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Effects of Diversification of Rainfed Cropping Systems to Enhance Sustained Yields for Semi-Arid Tropical Agroecosystems: Effects of 11–Years of Farmers' Practice

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Semi-arid tropical (SAT) soils cover approximately 11 million hectares (Mha) globally. Soils in SAT regions are prone to degradation if poorly managed, and approximately 38% of the developing countries' poor who depend on these soils for their livelihood are at risk of malnutrition. Agronomic practices that can improve soil quality, and can sustain or improve crop productivity are critical for SAT agroecosystems. The objective of this study was to investigate the 11-year effects of farmer-imposed agronomic practices (cropping system and fertilization) on soil organic carbon (SOC), nitrogen (N), phosphorus (P), sulphur (S), and micronutrients [zinc (Zn) and boron (B)], and crop productivity in the Kothapally watershed, Andhra Pradesh, India. Rainfed diversified cropping systems with legumes in rotation or intercropping systems were compared with rainfed monoculture cotton systems. Soil samples were collected from each field of the participating twenty-three farmers in June 2010 and were compared with soil data collected in June 1999 from the same farmer's fields. All soil samples were analyzed (with 10% replication) in the laboratory for physical and chemical characteristics using analysis of variance, where we tested the effects of crop (independent variable) on the dependent variables, *e.g.* SOC stocks, at $p \leq 0.05$. Differences in the means were compared with a Tukey test. Relationships between SOC stocks and yield were evaluated with Pearson correlation analysis, and the sample size and correlation coefficients were reported when $p \leq 0.05$. Increased SOC stocks were observed in rainfed diversified cropping systems with legumes in rotation or intercropping systems compared to rainfed monoculture cotton cropping system (p = 0.0283), and SOC stocks (in 2010) were correlated with 2010 crop yields (r = 0.384, n = 23, $p \leq 0.05$). Overall, the 11-year study showed sustained crop productivity in rainfed diversified cropping systems compared to rainfed cotton cropping systems.

Key words: Legume-based intercropping systems, crop rotation, soil organic carbon, Bt cotton, Vertisols

The semi-arid tropical (SAT) region covers more than 11 million hectares (Mha) globally; and is home to approximately 38% of the developing countries' poor (Wani *et al.* 2007, 2011). Approximately one-tenth of the SAT region is located within India. Predominant soil types in SAT regions of India include Vertisols and Alfisols. Vertisols cover 72.9 Mha in India, and are prone to degradation when poorly managed in particular with low organic matter inputs to soil and sparse vegetation (Sharma *et al.* 2011). Long-term experiments at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Patancheru, India provided an opportunity to evaluate the hypotheses about improved agronomic management. Agronomic management practices that increased organic matter inputs to soil and subsequently soil quality such as soil organic carbon (SOC) and soil water holding capacity included legume-based cropping systems in rotation and intercropping systems, *e.g.* cotton in rotation with sorghum and pigeon pea compared to cereal crops (Sahrawat *et al.* 2005; Bhattacharyya *et al.* 2007; Ramesh *et al.* 2007).

The objective of the current study was to investigate the 11-year effects of farmer-imposed

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agronomic management practices (cropping systems) on SOC, and soil nitrogen (N), phosphorus (P), sulphur (S), and micronutrients [boron (B) and zinc (Zn)], and crop productivity in the Kothapally watershed, in Andhra Pradesh, India. Rainfed legume-based cropping systems were compared with rainfed cotton systems. Because a variety of crops were grown during the study period (1999-2010), the rainfed cropping systems were classified into three categories defined, and hereafter referred to as: “cotton”: *Bacillus thuringiensis* (Bt) cotton grown within the last 4–5 years of the study (n = 4); “mixed”: maize rotation with pigeon pea (M+pp) or maize intercropped with pigeon pea (M/pp) or sorghum rotation with pigeon pea (S+pp) or sorghum intercropped with pigeon pea (S/pp) grown predominantly throughout the study period (n = 7); and “diversified”: diverse crops were grown throughout the study period, including soybean, M+pp, chickpea, green gram, S+pp, cotton, and vegetables (n = 12). Fertilization management strategies adopted by farmers were recorded, and related to the changes in soil characteristics in farmers’ field.

Materials and Methods

Site Description

Adarsha watershed at Kothapally (KP) watershed (latitude 17°20′ to 17°24′ N and longitude 78°5′ to 78°8′ E, elevation 600-640 m), in Ranga Reddy district in the Krishna Basin covers 465 ha, of which 430 ha were cultivated. The watershed was characterized by an undulating topography with an average slope of approximately 2.5%. Soils are predominantly Vertisols and Alfisols (90%). The soil depth ranged from 30 to 120 cm, with medium to low water holding capacities (< 150 mm). The population dependent on these soils was the 1,492 residents of Kothapally village consisting of approximately 270 cultivating families and 4 non-cultivating families. The average landholding per household was 1.4 ha (Shiferaw *et al*. 2002).

Kothapally watershed was developed by the ICRISAT-led consortium comprising national partners including the Central Research Institute for Dryland Agriculture (CRIDA), the National Remote Sensing Agency now referred as Centre (NRSC); of state partners such as the District Water Management Agency (DWMA) of the Government of Andhra Pradesh, Non-Governmental Organizations (NGOs; M. Venkatarangaiya Foundation (MVF)); and the farmers of Kothapally through the Watershed Association, Watershed Committee, user groups (UGs), and self-help groups (SHGs) to establish a successful model watershed. The intention of this consortium was to showcase the long-term impacts of a participatory approach to watershed development on soil and water quality for improved livelihood systems. In a participatory approach, the primary stakeholders, *i.e.* the farmers were involved from the onset of the watershed development program. Thus, the interventions were designed recognizing the needs of individual farmers.

Most of 266 farmers in the Kothapally watershed adopted different interventions and out of them twenty-three of the farmers voluntarily participated in evaluation of legume-based cropping systems as a part of the watershed development program for enhancing crop productivity and soil quality. Four of the twenty-three farmers continued to grow mono-crop cotton predominantly, and within the last 4–5 years of the study, and thus were included in the category “cotton.” The differences in the twenty-three farmers’ management practices provided us with an opportunity to compare legume-based cropping systems with cotton systems. The farmers’ cropping systems changed from 1999 to 2010 (Table 1). The variation in selected crops was primarily due to market trends, where high-value cash crops such as cotton were favoured. Because various crops were grown during the 11-year study period (1999–2010), we classified cropping systems into three categories, *i.e.* cotton, mixed, and diversified, as defined in the introduction section of this manuscript. Two or more crops were grown per year. *Kharif* (rainy season) crops (sorghum, mung bean, soybean, pigeon pea, cotton, and rice) were planted during June or July, and harvested in February or March. *Rabi* (post-rainy season) crops (vegetables, oilseeds, pigeon pea) were planted in November, and harvested in February or March. Fallow period was from February or March until June of the following year. Crop yields were measured by farmers using a crop cutting method described as follows. Total yield per crop per field was cut and air-dried, and subsequently bagged and weighed. Each crop was bagged separately. The bag weight was weighed before the bag with yield was weighed, and then the bag weight was subtracted from total weight to give the total crop yield in kg dry weight. The farmer recorded crop yield in kg dry weight and total field area (in hectares) per respective crop and farmers’ field was reported per farmers’ written records (1999–2010) and used to calculate total yield

Table 1. Kothapally farmers' annual cropping systems and nutrient management practices (1999-2010), Andhra Pradesh, India

Category	Cropping system and nutrient management (1999-2010)[a]										
	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10
3	Soy	M+pp	Cotton	Tomato	Tomato	Cotton	S+pp	Cotton	Carrot	Eggplant	Tomato
	D+U	F+D+U	D+U+P	D+U	D+U+P	D+U+P	Mn+D	D+U+P	D+U+P	D+U+P	D+U+P
3	Soy+pp	Cotton+pp	S+pp	Cotton	M+pp	Cotton	S+pp	Cotton	Carrot	Cotton	Tomato
	D+U	Mn+D+U	D+U+P	D+U	F+D+U	D+U+P	D+U+P	D+U	D+U+P	D+U+P	D+U+P
3	Soy	M+pp	S+pp	Cotton	Paddy	Tomato	Cotton	Paddy	Tomato	Paddy	Cotton
	D+U	Mn+D+U	D+U	D+U+P	D+U+P	D+U+P	D+U	D+U+P	D+U+P	D+U+P	D+U+P
3	Green gram	M+pp	Cotton	Paddy	Cotton	Tomato	Paddy	Eggplant	Cotton	Paddy	Cotton
	D+U	Mn+D+U	D+U	D+U+P	D+U+P	D+U+P	D+U	D+U+P	D+U+P	D+U+P	D+U+P
3	Soy	M+pp	S+pp	Cotton	S+pp	Tomato	Paddy	Carrot	Paddy	Paddy	Tomato
	D+U	Mn+D+U	D+U+P	D+U	D+U+P	D+U	D+U+P	D+U+P	D+U+P	D+U+P	D+U+P
3	Soy	M+pp	Cotton	Paddy	Tomato	Carrot	Cotton	Paddy	Eggplant	Carrot	Paddy
	F+U+P	D+U+P	D+U+P	D+U+P	D+U+P	Mn+D+U+P	D+U+P	D+U+P	Mn+D+U+P	D+U+P	D+U+P
3	M+pp	Cotton	S+pp	Cotton	Paddy	Tomato	cp	Cotton	S+pp	Cotton	Paddy
	D+U	D+U	D+U+P	D+U+P	D+U	D+U+P	F+U+P	D+U+P	D+U+P	D+U	D+U+P
3	Soy	M+pp	Paddy+veg	Cotton	M+pp	Cotton	Paddy+tomato	Cotton	Cotton	S+pp	Cotton
	D+U	D+U	D+U+P	D+U+P	D+U	D+U+P	F+U+P	D+U+P	D+U+P	D+U	D+U+P
1	M+pp	Cotton	M+pp	Cotton	Cotton	Carrot	S+pp	Cotton	Cotton	Cotton	Cotton
	D+U	D+U+P	D+U	D+U+P	D+U+P	D+U	D	D+U+P	D+U+P	D+U+P	D+U+P
1	M+pp	Cotton	S+pp	Cotton	M+pp	Cotton	Cotton	Cotton	Cotton	Cotton	Cotton
	D+U	D+U+P	D	D+U+P	D+U	D+U+P	D+U+P	D+U+P	D+U+P	D+U+P	D+U+P
1	Soy	M+pp	Cotton	S+pp	Cotton	M; rabi- cp	Cotton	Cotton	Cotton	Cotton	cotton
	D	D+U	D+U+P	D	D+U+P	D+U	D+U+P	D+U+P	D+U+P	D+U+P	D+U+P
3	S+pp	Cotton	M+pp	Cotton	Carrot	Cotton	S+pp	Cotton	Carrot	Carrot	Carrot
	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	Soy	Cotton	S+pp	Cotton	M+pp	Cotton	Cotton	M+pp	Cotton	M+pp	Cotton
	D+U	D+U+P	D	D+U+P	D+U	D+U	D+U+P	D+U	D+U+P	D+U	D+U+P
2	Soy	M+pp	Cotton	S+pp	cotton	S+pp	Cotton	Fallow	Fallow	Cotton	Cotton
	D+U	D+U	D+U+P	D	D+U+P	D	D+U	D+U+P	NA	D+U	D+U+P
3	M+pp	Paddy	Tomato	Flowers	Cotton	Paddy	Tomato	Paddy; tomato	Cotton	Paddy	Cotton
	D+U	D+U+P	D+U	D+U	D+U+P	D+U+P	D+U+P	D+U	D+U+P	D+U+P	D+U+P
2	Soy	M+pp	Cotton	M+pp	pp	M+pp	Cotton	S+pp	Cotton	Cotton	Cotton
	D+U	D+U	D+U+P	D+U+P	D+U	D+U	D+U+P	D	D+U+P	D+U+P	D+U+P
2	Soy	M+pp	Cotton	M+pp	pp	M; rabi cp	Cotton	pp	Cotton	Cotton	Cotton
	D	D+U	D+U+P	D+U+P	D+U	D+U+P	D+U	D	D+U+P	D+U	D+U+P
1	M+pp	Cotton	S+pp	Cotton	M+pp	Cotton	S+pp	Cotton	Cotton	Cotton	Cotton
	D+U	D+U+P	D	D+U+P	D+U+P	D+U+P	D+U	D	D+U	D+U+P	D+U+P
3	Soy	M+pp	Cotton	S+pp	Cotton	M; rabi-tomato	Cotton	M+pp	Cotton	Tomato	Paddy
	D+U	D+U	D+U+P	D+U+P	D	D+U	D+U	D+U	D+U+P	D+U	D+U+P
3	S+pp	Cotton	M+pp	Cotton	M; rabi-cp	M+pp	Carrot	Cotton	Cotton+pp	Cotton	Cotton
	Mn+D+U	D+U+P	Mn+D+U	D+U+P	D+U	D+U+P	D+U+P	D+U+P	D+U+P	Mn+D+U	D+U+P
2	Green gram	M+pp	Cotton	S+pp	Cotton	M+pp	Cotton	S+pp	Cotton	Cotton	Carrots
	D+U	D	D+U+P	D+U	D+U+P	D+U	D+U+P	D	D+U+P	D+U+P	D+U+P
2	Soy	M+pp	Cotton	M+pp	Cotton	S+pp	Cotton	Cotton+pp	Cotton	Cotton	Cotton
	D+U	D+U	D+U+P	D+U+P	D+U	D	D+U+P	D+U+P	D+U+P	D+U+P	D+U+P
2	Soy	M; rabi-cp	Cotton	S+pp	Cotton	S+pp	Cotton	M+pp	Cotton	Cotton	Cotton
	D+U	D+U	D + U	D+U+P	D	D	D+U+P	D	D+U+P	D+U+P	D+U+P

[a]Cropping systems categories were defined as follow: 1: cotton: cotton grown within the last 4–5 of the study (n = 4); 2: mixed: maize rotation with pigeon pea (M+pp) or maize intercropped with pigeon pea (M/pp) or sorghum rotation with pigeon pea (S+pp) or sorghum intercropped with pigeon pea (S/pp) grown predominantly throughout the study period (n = 7); and 3: diversified: a diversity of crops grown throughout the study period, including soybean, M+pp, chickpea, green gram, S+pp, cotton, and vegetables (n = 12). Farmyard manure (FYM) application 5–10 t ha^{-1} and inorganic fertilizer nitrogen, phosphorus, potassium (NPK) (on average, at a rate of 60:30:30; using diammonium phosphate (D), urea (U), and muriate of potash (P)). Micronutrients (Mn) (boron and zinc) were applied every three or four years per recommended rates for the area.

in kg dry weight per hectare, where total yield in kg dry weight was divided by total hectares per respective crop and farmer's field. Nutrient management strategies adopted by farmers were also recorded (Table 1). Fertilization practices included farmyard manure (FYM) application 5–10 t ha^{-1} (split into 2-3 installments) and inorganic fertilizer N, P, K, on average, at a rate of 60:30:30; using diammonium phosphate (DAP), urea, and muriate of potash (MOP). Sulfur was added as gypsum every third year. Micronutrients (B and Zn) were applied every three or four years as per recommended rates for the area.

Table 2. Methods used for analysis of soil samples for plant available nutrients for the study of the effects of 11–year (1999-2010) of farmers' practice in Kothapally, Andhra Pradesh, India

Measure	Method	Reference
Extractable phosphorus	Olsen P	Olsen and Sommers (1982)
Extractable potassium	Exchangeable K	Thomas (1982)
Extractable zinc	DTPA extractable Zn	Lindsay and Norvell (1978)
Extractable boron	Hot water soluble boron	Keren (1982)
Extractable sulphur	Calcium chloride dehydrate extractable	Tabatabai (1982)

Crop residues were often removed for fodder for livestock.

Soil Sampling and Analysis

Soil samples were collected from each field of the participating twenty-three farmers in June 2010 and were compared with soil data collected in June 1999 from the same farmers' fields. Soil samples were collected from 0–30 cm soil depth in both June 1999 and June 2010, before planting of *kharif* crops. Three soil cores were collected randomly from each field and mixed to create a homogenous composite sample per plot. Bulk density (BD) was determined on 100 cm^{-3} volume, and wet and dry (60 ºC for three days) weight for each core for each plot in 2010 only (n = 3). The BD values from 2010 were used to calculate SOC stocks for 1999 and 2010, using Eq. [1].

All soil samples were analyzed (with 10% replication) in the laboratory for physical and chemical characteristics. All sample information was encrypted prior to submission to the laboratory as a quality control measure. The homogenous composite soil samples were air-dried and sieved through a 2-mm sieve. A sub-sample of the 2-mm sieved soil was further ground and sieved through a 53-µm sieve for analysis of SOC using the Walkley-Black method and N (organic, NH_4^+, NO_3^-) using the Kjeldahl method. Plant available nutrients were measured using methods outlined in table 2.

Calculations

The SOC stocks were calculated using Eq. [1].

$$\text{SOC stock (Mg ha}^{-1}) = \text{BD (Mg m}^{-3}) \times \text{depth (cm)} \times \text{SOC (g g}^{-1}) \times 100 \quad [1]$$

where, BD is bulk density (Mg m^{-3}) and SOC is soil organic carbon (g g^{-1}).

Statistical Analysis

The analysis of variance (ANOVAs) was done to compare SOC stocks, and soil N, P, S, B, and Zn amongst plots, where the effects of cropping system (i.e. the independent variables) were tested on the dependent variables, *e.g.* soil C stocks, at $p \leq 0.05$. Data was then pooled according to cropping system category and sample size per category to compare an integrated value for the cotton system with the value from mixed system with the value from diversified system, allowing comparison of each dependent variable (*e.g.* soil N) per cropping system category, *i.e.* the cotton system *vs.* the mixed system *vs.* the diversified system. The pooled data were weighted, considering the sample size of each cropping system category, *i.e.* cotton (n = 4), mixed (n = 7), and diversified (n = 12). Differences in the means were compared with Tukey test. Relationships between SOC stocks (in 2010) and yield were evaluated with Pearson correlation analysis, and the sample size and correlation coefficients were reported for $p \leq 0.05$.

Results and Discussion

Soil Analysis

The average BD for soils in Kothapally watershed was 1.32 Mg m^{-3}. Table 3 shows soil chemical analysis results for SOC stocks, and soil N, P, S, micronutrients (B and Zn), and pH per cropping system category (cotton, mixed, and diversified) for 1999 and 2010. Table 3 also shows average yields for 1999 and 2009 per cropping system category (cotton, mixed, and diversified). Soils were alkaline with pH ranging from 8.0 to 8.5 for 1999 and 2010 (Table 3). In order to discuss the chemical analysis results with farmers one map per each soil chemical characteristic was generated to display the results for both 1999 and 2010 in a side-by-side comparison. Twenty of the twenty three farmers attended the discussion. In the presentation of soil-test results and discussion with farmers, the farmers indicated that they had observed reduced yields in 2007/08-10 as a result of what they assumed was decreased soil quality. The farmers' indicated they started to address this issue during the 2009-10 growing seasons by planting a wider diversity of crops, emulating the successful practices of their neighboring farmers, as well as taking advantage of current market trends.

Table 3. Average soil chemical analysis results with standard deviation and average yields with standard deviation per cropping system category for Kothapally farmers' fields, June 1999 and June 2010, Andhra Pradesh, India

Cropping system	pH	Avail-S (mg kg^{-1})	Avail-B (mg kg^{-1})	Avail-Zn (mg kg^{-1})	Avail-P (mg kg^{-1})	Avail-N (mg kg^{-1})	SOC (Mg ha^{-1})	Yield (kg ha^{-1})
June 1999								
Mixed	8.22 ± 0.12	15.76 ± 2.87	0.08 ± 0.05	0.80 ± 0.21	2.89 ± 1.55	451.91 ± 89.11	23.93 ± 4.34	583.33 ± 231.66
Cotton	8.19 ± 0.11	12.92 ± 3.23	0.13 ± 0.09	0.75 ± 0.13	2.23 ± 3.33	496.08 ± 166.26	25.44 ± 4.23	2000.00 ± 1113.55
Diversified	8.32 ± 0.14	13.97 ± 1.70	0.13 ± 0.08	0.89 ± 0.40	1.80 ± 2.11	426.00 ± 77.32	22.18 ± 4.69	880.00 ± 554.08
June 2010								
Mixed	8.04 ± 0.08	9.66 ± 4.48	0.49 ± 0.22	0.95 ± 0.69	8.66 ± 5.25	567.14 ± 109.44	18.16 ± 6.41	850.00 ± 251.00
Cotton	8.07 ± 0.09	5.49 ± 0.68	0.31 ± 0.03	0.57 ± 0.19	6.69 ± 3.21	489.50 ± 122.60	18.81 ± 8.31	950.00 ± 57.73
Diversified	8.09 ± 0.13	11.52 ± 4.96	0.68 ± 0.32	0.93 ± 0.70	8.83 ± 4.17	665.75 ± 148.78	22.01 ± 7.25	920.00 ± 192.35

Overall, the soils in the Kothapally watershed were low in organic matter and nutrient reserves especially P, S and micronutrients (B and Zn). We observed that balanced nutrient management (by applying deficient nutrients as per the soil test) gave the best results in terms of sustained increased yield. Previous studies showed the application of organic matter through crop residues and manure was also essential for sustained SOC levels (Sahrawat and Wani 2013). However, crop residues from Bt cotton (or other genetically modified crop that expressed Cry Proteins) should be applied to soil with caution due to environmental impacts of toxins released from decomposition of these residues to microbial organisms (Flores *et al.* 2005).

Effects of Cropping Systems: Cotton, Mixed and Diversified

Table 4 shows the results of the comparison of each dependent variable per cropping system category, *i.e.* the cotton system *vs.* the mixed system *vs.* the diversified system. The diversified cropping systems showed greater SOC stocks compared to cotton cropping systems (p = 0.028) (Table 4). Crop yields (in 2010) were positively correlated with SOC stocks (in 2010) ($r = 0.384$, $n = 23$, $p \leq 0.05$) (data not shown). Previous studies showed inorganic N-fertilizer and N-fixing legume inputs in the system indirectly supported SOC accrual (Wani *et al*. 2007). In the current study, increased soil N was observed with integrated management practices, with continuous cropping (rotation and intercropping) with legumes, *i.e.* in mixed and in diversified cropping systems, and with N-fertilizer additions (Tables 1 and 3). Sharma *et al.* (2011) showed similar results for rainfed intercropping systems.

Reduced plant available S was observed in cotton cropping systems compared to diversified cropping systems (p = 0.001) (Tables 3 and 4), and possibly due to high S demands of cotton crops. No S was added to soil through annual fertilization, since only DAP, urea, and MOP were used. Although S was added *via* gypsum every third year low organic matter content in the soils could have possibly resulted in its low soil retention.

Overall, the lack of appropriate nutrient management practices at the farm level was identified an an important constraint for increasing crop productivity (Rego *et al.* 2007). It has been found that nutrient imbalance along with multi-nutrient deficiencies are holding back the yields of rainfed crops in spite of the inherent genetic potential even in

Table 4. Difference between 1999 and 2010 contrasted values per cropping system category for Kothapally farmers' fields, Andhra Pradesh, India

Cropping system	pH	Avail-Zn (mg kg^{-1})	Avail-S (mg kg^{-1})	Avail-B (mg kg^{-1})	Avail-P (mg kg^{-1})	Kjed N (mg kg^{-1})	SOC (Mg ha^{-1})
Mixed	-0.015	0.022	-0.872	0.057	0.827	16.479	-0.825
Cotton	-0.010	-0.044	-1.857	0.046	1.118	-1.646	-1.658
Diversified	-0.018	0.004	-0.203	0.045	0.583	19.875	-0.014
	ns	ns	ab	ns	ns	ns	ab
	ns	ns	b	ns	ns	ns	b
	ns	ns	a	ns	ns	ns	a
P values	0.423	0.438	0.001	0.642	0.509	0.460	0.028

[a]Cropping system categories were defined as follow: cotton: cotton grown within the last 4–5 of the study (n = 4); mixed: maize rotation with pigeon pea (M+pp) or maize intercropped with pigeon pea (M/pp) or sorghum rotation with pigeon pea (S+pp) or sorghum intercropped with pigeon pea (S/pp) grown predominantly throughout the study period (n = 7); and diversified: a diversity of crops grown throughout the study period, including soybean, M+pp, chickpea, green gram, S+pp, cotton, and vegetables (n = 12). Differences were calculated as 2010 values minus 1999 values, and contrasted values were calculated using pooled data according to cropping system category, and weighted values were applied based on sample size, where cotton n = 4, mixed n = 7, and diversified n = 12. Differences in the means were compared with a Tukey test, at $p \leq 0.05$.

water-deficit conditions. Balanced nutrition of crops holds the key for optimal use of rainwater (Sahrawat and Wani 2013) and realizing potential yields in semi-arid cropping systems.

Conclusions

The SOC stocks were greater in diversified cropping systems with legume-based cropping systems, compared to cotton cropping system in a semi-arid agricultural production system with farmer imposed practice after an 11-year period. Crop yields (in 2010) were determined to be positively correlated with SOC stocks (in 2010). Sustainable yield potentials in diversified cropping systems can be achieved through supplemental balanced nutrient applications, perhaps even with water-deficient conditions. Adequate S uptake by the plants, particularly in cotton, might be accomplished through application of organic amendments, such as manures at higher rates. Further research is needed to relate diversified cropping systems with precipitation patterns and nutrient management practices in order to optimize conditions for crop growth in the SAT soils.

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