water demand in wet years. The average pigeon pea yield in dry years was 0.7 t/ha compared to 1.1 t/ha and 1.34 t/ha in normal and wet years, respectively. This is the reason sorghum/pigeon pea intercropping is widely practiced in the Vertisols of northern Karnataka, southern Telangana and Maharashtra states (Rao and Willey, 1983; Wani et al., 2017). A similar trend was observed in maize-chickpea sequential cropping, where maize yields were the best in dry years (4.79 t/ha) compared to normal (4.33 t/ha) and wet years (4.09 t/ha). Average chickpea yield increased with increase in rainfall during monsoons as it directly affected residual soil water content levels (Fig. 4b-c).

A comparison of sorghum equivalent yield estimated for all four cropping systems during dry, normal and wet years (Table 4) showed that SEY in sole sorghum ranged from 1.1 t/ha to 1.16 t/ha compared to 2.13 t/ha to 2.59 t/ha in sorghum/pigeon pea intercropping. It ranged between 5.93 t/ha and 7.0 t/ha in sorghum/pigeon pea and 6.4 t/ha and 6.7 t/ha in maize-chickpea sequential cropping. This clearly indicates that sorghum/pigeon pea intercropping and maize-chickpea sequential cropping systems are superior to traditional practices. While overall productivity increased with increasing rainfall in the improved practice, it was mostly stagnant in the traditional practice during the study period (1976–2009).

3.2.2. *Alfisols*

Matric potential head was measured at 60–105 cm depth under different cropping systems (sole sorghum, sole castor (Fig. 5a) and groundnut/pigeon pea and sorghum/pigeon pea (Fig. 5b) in both raised beds and flat beds. In sole sorghum and castor, matric potential head reached a matric potential of - 600 to - 700 cm indicating that the crops have utilized residual moisture up to 1 m depth. While matric potential head in the rainy season generally ranged from 0 to – 300 cm, it increased during dry spells and post-rainy period. More water depletion was recorded in intercropping compared to sole cropping. Matric potential heads with 60–105 cm soil layers in almost all the years reached to about – 600 to - 800 cm. A comparison between raised beds and flat beds revealed lower matric potential head in the former than in the latter most of the time, suggesting that raised beds harvested extra surface runoff which was available for subsequent crop utilization. Fig. 5 also shows the sensitivity of matric potential heads to total rainfall and its distribution. For example, matric potential head was much higher (> - 300 cm) in wet years (2006–2007) compared to normal years (2003–2004).

Groundnut/pigeon pea intercropping and sole sorghum were grown on raised beds and flat beds during 2002–2006. The average crop yield obtained from sole sorghum was 2.2 t/ha (range: 1.3–2.5 t/ha) under flat beds compared to 2.5 t/ha (range: 1.7–2.95 t/ha) under raised beds (Fig. 6a & b). In the groundnut/pigeon pea intercrop, average groundnut

Table 4
Performance indicators in Vertisols in dry, normal and wet years.

System		Dry years ($n = 5$)		Normal years ($n = 20$)		Wet years ($n = 9$)	
		Improved practice	Traditional practice	Improved practice	Traditional practice	Improved practice	Traditional practice
Rainfall		535 (48)[1]	535	750 (117)	750	1100 (78)	1100
Runoff		12 (14)	47 (46)	80 (64)	152 (84)	250 (56)	379 (59)
Effective rainfall		523 (38)	488 (36)	670 (81)	598 (73)	850 (61)	721 (47)
Measured crop yield (t/ha)							
i) Sorghum/pigeon pea	Sorghum	3.91 (0.77)	-	3.52 (0.38)	-	3.11 (1.03)	-
	Pigeon pea	0.70 (0.45)	-	1.05 (0.33)	-	1.34 (0.18)	-
ii) Maize-chickpea	Maize	4.79 (1.83)	-	4.33 (0.88)	-	4.09 (0.93)	-
	Chickpea	1.15 (0.50)	-	1.42 (0.37)	-	1.57 (0.39)	
iii) Fallow-sorghum	Post-rainy sorghum	-	1.10 (0.67)	-	1.16 (0.57)	-	1.08 (0.48)
iv) Fallow-chickpea	Chickpea	-	1.15 (0.18)	-	1.20 (0.41)	-	0.99 (0.33)
Sorghum equivalent yield (t/ha)							
i) Sorghum/pigeon pea		5.93 (1.27)	-	6.58 (1.23)	-	7.00 (1.51)	-
ii) Maize-chickpea		6.47 (2.48)	-	6.66 (1.31)	-	6.78 (1.43)	-
iii) Fallow-sorghum		-	1.10 (0.67)	-	1.16 (0.57)	-	1.08 (0.48)
iv) Fallow-chickpea		-	2.48 (0.38)	-	2.59 (0.88)	-	2.13 (0.71)
Sorghum equivalent WP (kg/m^3)							
i) Sorghum/pigeon pea		1.10 (0.18)	-	1.02 (0.12)	-	0.80 (0.10)	-
ii) Maize-chickpea		1.25 (0.39)	-	0.99 (0.25)	-	0.81 (0.16)	-
iii) Fallow-sorghum		-	0.17 (0.15)	-	0.20 (0.10)	-	0.15 (0.06)
iv) Fallow-chickpea		-	0.51 (0.08)	-	0.44 (0.16)	-	0.30 (0.10)
Net return (US$/ha)							
i) Sorghum/pigeon pea		889 (119)	-	1037 (280)	-	1134 (344)	-
ii) Maize-chickpea		1241 (563)	-	1284 (298)	-	1311 (324)	-
iii) Fallow-sorghum		-	87 (172)	-	150 (130)	-	134 (109)
iv) Fallow-chickpea		-	333 (87)	-	358 (200)	-	252 (162)
Economic WP (US$/m^3)							
i) Sorghum/pigeon pea		0.16 (0.02)	-	0.16 (0.03)	-	0.13 (0.03)	-
ii) Maize-chickpea		0.24 (0.09)	-	0.19 (0.05)	-	0.16 (0.04)	-
iii) Fallow-sorghum		-	0.016 (0.03)	-	0.025 (0.02)	-	0.018 (0.01)
iv) Fallow-chickpea		-	0.07 (0.02)	-	0.06 (0.04)	-	0.04 (0.02)

Note: n = number of years. [1] Numbers in parentheses indicate standard deviation.

yield was 0.3 t/ha (0.2–1.25 t/ha) on flat beds compared to 0.35 t/ha (0.3–1.5 t/ha) on raised beds. Pigeon pea which was harvested 3 months after groundnut gave 1 t/ha under flat beds compared to 1.3 t/ha under raised beds. Raised beds had an advantage of about 5–20% in terms of crop productivity. A large variability in yield was observed during the study years. Experiments were undertaken during 2007–2009 with sole castor and sorghum/pigeon pea intercrop under raised beds and flat beds. Average yield obtained from sole castor from flat beds and raised beds were 0.6 t/ha and 0.9 t/ha, respectively (Fig. 6c and d). In the sorghum/pigeon pea intercrop, sorghum yield was 1.4 t/ha in flat beds compared to 2.0 t/ha in raised beds while pigeon pea yielded 0.6 t/ha on flat beds compared to 0.8 t/ha on raised beds.

Table 5 shows the yields from different cropping system under both land form conditions in dry, normal and wet years in Alfisols. Between 2002 and 2006, 2 years were normal with 750 mm rainfall, 2 were wet with 1070 mm rainfall and 1 year was dry with 573 mm rainfall. Yields from sole sorghum were the highest in wet years (2.6–2.8 t/ha) followed by dry and normal years. In the groundnut/pigeon pea intercrop, average groundnut yield in normal years ranged between 0.3 t/ha and 0.4 t/ha and pigeon pea yielded between 0.65 t/ha and 0.87 t/ha; however, yields obtained during dry and wet year were relatively higher. Rainfall distribution played an important role in fulfilling crop-water requirement. For example, the year 2002 was a dry year with 573 mm rainfall, but better rainfall distribution led to maximum yields (Fig. 2). Highest productivity was achieved in the sorghum/pigeon pea intercrop (6.5–7.8 t/ha) followed by sole castor (3.8–4.5 t/ha), groundnut/pigeon pea intercrop (2.62–3.5 t/ha) and sole sorghum (1.7–2.1 t/ha).

3.3. *Production function*

3.3.1. *Vertisols*

A production function was developed to describe the relationship between effective rainfall and crop yield. Fig. 7a shows the relationship between effective rainfall and yield of sorghum or maize and chickpea or pigeon pea obtained during different years. Fig. 7b and c show the relationship between effective rainfall and yield of sorghum and chickpea grown on flat beds. Higher effective rainfall had a negative impact on maize and sorghum yields in flat beds while it had a positive impact on chickpea or pigeon pea yields in raised beds. Higher residual moisture helped both intercropped and sequential crops meet their water requirements when grown on raised beds.

It is interesting to note that in the traditional system of farming in which land is left fallow during the rainy season and a sole sorghum or chickpea crop is grown using residual moisture, there was no positive correlation with effective monsoon rainfall. Therefore, there was no additional yield gain in sole cropping compared to intercropping; rather, it correlated negatively as yield declined when soil water content was higher during wet years.

3.3.2. *Alfisols*

The relationship between effective rainfall and sole sorghum yield in Alfisols is presented in Fig. 8a. The relationship between crop yield and rainfall was positive up to 600 mm, after which it turned negative. Sorghum requires less water that is largely met with around 600 mm of rainfall, and hence yields optimally (Bell et al., 2020; Assefa et al., 2010). High rainfall may affect the crop negatively as it is sensitive to prolonged moisture availability and waterlogging that hinders grain formation. The relationship between effective rainfall and groundnut and pigeon pea yields did not show a clear trend. Rainfall variability rather than total rainfall received appeared more responsible for crop

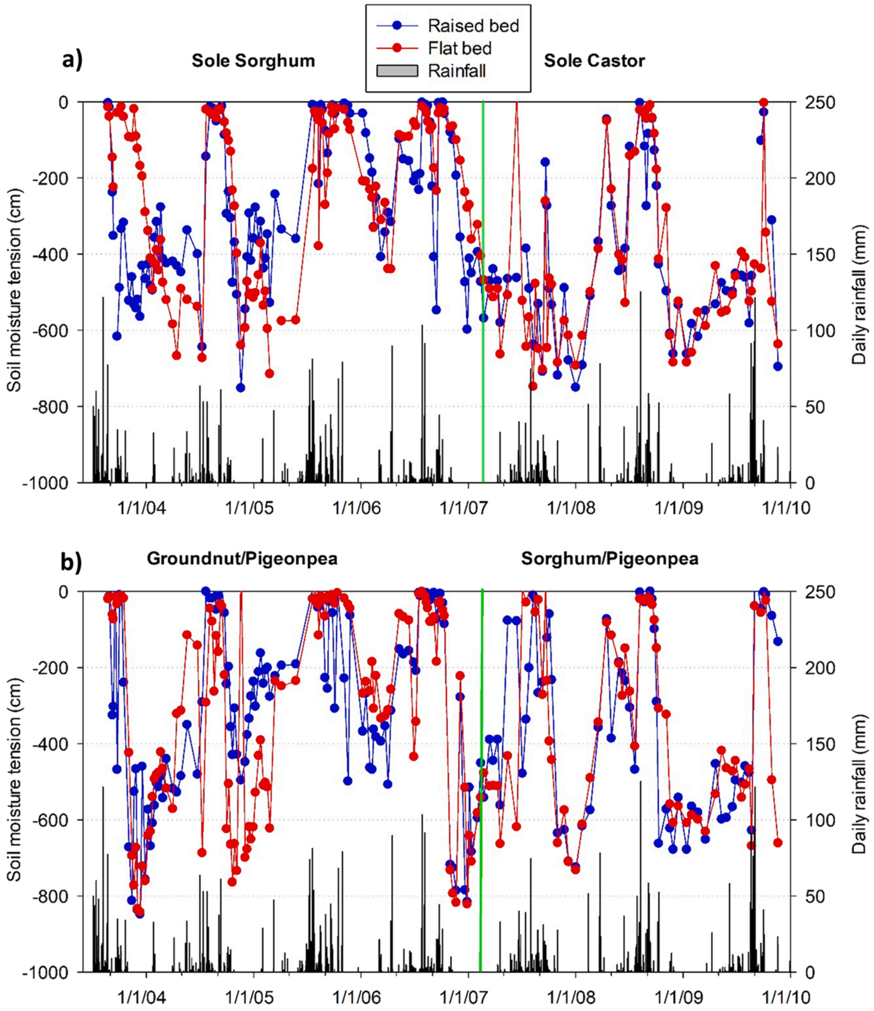

Fig. 5. Matric potential head measured in raised bed and flat bed fields in different cropping systems between 2003 and 2009.

yield. The production function for castor and pigeon pea crops could not be established under the second phase of these experiments as adequate data sets were not available.

3.4. *Water productivity and net returns*

3.4.1. *Vertisols*

Table 4 compares the annual net returns obtained from improved practices (sorghum/pigeon pea intercrop and maize-chickpea sequential crop) and traditional practices (fallow-sole sorghum or chickpea). During normal years, average annual net returns from the improved practice was US$ 1037–1284/ha compared to US$ 150–358/ha from the traditional practice. In dry years, it was US$ 889–1241/ha/year from the improved practice compared to US$ 87–333/ha/year from the traditional one. Net returns in normal and wet years were higher than in dry years in the improved practice. Only normal years showed better net returns compared to dry and wet years in the traditional practice. This suggests that with increased rainfall, there was effective resource utilization resulting in better returns under the improved practice compared to the poor resource utilization in the traditional practice. Annual net returns from maize-chickpea sequential cropping (US$ 1284/ha) was the best followed by sorghum/pigeon pea intercropping (US$ 1037/ha) and sole chickpea (US$ 358/ha) and sole post-rainy sorghum (US$ 150/ha).

The sorghum equivalent water productivity (SE-WP) in Vertisols is presented in Fig. 9a-d and Table 4. The amount of water captured within the landscape (rainfall–runoff) was taken in to account to estimate water productivity. However, a fraction that might have percolated deep was not included in this analysis. Water productivity in the improved practice ranged between 0.8 kg/m^3 and 1.25 kg/m^3 compared to between 0.08 kg/m^3 and 0.16 kg/m^3 in the traditional system, clearly indicating that the former was 5–8 times better than the latter. Water productivity in the improved practice was the highest in dry years (1.1–1.25 kg/m^3) followed by normal (0.99–1.02 kg/m^3) and wet years (0.80–0.81 kg/m^3). Under the traditional practice, it was relatively higher in normal years (0.20–0.44 kg/m^3) and dry years (0.17–0.51 kg/m^3) compared to wet years (0.15–0.30 kg/m^3). Economic water productivity (EWP) was calculated in Vertisols (Table 4 and Fig. 10 a-d), demonstrating the economic returns from the use of every m^3 of fresh water in different cropping systems. In the improved practice, it ranged between US$ 0.13 and US$ 0.24/m^3 compared to between US$ 0.02 and US$ 0.07/m^3 in the traditional practice. In maize-chickpea sequential cropping it was the highest (US$ 0.16–0.24/m^3) followed by the sorghum/pigeon pea intercrop (US$ 0.13–0.16/m^3), sole chickpea (US$ 0.04–0.07/m^3) and post-rainy sorghum (US$ 0.016–0.025/m^3).

3.4.2. *Alfisols*

Net returns from different cropping systems in Alfisols are presented in Fig. 10 e-h and Table 5. Under the groundnut/pigeon pea intercrop during dry year, net return was US$ 1637–1821/ha compared to US$ 429–553/ha in a normal year and US$ 1099–1139/ha in wet years. As rainfall variability played an important role in crop production, especially in Alfisols, the net income from dry years was highest, compared to that from normal and wet years. However, long-term data are needed

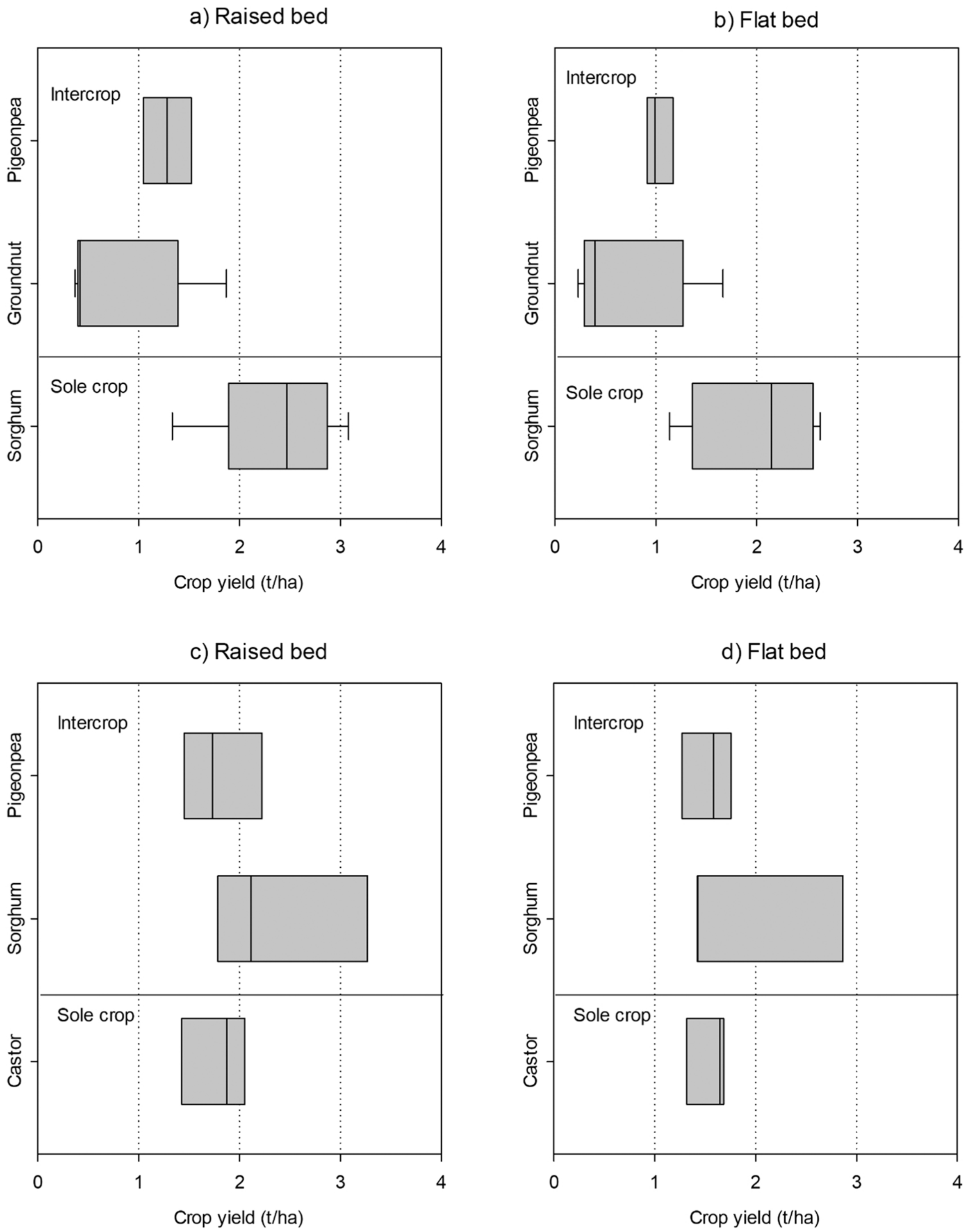

Fig. 6. A comparison of yields under different cropping systems (sole and intercropping) under raised bed and flatbed conditions in Alfisols.

for a better understanding of the trend. In the second phase of the experiments, net returns obtained from sorghum/pigeon pea intercrop was US$ 1345–1569/ha and from sole castor US$ 766–831/ha. Raised beds helped realize a gain of US$ 100/ha on an average. A comparison of all the four cropping systems showed maximum net return accruing from sorghum/pigeon pea intercrop (US$ 1345–1569/ha) followed by sole castor (US$ 766–831/ha) and groundnut/pigeon pea intercrop (US$ 429–553/ha) and sole sorghum (US$ 275–308/ha).

Further, a comparison of sorghum equivalent WP indicated that water productivity from raised beds was 0.39–1.14 kg/m^3 compared to 0.30–1.0 kg/m^3 in flat beds. The highest water productivity was obtained from sorghum/pigeon pea intercrop (1.0–1.14 kg/m^3) followed by sole castor (0.61–0.67 kg/m^3), groundnut/pigeon pea intercrop (0.5–0.66 kg/m^3) and sole sorghum (0.3–0.39 kg/m^3). The economic water productivity (EWP) in sorghum/pigeon pea intercrop was US$ 0.21–0.23/m^3 followed by sole castor (US$ 0.12–0.13/m^3), groundnut/pigeon pea intercrop (US$ 0.08–0.11/m^3) and sole sorghum (US$ 0.05–0.06/m^3) (Fig. 10 e-h and Table 5).

3.5. *Estimation of crop and water productivity parameters*

Table 6 shows the results of MLR and RF model validation for estimating four different crop and water productivity parameters. As expected, the RF approach provided a superior prediction accuracy with R^2 values in the range of 0.74 for the SEY to 0.80 for the EWP compared to the MLR approach (R^2 range: 0.59–0.70). Resulting RMSE values ranged from US$ 0.04 /m^3 for EWP to US$ 236 /ha for the net income. We also performed a 10-fold cross validation (results not shown) and observed superior performance of RF models over MLR approaches. Consistently lower performance of the MLR models implies that there are non-linear relationships in these datasets which MLR models fail to capture. The resulting rank correlation coefficients (Kendall tau) shown in the Table 7 also suggest the presence of strong nonlinearity for both land form and cropping system features. Although extensive hyperparameter tuning was conducted to find out the best set of hyperparameters leading to the minimum cross-validated prediction error, we observed overfitting in the case of net income with its high bias value at US$ 17.13/ha. Nevertheless, the scatter plots in Fig. 11 show close proximity of

Table 5
Performance indicators of Alfisols in dry, normal and wet years.

Particulars		Dry years ($n = 1$)		Normal years ($n = 2$)* ($n = 3$)* *		Wet years ($n = 2$)	
Land form treatment		Flat bed	Raised bed	Flat bed	Raised bed	Flat bed	Raised bed
Rainfall (mm)		573	573	752	752	1070	1070
Runoff (mm)		6	9	130	115	274	257
Effective rainfall (mm)		566	563	622	637	795	812
Measured crop yields (t/ha)							
1. Sole sorghum	Sorghum	2.14	2.47	1.71 (0.73)	2.16 (0.88)	2.63	2.80
2. Groundnut/ pigeon pea intercrop	Groundnut	1.67	1.87	0.31 (0.08)	0.40 (0.03)	1.14	1.23
	Pigeon pea	1.30	1.51	0.65 (0.57)	0.87 (0.79)	0.94	1.03
3. Sole castor	Castor	-	-	1.52 (0.27)	1.75 (0.43)	-	-
4. Sorghum/ pigeon pea intercrop	Sorghum	-	-	2.06 (1.11)	2.48 (1.04)	-	-
	Pigeon pea	-	-	1.52 (0.33)	1.82 (0.52)	-	-
Sorghum equivalent yield (t/ha)							
1. Sole sorghum		2.14	2.47	1.71 (0.73)	2.16 (0.88)	2.63	2.80
2. Groundnut/ pigeon pea intercrop		7.99	9.12	2.67 (1.45)	3.53 (2.26)	5.62	6.11
3. Sole castor		-	-	3.84 (0.68)	4.45 (1.09)	-	-
4. Sorghum/ pigeon pea intercrop		-	-	6.49 (0.40)	7.79 (0.75)	-	-
Sorghum equivalent WP (kg/m^3)							
1. Sole sorghum		0.38	0.44	0.30 (0.13)	0.39 (0.17)	0.33	0.34
2. Groundnut/pigeon pea intercrop		1.41	1.62	0.50 (0.31)	0.66 (0.44)	0.71	0.75
3. Sole castor		-	-	0.61 (0.22)	0.67 (0.24)	-	-
4. Sorghum/pigeon pea intercrop		-	-	1.00 (0.17)	1.14 (0.18)	-	-
Net return (US$/ha)							
1. Sole sorghum		375	377	275 (167)	308 (199)	485	452
2. Groundnut/pigeon pea intercrop		1637	1821	429 (329)	553 (512)	1099	1139
3. Sole castor		-	-	766 (154)	831 (248)	-	-
4. Sorghum/pigeon pea intercrop		-	-	1345 (90)	1569 (171)	-	-
Economic WP (US$/m^3)							
1. Sole sorghum		0.07	0.07	0.05 (0.03)	0.06 (0.03)	0.06	0.06
2. Groundnut/pigeon pea intercrop		0.29	0.32	0.08 (0.06)	0.11 (0.09)	0.14	0.14
3. Sole castor		-	-	0.12 (0.05)	0.13 (0.05)	-	-
4. Sorghum/pigeon pea intercrop		-	-	0.21 (0.03)	0.23 (0.03)	-	-

Note: Figures in parentheses indicate standard deviation. *First phase of the experiment (2002–2006); ** Second phase of experiment (2007–2009).

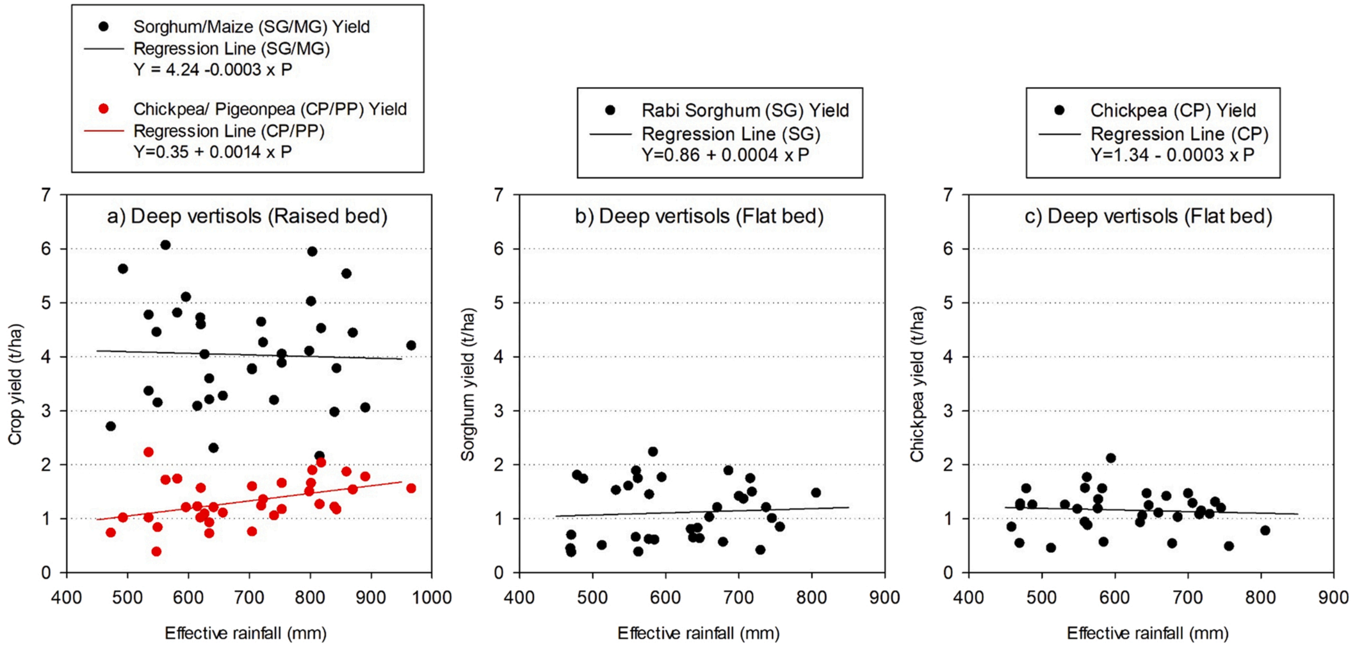

Fig. 7. Relationship between effective rainfall (rainfall– runoff) and crop yields under different cropping systems in Vertisols.

observed vs. predicted response variables around 1:1 line suggesting that the RF model captured the observed variability in our datasets.

The results of interpretive machine learning approach captured with the SHAP values are summarized in Fig. 12. We considered five key feature variables of cropping systems, effective rainfall, land form, soil order, and water regime (wet vs. dry soil water regimes). Fig. 12 shows these feature variables ranked in descending order of importance based on mean absolute SHAP values for each of the four predicted variables (*SEY*, *EWP*, NI_a, and *EWP*). Each point on the SHAP plot represents a data point in the trained model and has the same unit as its predicted variable (e.g., SHAP value for SEY has the unit of t/ha). Because four out of five feature variables were categorical in nature, SHAP plots show clustering of points along the x-y plane. Annotations for each cluster belonging to a subclass (shown as numbers) of these categorical variables are also

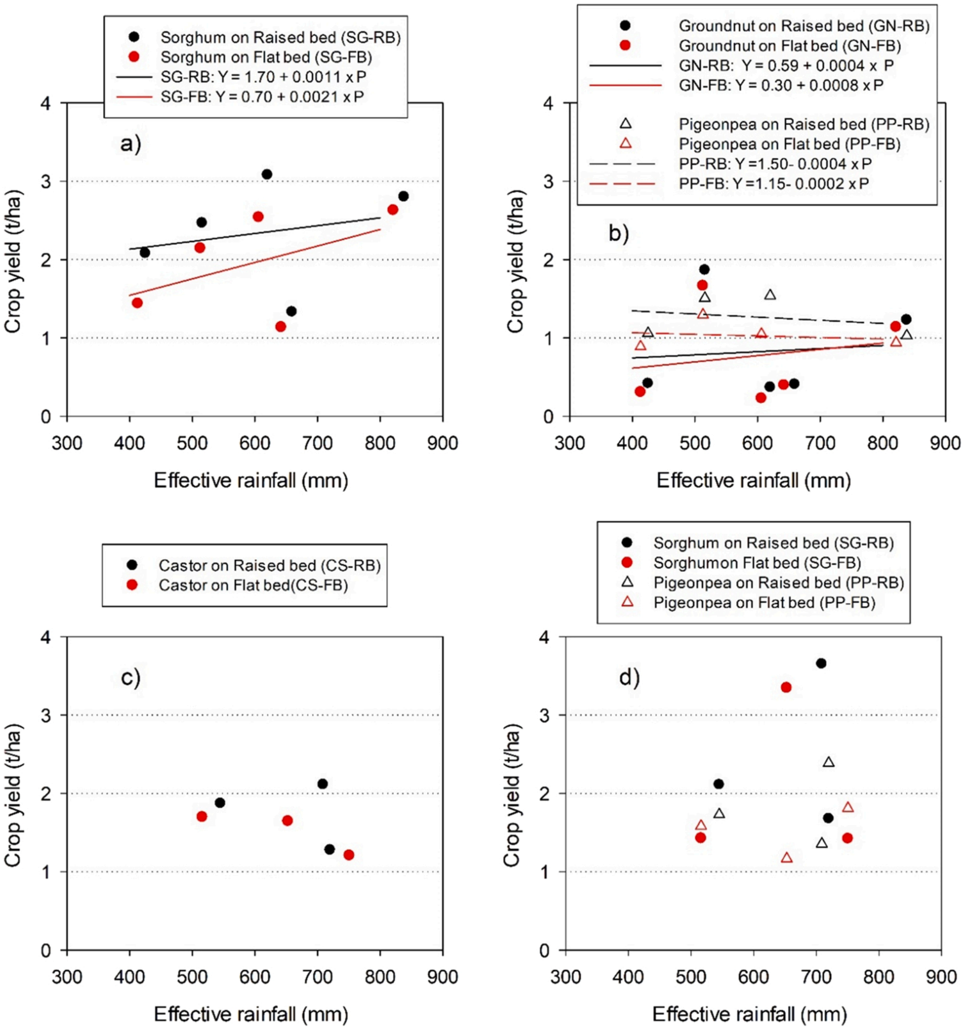

Fig. 8. Relationship between effective rainfall and crop yields under different cropping systems in Alfisols.

shown in this figure. Interestingly, cropping system shows the highest mean feature importance for all the productivity parameters (response variables) followed by effective rainfall in three out of four cases. Specifically, the sorghum/pigeon pea intercropping (subclass 1) and maize-chickpea sequence (subclass 2) have a positive impact on all the productivity parameters; practicing these cropping systems increased the mean *SEY* values up to 2 t/ha (Fig. 12A) and NI_a to about US$ 250–750/ ha (Fig. 12C). On the other hand, fallow-sorghum (subclass 3) and sorghum-fallow (subclass 7) cropping sequences negatively influenced all the productivity parameters reducing *SEY* to the tune of 1.75 t/ha (Fig. 12A) and NI_a up to US$ 416 /ha (Fig. 12C). In the case of land form, the BBF land form showed positive influence on SEY with an increase in the yield in the range of 0.5–1 t/ha (Fig. 12A) whereas the flat bed type of land form has a significant negative impact on *SEY* reducing yield to the tune of 0.24–0.69 t/ha (Fig. 12A). Fig. 12 also shows that soil order plays a distinct role in influencing both yield and water use with superior overall system performance in Alfisols than in Vertisols. Although effective rainfall greater than 750 mm appears to increase *SEY* to the tune of 0.25–1.25 t/ha (Fig. 12A), wet or dry water regimes appear to play a limited role in influencing productivity parameters except for the net income, which can increase for the wet years (water regime: 3). Thus, the SHAP values show consistent and quantifiable influence each feature variable bears on yield and water productivity parameters.

4. Discussion

4.1. Opportunities for sustainable crop intensification

The preceding section revealed how improved practices comprising land form management and a selection of suitable cropping systems not only enhanced resource (land and water) use efficiency but also led to higher productivity. The raised bed method and dry sowing in Vertisols facilitated double cropping in a year compared to single cropping in the traditional practice. The long-term field experiments also revealed that such intercropping and sequential cropping used available moisture more efficiently than in the traditional practice. In the improved practice, total production increased with increasing rainfall as there was consistent demand to utilize soil wetness for crop use. On the contrary, the traditional practice that targeted only the post-rainy season to cultivate crops, failed to use soil wetness effectively. A significant amount of soil wetness that builds up during the rainy season is lost to non-productive evaporation in the absence of crop cover while only marginal use of residual soil wetness occurs during the post-rainy season. In such conditions, water productivity was 4–5 times lower in the traditional practice compared to the improved practice. Under the improved practice, when the first crop which is generally of a short duration is harvested, the intercrop which is often of a long duration and with deep roots, avails the space and moisture from deeper soil layers to pick up growth. So even if the rains are in excess of normal, the deep-rooted, long-duration crop can make use of the additional moisture to

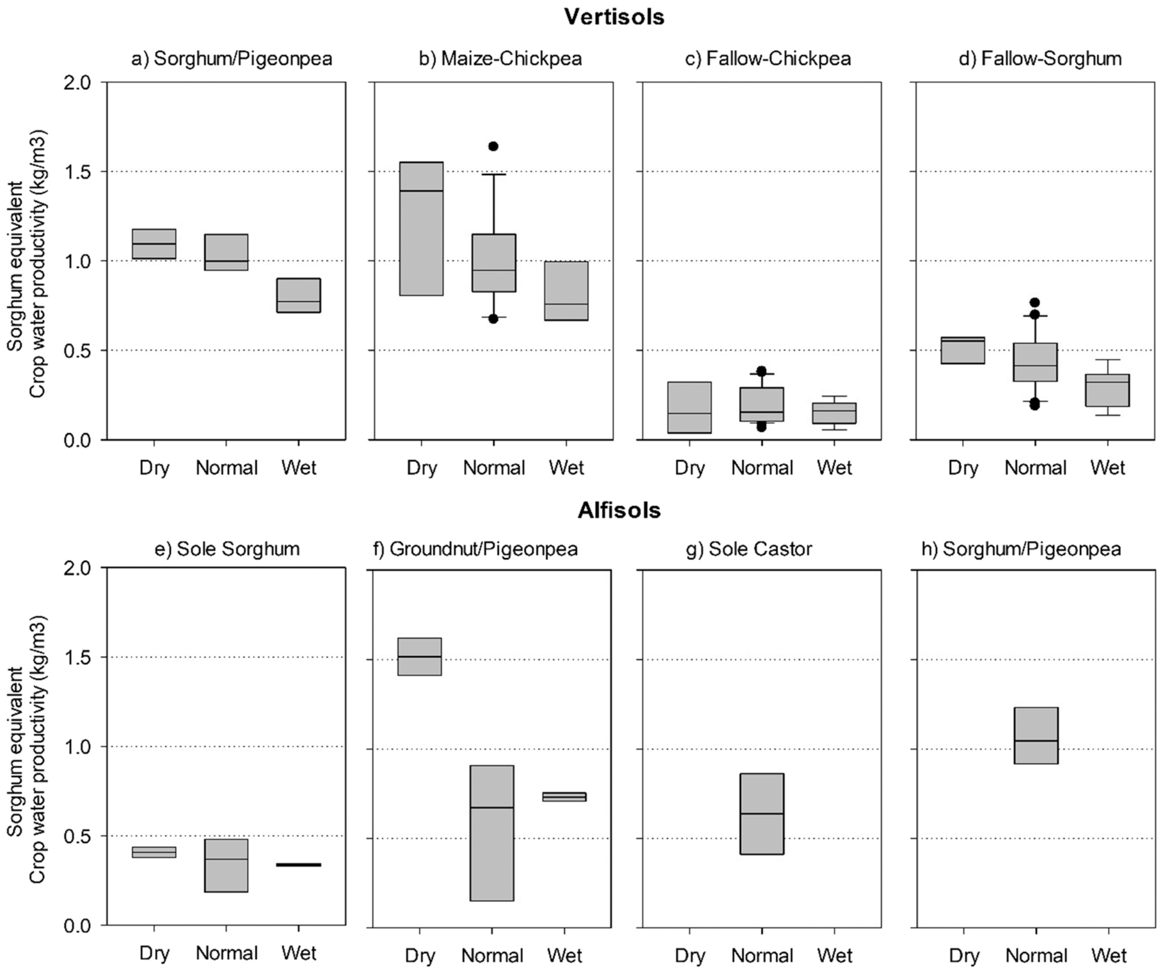

Fig. 9. Sorghum equivalent water productivity in different cropping systems in Vertisols and Alfisols under dry, normal and wet years.

produce better yields. This holds true for both intercrops and sequential crops. In sequential cropping, preparing the seed bed immediately after harvesting the preceding crop is convenient under the improved practice compared to the traditional one. This is so because the preceding crop creates a favorable moisture regime quickly and sowing can be undertaken immediately after the harvest or by taking up sowing in the inter spaces (relay crop). Under the traditional practice, high moisture availability, especially in the top soil layers, could hinder timely sowing and delayed rains could further prolong sowing.

In Alfisols, rainfall distribution rather than total amount of rainfall is more critical to crop growth. The soil's poor water retention capacity coupled with the absence of supplemental irrigation affects crops adversely during dry spells. For example, groundnut yield was much lower during 2003 which was a normal year compared to that in 2002 which was a dry year. A spell of about 25 dry days during the crop season severely affected groundnut yields in 2003. This goes to show the importance of the choice of a cropping system in Alfisols. Of the four cropping systems tested in two phases, sorghum/pigeon pea intercrop performed the best. Since sorghum requires less water, it can partially withstand water scarce conditions while pigeon pea can utilize residual moisture from deep soil layers. The poor yield of groundnut was largely responsible for the poor performance of the system, especially due to the long dry spells which are common in the SAT (Singh et al., 2014b). One or two supplemental irrigations could dramatically improve crop yields (Mandal et al., 2020). Sole castor performed better than groundnut/pigeon pea intercrop and sole sorghum both in terms of net returns and water productivity. Castor is a commercial oilseed crop that is drought tolerant and also gives better economic returns (Babita et al., 2010).

The performance of all the four cropping systems was better under raised beds due to better drainage facility. Pathak et al. (2016) have shown that raised beds in Alfisols were helpful in harvesting 10–15 mm of additional soil water content while reducing soil loss by more than 50% (Anantha et al., 2021a; Anantha et al., 2021b). All these factors contributed to a yield gain of 5–15% and additional economic returns of US$ 80–100/ha (including the additional cost of preparing raised beds).

4.2. Comparison with other studies

A few studies have explained the importance of land form management in crop intensification, improving soil hydraulic properties and crop yields in similar agro-ecological regions. Nouri et al. (2019) reported results from a 34-year long term study in the Alfisols of sub-humid southeastern USA, in which tillage and cover crops had an impact on soil hydraulic properties. The incorporation of cover crops and no tillage practices improved infiltration rate and saturated hydraulic conductivity, which was largely due to aggregation of soil structure. Liu et al. (2020) using data from 4 years of field study conducted in the rainfed agriculture system of arid and semi-arid provinces of China reported enhanced maize yield, 50% more water use efficiency and economic benefits minimum by 140% through the use of ridge-furrow system of land form treatment and plastic mulching compared to control treatments. Three years of field experiments in Alfisols (Jensen et al., 2003) in semi-arid Tanzania demonstrated the advantage of climate risks mitigation practices such as tied-ridges and nutrient application to bridge the yield gap in a maize-based cropping system. A combination of tied-ridge tillage and balanced fertilizer led to

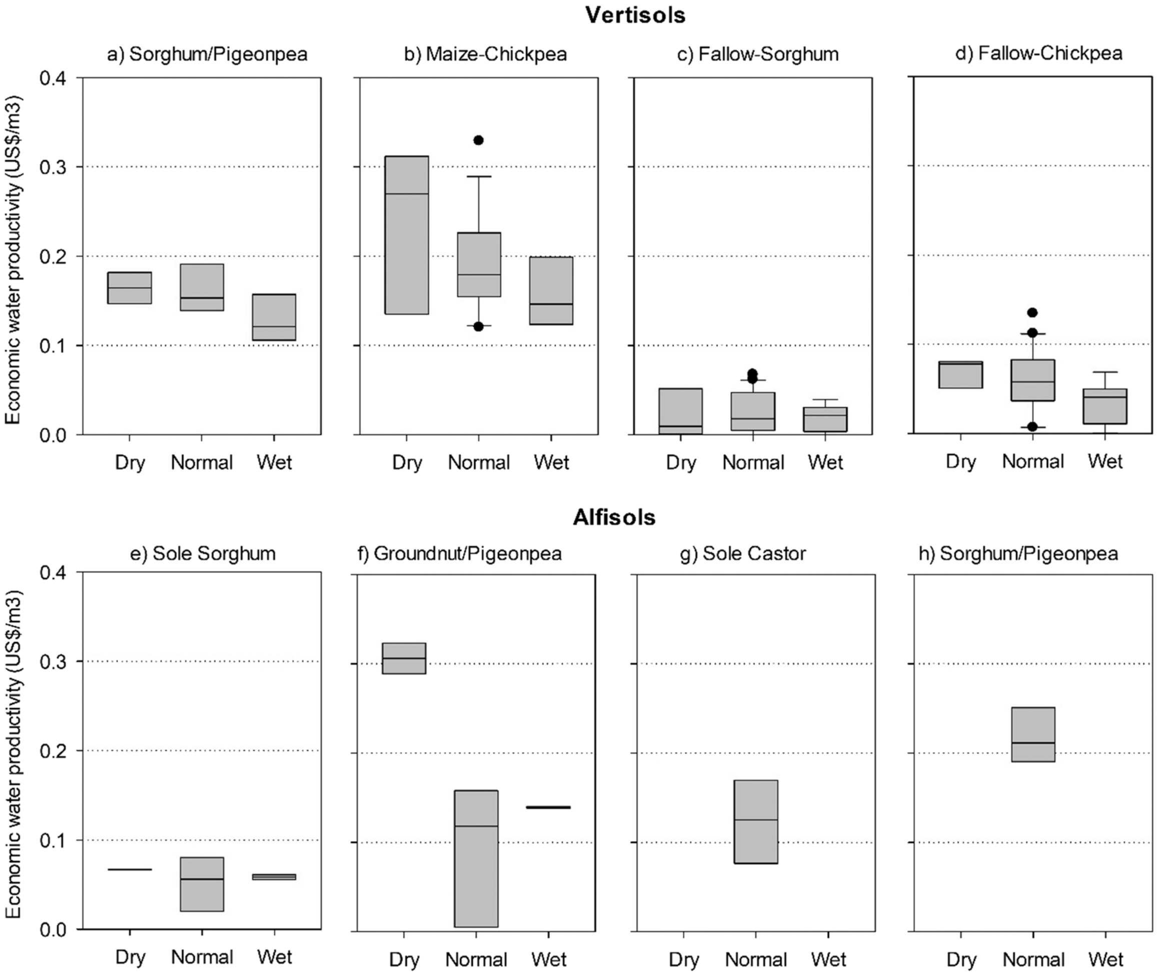

Fig. 10. Economic water productivity in different cropping systems pin Vertisols and Alfisols during dry, normal and wet years.

Table 6
Coefficient of determination (R^2), root-mean-squared error (RMSE), and bias values in the validation dataset ($n = 40$) of crop and water productivity parameters using multiple linear regression (MLR) and random forest (RF) models.

Productivity parameters	MLR			RF		
	R^2	RMSE	Bias	R^2	RMSE	Bias
Sorghum equivalent yield (t/ha)	0.66	1.63	-0.45	0.74	1.42	-0.23
Equivalent water productivity (kg/m^3)	0.68	0.27	-0.06	0.80	0.21	-0.03
Net income (US$/ha)	0.70	273	-21.44	0.78	236	17.13
Economic water productivity (US$/ m^3)	0.59	0.05	0.00	0.79	0.04	0.00

Table 7
Rank correlation coefficients (Kendall Tau) between crop and water productivity parameters.

Productivity parameters	Soil order	Land form	Cropping system	Water regime	Effective rainfall (mm)
Sorghum equivalent yield (t/ha)	0.14	0.57	-0.21	-0.04	0.16
Equivalent water productivity (kg/ m^3)	0.15	0.56	-0.22	-0.16	0.02
Net income (US $/ha)	0.18	0.55	-0.22	-0.05	0.17
Economic water productivity (US $/ m^3)	0.19	0.54	-0.22	-0.14	0.06

maize yields of 6 t/ha compared to 1 t/ha using farmer's practice. Rao et al. (2015) studied the feasibility of double cropping in Vertisols and balanced fertilizer application using 15 years of long-term data in the SAT of southern India. Sorghum-chickpea or mungbean-sorghum sequential cropping showed better resource use efficiency (land, water and nutrients) compared to sole chickpea grown under traditional farmer's practice.

Our results demonstrate the possibility of bridging large yield gaps in the dry semi-arid tropics. The application of supplemental irrigation can reduce the risk of intermittent dry spells common in the SAT that impact profitable crop production in Alfisols (Kumar et al., 2016). The results also indicate that about 17% (~130 mm) of runoff that was generated during normal years holds potential for rainwater harvesting for supplemental irrigation. The construction of a 300 m^3 (10mx10mx3m) farm pond can harvest about 50% of the runoff generated from 1 ha considering a minimum of two fillings during the rainy season (Singh et al., 2014a; Anantha et al., 2021b; Garg et al., 2021). The water will be enough to provide one or two life-saving irrigations during critical crop growth stages coinciding with dry spells. Results of the machine learning-based interpretations are also consistent with the previous studies. For instance, Sreedevi et al. (2006) have shown that the maize/chickpea and sorghum/pigeon pea intercropping systems are beneficial where farmers could profit to the tune of US$ 365–430/ ha,

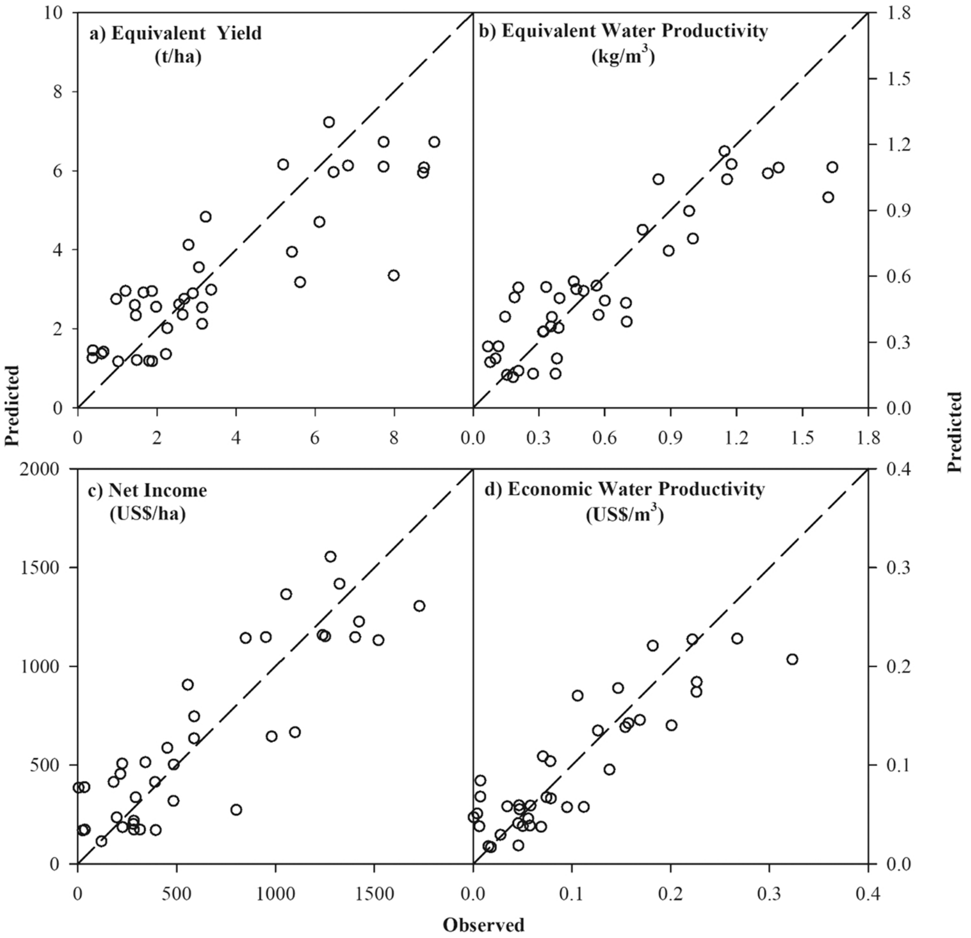

Fig. 11. Scatter plots between observed vs. predicted sorghum equivalent yield (a), equivalent water productivity (b), net income (c), and economic water productivity (d) values in the validation dataset obtained using the random forest model.

respectively. They also showed that the BBF type of land form practice can increase both sorghum yield and water productivity compared to the flat bed land form. Conservation of both soil and soil water contents in the BBF system of land preparation benefits farmers while draining out excess water during heavy rains. Similarly, the SHAP value results are consistent with the observations of higher sorghum yield in Alfisols than Vertisols conducted in the same study site (Sahrawat et al., 1995). This study also provides an in depth understanding of how various cropping systems can optimize available resources for sustainable crop intensification.

5. Conclusions

Long-term field experiments were undertaken on Alfisols and Vertisols at the ICRISAT research farm to evaluate different cropping systems. In Vertisols, a 34-year experiment was undertaken following double cropping (improved practice) on raised beds and comparing it with a sole crop on flat beds (traditional practice). Sorghum/pigeon pea intercrop or maize-chickpea sequential cropping was followed under the improved practice whereas sole sorghum and chickpea were grown using residual soil water content under the traditional practice. Field experiments in Alfisols were undertaken for 8 years between 2002 and 2009 by following raised bed and flat bed methods. Experiments were undertaken in two phases. The cropping systems followed during the first phase were groundnut/pigeon pea intercrop and sole sorghum between 2002 and 2006 and during the second phase between 2007 and 2009 sorghum/pigeon pea intercrop and sole castor. Surface runoff and soil water contents were monitored in all the experimental watersheds along with agronomic measurements. Following are key findings of the study:

- The average runoff generated in Vertisols during a normal year was 10% of the total rainfall received (750 mm) compared to 17% in Alfisols. Runoff recorded in the dry years was less than 4% of the total rainfall in both the soil types. Alfisols which have poor water retention capacity provide the opportunity to harvest surface runoff through low- cost water harvesting structures (such as farm ponds)
- Vertisols have immense potential for sustainable crop intensification by following land form management treatments such as raised beds and appropriate cropping systems (cereals/pulses rotation or intercropping). Improved methods of cultivation in Vertisols produced 6.0–7.0 t/ha SEY compared to only 1.0–2.6 t/ha SEY with traditional practices. Net returns obtained with improved production systems ranged between US$ 800/ha and US$ 1300/ha compared to US$ 92/ha and US$ 350/ha in the traditional practice. Further, technical and economic water productivity were 3–5-folds higher in improved practices compared to traditional practices. Maize-chickpea sequential cropping was superior followed by sorghum/pigeon pea intercropping, sole chickpea and sole sorghum.
- In Alfisols, raised beds performed better than flat beds in terms of additional crop yield (10–15%) and net returns (US$ 80–100/ha/year). In terms of net returns, sorghum/pigeon pea intercrop (US$ 1340–1570/ha/year) was the best followed by sole castor (US$ 760–830/ha/year), groundnut/pigeon pea

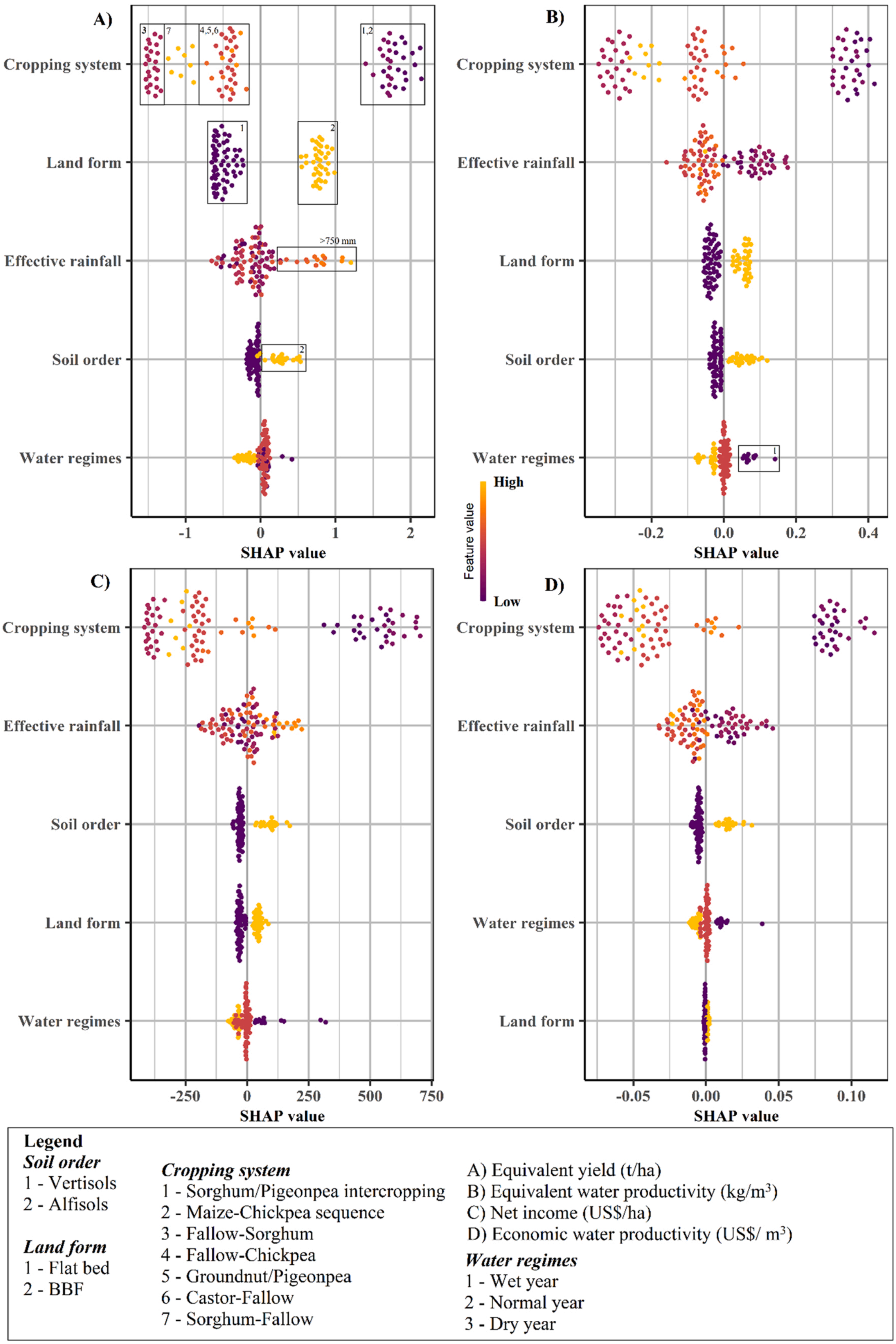

Fig. 12. SHAP summary plots from the random forest model for the sorghum-equivalent yield (A), equivalent water productivity (B), net income (C), and economic water productivity (D).

intercrop (US$ 430–550/ha/year) and sole sorghum (US$ 270–300/ha/year). Castor and pigeon pea being drought tolerant as well as high value crops, brought higher economic returns compared to sole sorghum or groundnut/pigeon pea intercropping. Intermittent droughts in groundnut crop led to poor yields even during normal years.

- Effective rainfall strongly correlated with pigeon pea or chickpea yields in Vertisols under raised beds. Available soil water content was utilized more productively compared to that in the traditional practice. Despite raising a crop during the rainy season, chickpea which was cultivated post monsoon performed equally or better under the improved practice compared to the traditional one.
- Intercropping and raised beds were found to be promising interventions, especially in Alfisols, for better resource utilization. In Vertisols, raised beds coupled with improved cultivation practices were promising options for crop intensification and enhanced resource use efficiency.

The study provided insights into the performance of different cropping systems in major soil types in the SAT apart from revealing opportunities to harvest surface runoff through low-cost rainwater harvesting structures and adopting suitable cropping systems to achieve higher system productivity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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