Available online at www.sciencedirect.com

SCIENCE DIRECT®

Soil & Tillage Research 83 (2005) 246–259

Soil & Tillage Research

www.elsevier.com/locate/still

Long-term soil management effects on crop yields and soil quality in a dryland Alfisol

K.L. Sharma[a,*], Uttam Kumar Mandal[a], K. Srinivas[a], K.P.R. Vittal[a], Biswapati Mandal[b], J. Kusuma Grace[a], V. Ramesh[a]

[a]*Division of Resource Management, Central Research Institute for Dryland Agriculture, Santhoshnagar, P.O. Saidabad, Hyderabad-500 059, India*

[b]*Bidhan Chandra Krishi Vishwavidyalaya, Kalyani-741235, West Bengal, India*

Received 8 May 2003; received in revised form 21 July 2004; accepted 4 August 2004

Abstract

A long-term experiment was conducted with the objective of selecting the appropriate land management treatments and to identify the key indicators of soil quality for dryland semi-arid tropical Alfisols. The experiment was conducted using a strip split–split plot design on an Alfisol (Typic Haplustalf) in southern India under sorghum (*Sorghum vulgare* (L))-castor (*Ricinus communis* (L)) bean rotation. The strip constituted two tillage treatments: conventional tillage (CT) and minimum tillage (MT); main plots were three residues treatments: sorghum stover (SS), gliricidia loppings (GL), 'no' residue (NR) and sub plots were four nitrogen levels: 0 (N_0), 30 (N_{30}), 60 (N_{60}), and 90 kg ha^{-1} (N_{90}). Soil samples were collected after the sixth and seventh year of experimentation and were analyzed for physical, chemical and biological parameters. Sustainable yield index (SYI) based on long-term yield data and soil quality index (SQI) using principal component analysis (PCA) and linear scoring functions were calculated. Application of gliricidia loppings proved superior to sorghum stover and no residue treatments in maintaining higher SQI values. Further, increasing N levels also helped in maintaining higher SQI. Among the 24 treatments, the SQI ranged from 0.90 to 1.27. The highest SQI was obtained in $CTGLN_{90}$ (1.27) followed by $CTGLN_{60}$ (1.19) and $MTSSN_{90}$ (1.18), while the lowest was under $MTNRN_{30}$ (0.90) followed by $MTNRN_0$ (0.94), indicating relatively less aggradative effects. The application of 90 kg N ha^{-1} under minimum tillage even without applying any residue ($MTNRN_{90}$) proved quite effective in maintaining soil quality index as high as 1.10. The key indicators, which contributed considerably towards SQI, were available N, K, S, microbial biomass carbon (MBC) and hydraulic conductivity (HC). On average, the order of relative contribution of these indicators towards SQI was: available N (32%), MBC (31%), available K (17%), HC (16%), and S (4%). Among the various treatments, $CTGLN_{90}$ not only had the highest SQI, but also the most promising from the viewpoint of sustainability, maintaining higher average yield levels under sorghum–castor rotation. From the view point of SYI, CT approach remained superior to MT. To maintain the yield as well as soil quality in Alfisols, primary tillage along with organic residue and nitrogen application are needed.

Keywords: Soil quality assessment; Soil quality indicators; Alfisol; Tillage; Crop residue; India

---

* Corresponding author. Tel.: +91 40 24530161/286 (O)/+91 40 55827134 (R); fax: +91 40 24531802/24535336.
E-mail address: klsharma@crida.ap.nic.in (K.L. Sharma).

0167-1987/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2004.08.002

1. Introduction

Soil is a key natural resource and soil quality is the integrated effect of management on most soil properties that determine crop productivity and sustainability. Good soil quality not only produces good crop yield, but also maintains environmental quality and consequently plant, animal and human health. Unfortunately, with the advancement of agriculture, soils are being degraded at an alarming rate by wind and water erosion, desertification, and salinization because of misuse and improper farming practices. Growing of crops one after another without giving due consideration to nutrient requirement has resulted in decline in soil fertility, especially of nitrogen (Ghosh et al., 2003). Soil quality assessment has been suggested as a tool for evaluating sustainability of soil and crop management practices (Hussain et al., 1999). Hence, there is a need to develop criteria to evaluate soil quality and to take corrective actions to improve it. Assessing soil quality is difficult, because unlike water and air quality for which standards have been established primarily by legislation, soil quality assessments are purpose-oriented and site specific (Karlen et al., 1994a). However, a quantitative assessment of soil quality could provide much needed information on the adequacy of the world's soil resource base in relation to the food and fibre needs of a growing world population.

To assess soil quality, indicators (soil properties) are usually linked to soil function (Hornung, 1993; Howard, 1993; Doran and Parkin, 1994; Karlen and Stott, 1994; Larson and Pierce, 1994; Acton and Gregorich, 1995; Doran et al., 1996; Karlen et al., 1996). Several indicators have been suggested reflecting changes over various spatial and temporal scales. Improved soil quality often is indicated by increased infiltration, aeration, macropores, aggregate size, aggregate stability and soil organic matter and by decreased bulk density, soil resistance, erosion and nutrient runoff (Parr et al., 1992). Microbial biomass, respiration, and ergosterol concentrations are biological measurements that have been suggested as indicators for assessing long-term soil and crop management effects on soil quality (Karlen et al., 1992). Periodic assessment of soil test properties has also been suggested as essential for evaluating the chemical aspects of soil quality (Arshad and Coen, 1992; Karlen et al., 1992). A valid soil quality index would help to interpret data from different soil measurements and show whether management and land use are having the desired results for productivity, environmental protection, and health (Granatstein and Bezdicek, 1992). Moreover, can these indexes provide an early indication of soil degradation and the need for remedial measures, and characterize changes in soil properties that would reflect the extent of rehabilitation or regeneration of degraded soils?

Maintaining soil quality at a desirable level is a very complex issue due to involvement of climatic, soil, plant and human factors and their interactions. This issue is even more challenging in case of dryland agriculture. A very fragile natural resource base typifies many of the dryland areas. Soils are often coarse-textured, inherently low in fertility, organic matter, and water holding capacity, and susceptible to wind and water erosion. In the Indian subcontinent, about 24% of the total geographical area (Prasad and Biswas, 1999) or 79.7 Mha of soils are Alfisols, making it the most dominant soil order in dryland regions of India. These soils encounter several problems including water erosion, shallow soil depth, subsurface gleying, restricted rooting depth, low water and nutrient retention, hard setting tendencies, and crust formation (El-Swaify et al., 1987). These soils are also nearly exhausted of organic matter and thus have poor structure, low water retention capacity and low fertility (Singh et al., 1998). Poor agricultural management and climatic extremes have significantly contributed towards the land degradation and deterioration of soil quality in these regions.

There is an urgent need to adopt appropriate soil and plant management practices that reduce soil degradation or maintain soil quality at a desirable level in dryland regions. Zero- or reduced tillage crop production practices, coupled with proper residue management can maintain or improve soil organic matter and has the potential to substantially increase long-term crop production in semi-arid rain fed regions (Smith and Elliott, 1990). However the adoption of zero tillage is often limited by the need to have an adequate plant density in soils with a compacted seed zone or poor seed–soil contact (Jones et al., 1990). Primary tillage is deemed crucial for successful continuous cropping of semi-arid tropical

Alfisols in India, because these soils undergo severe hardening during the dry season and tillage is required to create a favorable zone for root penetration and rainfall infiltration (El-Swaify et al., 1985). Maintaining soil organic matter is also crucial in dryland farming system. As temperature increases and precipitation decreases, the oxidation of organic matter is very fast and development of sustainable farming systems becomes more difficult.

To date, the majority of soil quality research has been conducted on soils in temperate regions. Soil quality research on tropical soils is much more limited (Ericksen and McSweeney, 2000; Palm et al., 1996). In recent years, soil quality research has focused on the linkages among management practices and systems, observable soil characteristics, soil processes, and performance of soil functions (Lewandowski et al., 1999). Choosing the appropriate soil attributes to include in an index requires consideration of soil function and management goals that are site specific and oriented to a users focus on sustainability rather than just crop yields. It is important that any index of soil quality must consider soil function, and these functions are varied and often complex. A soil, which is considered of high quality for one function may not be so for other functions. As a consequence, there are potentially many soil properties, which might serve as indicators of soil quality and research is required to identify the most suitable one (Nortcliff, 2002).

Recognizing the importance of soil quality in dryland Alfisols, the present investigation was conducted with the objective of selecting appropriate land management treatments for dryland Alfisols in India. To do so, several biological, chemical and physical indicators of soil quality were evaluated using data collected form a long-term tillage-residue–nitrogen management experiment. Strategies for using these indicators to develop an overall soil quality index that is meaningful to dryland agricultural systems were evaluated.

2. Materials and methods

2.1. Field site, experiment layout and treatments

A field experiment was conducted at Hayathnagar Research Farm (17°18′N latitude, 78°36′E longitude and an elevation of 515 m above mean sea level) of Central Research Institute for Dryland Agriculture, Hyderabad, India. The farm represents a semi-arid tropical region with hot summers and mild winters and a mean annual temperature of 25.7 °C. The mean maximum temperature during March–May varies from 35.6 to 38.6 °C. Mean minimum temperature during the winter months (December, January and February) ranges from 13.5 to 16.8 °C. Mean annual rainfall is 746 mm and accounts for approximately 42% of annual potential evapotranspiration (1754 mm). Nearly 70% of the total precipitation is received during the southwest monsoon season (June–September). Soils in the experimental field (Table 1) belong to Hayathnagar soil series (Typic Haplustalf). They have a sandy surface layer, with increasing clay content in the sub soil.

The experiment was laid out in a strip split–split plot design with three replications and was maintained since 1995 with sorghum (*Sorghum vulgare* (L)) and castor (*Ricinus communis* (L)) in a 2-year rotation. The strip constituted two tillage treatments: MT (weeding occasionally with blade harrow or chemical spray and only plough planting) and conventional tillage (CT) (two ploughing before planting + one plough planting + harrowing + operation for top dressing). In the CT strip, ploughing was done with a bullock-drawn country plough to a depth of 10–12 cm at the onset of monsoon during the first week of June. At the time of sowing, the same country plough was

Table 1
Initial physical and chemical characteristics of the experimental site

Characteristics	Description
Soil order	Alfisol
Soil series	Hayathnagar
Coarse sand (g kg^{-1} soil)	657
Fine sand (g kg^{-1} soil)	110
Silt (g kg^{-1} soil)	100
Clay (g kg^{-1} soil)	133
Moisture at field capacity (% w/w)	8.33
pH (soil:water, 1:2)	5.3
EC (dS m^{-1})	0.087
Organic carbon (g kg^{-1})	3.7
CEC (C mol (p+) kg^{-1})	14.5
Total P (mg kg^{-1})	210
0.01 M $CaCl_2$ extractable sulphur (mg kg^{-1})	7.0
Available N ($KMnO_4$ method) (kg ha^{-1})	145.6
Available P (0.5 M $NaHCO_3$ extractable (kg ha^{-1})	12.54
Available K (kg ha^{-1})	179.2

used to open a furrow of 5–7 cm depth and seeds were placed by hand in the furrow (also called plough planting). The main plot treatments constituted three residue treatments: dry sorghum stover (SS) (N content of 5 g kg^{-1} and C:N ratio of 72) applied at 2 t ha^{-1}, fresh gliricidia loppings (*Gliricidia maculata*) (GL) (N content of 27.6 g kg^{-1} and C:N ratio of 15) applied at 2 t ha^{-1} (fresh weight) and no residue (NR). Sub plot (4.5 m × 6 m) treatments consisted of four N rates 0 (N_0), 30 (N_{30}), 60 (N_{60}) and 90 kg N ha^{-1} (N_{90}). Residues were applied at the surface, 2 weeks after sowing and allowed to decompose in the same plot. Residues acted as a mulch as well as source of organic matter.

Nitrogen was applied in two equal splits, one at sowing and another 45 days after sowing. In total, 24 treatment combinations were evaluated. Phosphorus was applied to each crop at 13 kg P ha^{-1}. Crops were sown in the second or third week of June each year depending upon rainfall. Sorghum was harvested at ground level during the second week of October and castor was harvested during February. The residue obtained from the harvest of sorghum was used as dry fodder to feed the farm bullocks and some of it was preserved for application to the field during the succeeding year. Castor stalks were removed from the field for using them either as domestic fuel or for farm compost.

2.2. Soil sampling, processing and analysis

Soil samples were collected from the 0 to 15 cm soil depth after the harvest in the sixth and seventh year (2000, 2001) and analyzed for various soil physical, chemical and biological properties. Composite soil sampling procedure was followed and at least four spots were chosen randomly to collect the soil sample from each plot. For determination of bulk density (BD) and saturated hydraulic conductivity (HC), four undisturbed soil cores from each plot were collected in a metal core of 5.6 cm inner diameter and 4.1 cm height. Bulk density and HC were measured by the core method (Blake and Hartge, 1986) and constant head method (Klute, 1965). Soil texture was determined by the Bouyoucos hydrometer method (Gee and Bauder, 1986). Aggregate size distribution was determined by wet sieving (Yoder, 1936) and values were expressed as mean weight diameter (MWD) after oven drying (van Bevel, 1949). The soil samples were placed on the uppermost one of a nest of sieves (sizes: 4.75, 2.0, 1.0, 0.5, 0.25 and 0.1 mm arranged in descending order) and subjected to the slaking action of water by moving the nest of sieves mechanically upward and downward. The results were corrected for the coarse primary particles retained on each sieve. This was done by dispersing the material collected from each sieve, using a mechanical stirrer, sodium hexa metaphosphate as a dispersing agent and then washing the material back through the same sieve. Weight of sand retained after the second sieving was subtracted from the total weight of undispersed material retained after the first sieving. The percentage of water stable aggregates (%SA) was calculated using the relationship given by Hillel (1980)

$$\%\,\mathrm{SA} = 100 \times \frac{\text{weight retained} - \text{weight of sand}}{\text{total sample weight} - \text{total weight of sand}}$$

Soil water retention at permanent wilting point (PWP) and field capacity (FC) were measured in pressure plate apparatus at −1.5 and −0.033 MPa (Cassel and Nielsen, 1986). The difference between PWP and FC was calculated as available water.

A representative portion of each soil sample was air dried, powdered and passed through 0.2 mm sieve for determination of organic carbon (OC) by Walkley and Black's method (Jackson, 1967). Available soil nitrogen was determined by alkaline-$KMnO_4$ method given by Subbaiah and Asija (1956), which primarily measures easily oxidizable N using Kjeltec Auto 1030 Analyzer made by Tecator in Sweden. Available P (Olsen P) was determined by sodium bicarbonate ($NaHCO_3$) extraction and subsequent colorimetric analysis (Olsen et al., 1954). Exchangeable K (Hanway and Heidel, 1952), Ca and Mg (Lanyon and Heald, 1982) were determined using an ammonium acetate extraction followed by emission spectrometry. Zinc, Fe, Cu and Mn were determined using the DTPA (diethylene triamine penta acetic acid) micronutrient extraction method developed by Lindsay and Norvell (1978). The micronutrient concentrations in the DTPA extract were measured by using inductively coupled plasma spectrometer (ICP-XP model, simultaneous system of GBC Australia). To determine the available B in soil, the hot water soluble B method of Berger and

Truog (1944) was followed. Available sulphur was determined after extracting with 0.15% $CaCl_2$ (Williams and Steinbergs, 1959). Electrical conductivity (Rhoades, 1982) and pH of water-saturated pastes were measured using conductivity and pH meter, respectively. Microbial biomass carbon (MBC) and nitrogen (MBN) determinations were made using chloroform fumigation technique as described by Jenkinson and Powlson (1976) and Jenkinson and Ladd (1981). The dehydrogenase activity (DHA) was measured by using tri-phenyl tetrazolium chloride (Lenhard, 1956).

2.3. Soil quality index (SQI)

To determine a soil quality index, four main steps were followed: (i) define the goal, (ii) select a minimum data set (MDS) of indicators that best represent soil function, (iii) score the MDS indicators based on their performance of soil function and (iv) integrate the indicator scores into a comparative index of soil quality.

In general, soil organic carbon (or organic matter) is considered to be the universal indicator of soil quality (Rasmussen and Collins, 1991). However, the ultimate outcome of good soil quality is yield or economic produce because it serves as a plant bioassay of the interacting soil characteristics. In the present study, the average yield of sorghum and castor crops individually and sustainable yield index (for 8 years from 1995 to 2002 considering equivalent sorghum grain yield) for each treatment were defined as the goals because the farmers like to get more productivity from each unit land. To get an equivalent economic value for both crops, castor yield was multiplied by 1.8, since the Indian market price of 1 kg of castor is 1.8 times the price of sorghum. The sustainable yield index (SYI) (Singh et al., 1990) was calculated based on sorghum yield equivalents, according to:

$$\mathrm{SYI} = \frac{\bar{Y} - \sigma}{Y_{\max}}$$

where $\bar{Y}$ was average yield of a treatment, σ was treatment standard deviation and $Y_{\max}$ was maximum yield in the experiment over years.

To select a representative minimum data set (MDS) (Doran and Parkin, 1994; Andrews et al., 2002a) only those soil properties that showed significant treatment differences were selected. Significant variables were chosen for the next step in MDS formation through principle component analysis (PCA) (Andrews et al., 2002a,b; Shukla et al., 2004). Principal components (PC) for a data set are defined as linear combinations of variables that account for maximum variance within the set by describing vectors of closet fit to the n observation in p-dimensional space, subject to being orthogonal to one another. The principal components receiving high eigen values and variables with high factor loading were assumed to be variables that best represented system attributes. Therefore, only the PCs with eigen values ≥ 1 (Brejda et al., 2000) and those that explained at least 5% of the variation in the data (Wander and Bollero, 1999) were examined. Within each PC, only highly weighted factors were retained for MDS. Highly weighted factor loadings were defined as having absolute values within 10% of the highest factor loading. When more than one factor was retained under a single PC, multivariate correlation coefficients were employed to determine if the variables could be considered redundant and therefore eliminated from the MDS (Andrews et al., 2002a). Well-correlated variables were considered redundant and only one was considered for the MDS. The rest were eliminated from the data set. If the highly weighted variables were not correlated, each was considered important and was retained in the MDS. As a check of how well the MDS represented the management system goals, multiple regression was performed using the indicators retained in the MDS as independent variables and the end point measures like SYI, average yield of castor and average yield of sorghum as dependent variables. If any variable within the MDS did not contribute to the coefficient of determinant of multiple regressions of the variables, it was also dropped from the MDS.

After determining the MDS indicators, every observation of each MDS indicator was transformed using a linear scoring method (Andrews et al., 2002b). Indicators were arranged in order depending on whether a higher value was considered ‘‘good’’ or ‘‘bad’’ in terms of soil function. For ‘more is better’ indicators, each observation was divided by the highest observed value such that the highest observed value received a score of 1. For ‘less is better’ indicators, the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received a score of 1. In the present study, as all the indicators that were retained in the minimum data set were considered good when in increasing order, they were scored, as "more is better". Once transformed, the MDS variables for each observation were weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage, divided by the total percentage of variation explained by all PCs with eigenvectors >1, provided the weighted factor for variables chosen under a given PC. We then summed up the weighted MDS variables scores for each observation using the following equation:

$$\mathrm{SQI} = \sum_{i=1}^{n} W_{\mathrm{i}} S_{\mathrm{i}}$$

where S is the score for the subscripted variable and W_{i} is the weighing factor derived from the PCA. Here the assumption is that higher index scores meant better soil quality or greater performance of soil function. Further, the percent contribution of each final key indicator was also calculated. The SQI values so obtained were tested for their level of significance at $P = 0.05$.

3. Results and discussion

3.1. Effect of land management on crop yield

Out of 8 years of experimentation, sorghum (1995, 1997, 1999, and 2001) and castor were grown for 4 years each (1996, 1998, 2000 and 2002) (Table 2). Tillage, residue and N levels played a significant role in influencing the yields of sorghum and castor when studied as individual factors. Conventional tillage was superior to MT for yield of both crops in rotation. Application of gliricidia loppings resulted in significantly higher yield of crops compared to sorghum residue and no residue. Increasing N increased yield of castor and sorghum. The interactive effect of tillage and N on crop yield was significant. When all three factors (tillage × nitrogen × residues) were considered together, interactions were not significant. Despite the three factor interactions were not significant, the average yield of sorghum was highest under CTGLN_{90} (1589 kg ha^{-1}) followed by CTSSN_{90} (1476 kg ha^{-1}) and CTGLN_{60} (1459 kg ha^{-1}). Highest castor yield was recorded under CTGLN_{90} (1090 kg ha^{-1}) followed by CTGLN_{60} (1039 kg ha^{-1}) and CTNRN_{90} (1037 kg ha^{-1}). The SYI was significantly higher under CT than under MT. Application of gliricidia residue to sorghum and castor crops resulted in higher SYI compared with other residue treatments. Since the nitrogen status of these soils was low, fertilizer N levels significantly influenced the SYI. The interactive effects of tillage × nitrogen and residue × nitrogen on SYI were significant. SYI was highest in CTSSN_{90} (0.60) followed by CTGLN_{60} (0.59) and CTGLN_{90} (0.58). The superiority of gliricidia loppings over sorghum stover was probably attributed to its higher N content (27.6 g kg^{-1} on dry weight basis). Our results of higher SYI under CT than MT are in contrast to the results of Karlen et al. (1994a,b) who found that use of zero tillage or applying supplemental crop residues in the non-glaciated major land resource area of the USA could improve soil quality compared with more intensive tillage practices or removal of crop residues.

3.2. Selection of indicators

Soil responses to different management practices are presented in Table 3. Among the 21 variables, when averaged over the other factors, tillage influenced nine variables, i.e. K, Mg, Cu, Mn, MBC, MBN, BD, HC, and MWD. A significant effect of residues was observed on EC, OC, available N, P, K, S, Zn, B, MBC, DHA, MBN, BD and MWD. Nitrogen levels significantly influenced pH, EC, OC, available N, P, K, S, Fe, Cu, Mn, B, MBC, MBN, DHA, BD, MWD and available water. For initial screening of indicators, parameters showing significance in two or more of seven treatment effects (Table 3) were considered important and retained for PCA analysis. Using these criteria, six soil properties (pH, Ca, Mg, Zn, Fe and available soil water) were dropped and the remaining 15 properties were selected for PCA.

3.3. Results of principal component analysis

In the PCA of 15 variables, five PCs had eigen value >1 and explained 78 % of the variance in the

Table 2
Long-term effects of land management treatments on crop yields and sustainable yield index

Tillage	Residues	N levels (kg ha^{-1})	Sorghum average yield (kg ha^{-1})	Castor average yield (kg ha^{-1})	SYI
Conventional tillage	Sorghum stover	N_0	624	529	0.46
		N_{30}	1052	816	0.36
		N_{60}	1355	917	0.53
		N_{90}	1476	1020	0.60
	Gliricidia loppings	N_0	664	622	0.39
		N_{30}	1091	949	0.43
		N_{60}	1459	1039	0.59
		N_{90}	1589	1090	0.58
	No residue	N_0	694	547	0.54
		N_{30}	1037	807	0.36
		N_{60}	1274	971	0.49
		N_{90}	1409	1037	0.53
Minimum tillage	Sorghum stover	N_0	517	270	0.20
		N_{30}	796	409	0.31
		N_{60}	925	560	0.39
		N_{90}	1003	671	0.51
	Gliricidia loppings	N_0	540	281	0.25
		N_{30}	886	466	0.35
		N_{60}	1037	568	0.41
		N_{90}	1119	715	0.46
	No residue	N_0	575	274	0.20
		N_{30}	826	396	0.25
		N_{60}	948	474	0.34
		N_{90}	1010	647	0.46
Tillage (T)			**	**	*
Residue (R)			**	**	*
Nitrogen (N)			**	**	**
T × R			NS	NS	NS
T × N			**	**	**
R × N			**	NS	*
T × R × N			NS	NS	NS

NS, non-significant at $P > 0.05$.

[*] Significant difference at $P = 0.05$.

[**] Significant difference at $P = 0.01$.

data (Table 4). Highly weighted variables under PC1 included available N, OC, MBC and MBN. A correlation matrix for the highly weighted variables under different PCs was run separately (Table 5). It was assumed that the variables having the highest correlation sum best represented the group. Among the four variables in PC1, MBC was chosen for the MDS because of its highest correlation sum. The organic carbon had the lowest correlation sum but was highly correlated with MBC ($r = 0.85$) and hence it was dropped. The variable with second lowest correlation sum was available N and it was retained for MDS. In PC2, K and HC were highly weighted but not correlated. Both were retained in MDS because of their relative importance in dryland agriculture. Under PC3 and PC4, EC, Cu and DHA were highly weighted variables. Andrews et al. (2002a) reported EC as an important soil quality indicator when the soils are with high pH (>7.5) range and the changes in EC are likely due to management decision. The soils under study were slightly acidic to neutral and the variations in EC between treatments were very low

Table 3
Effect of tillage, residues and nitrogen levels on soil quality indicators

Tillage	Residues	N levels	pH	EC	OC	N	P	K	Ca	Mg	S	Zn	Fe	Cu	Mn	B	MBC	DHA	MBN	BD	HC	MWD	Available water
CT	SS	N_0	6.6	0.07	5.7	198	49	241	5.2	1.6	9.3	1.0	7.2	0.7	20.2	1.1	126	18.8	38	1.6	2.9	0.2	4.5
		N_{30}	6.3	0.08	5.3	199	43	278	3.9	1.3	8.2	1.4	8.6	0.6	22.5	1.2	135	31.7	46	1.6	3.0	0.2	4.4
		N_{60}	6.3	0.06	6.1	201	43	280	4.7	1.5	9.2	1.1	8.3	0.7	24.6	1.2	160	31.1	57	1.5	3.6	0.3	5.3
		N_{90}	6.3	0.10	6.2	216	46	208	4.5	1.4	8.8	1.2	10.1	0.8	25.3	0.9	163	33.3	59	1.5	3.9	0.3	5.3
	GL	N_0	6.4	0.14	5.0	193	42	243	4.2	1.3	7.0	1.2	7.4	0.7	22.1	0.8	133	29.3	37	1.6	4.0	0.5	3.9
		N_{30}	6.3	0.07	5.6	193	41	255	4.0	1.5	8.1	1.2	8.7	0.7	23.1	0.9	151	33.4	48	1.6	3.9	0.2	4.5
		N_{60}	6.3	0.09	6.6	201	46	256	4.3	1.4	9.9	1.2	7.8	0.8	24.4	1.5	171	48.4	61	1.6	3.7	0.5	5.4
		N_{90}	6.2	0.05	6.4	251	46	247	4.7	1.4	6.9	1.3	9.6	0.7	27.4	1.3	183	64.4	79	1.5	3.8	0.5	4.3
	NR	N_0	6.3	0.11	3.6	160	36	234	4.5	1.3	9.0	1.1	8.4	0.7	19.7	0.5	109	26.5	36	1.6	3.6	0.1	4.6
		N_{30}	6.1	0.06	3.6	194	37	198	3.9	1.2	8.9	1.0	8.8	0.6	20.0	0.8	111	28.0	39	1.6	3.4	0.3	4.3
		N_{60}	6.1	0.08	3.8	204	34	252	3.9	1.2	6.3	1.1	9.3	0.7	26.2	0.7	115	30.7	44	1.6	3.2	0.3	4.4
		N_{90}	6.1	0.08	4.0	227	38	201	4.6	1.4	6.1	1.2	9.5	0.8	24.6	1.3	115	30.5	61	1.7	3.4	0.3	4.7
MT	SS	N_0	6.4	0.05	5.4	197	51	259	4.5	1.3	5.2	1.2	10.9	0.7	28.5	0.5	165	25.4	55	1.7	3.3	0.2	6.1
		N_{30}	6.1	0.07	5.7	207	48	207	6.7	2.1	5.9	1.0	10.2	0.7	28.2	0.9	173	27.5	61	1.6	3.2	0.1	5.4
		N_{60}	6.3	0.06	6.0	215	36	202	5.9	1.9	7.9	1.2	10.5	0.7	33.6	1.0	177	43.0	64	1.6	3.0	0.3	6.1
		N_{90}	5.9	0.08	6.3	251	39	193	4.3	1.6	5.5	1.2	10.7	0.6	32.1	1.0	180	37.2	69	1.6	3.1	0.7	5.2
	GL	N_0	6.4	0.09	4.0	177	40	196	5.3	1.9	9.9	1.0	10.2	0.6	22.4	0.7	140	27.7	47	1.7	3.0	0.2	3.3
		N_{30}	6.2	0.09	4.5	228	39	205	5.2	1.9	12.6	1.3	11.7	0.7	30.4	1.1	150	32.1	54	1.6	2.8	0.2	5.3
		N_{60}	6.2	0.09	5.5	234	46	244	4.1	1.6	6.0	1.0	9.1	0.6	29.5	1.3	170	28.1	63	1.6	2.7	0.2	5.8
		N_{90}	5.7	0.12	5.8	247	43	180	4.7	1.9	6.9	1.1	12.9	0.7	35.5	1.0	187	29.2	70	1.5	2.8	0.5	4.9
MT	NR	N_0	6.4	0.06	4.3	154	36	270	4.9	1.6	6.4	1.0	10.2	0.7	24.5	1.0	124	29.2	42	1.8	2.8	0.2	4.3
		N_{30}	6.0	0.06	4.4	175	38	154	4.9	1.6	7.4	0.9	9.8	0.6	26.8	0.7	130	32.0	48	1.7	2.8	0.2	5.1
		N_{60}	6.2	0.05	4.5	198	35	198	5.5	1.7	9.7	1.0	10.1	0.7	29.8	0.7	138	32.2	50	1.7	2.8	0.7	4.9
		N_{90}	6.1	0.09	4.5	235	34	216	4.0	1.6	9.3	1.2	10.3	0.6	32.8	0.9	142	32.4	76	1.6	3.0	0.3	4.9
Tillage (T)			NS	NS	NS	NS	NS	**	NS	*	NS	NS	NS	*	*	NS	**	NS	*	**	*	**	NS
Residue (R)			NS	**	**	**	**	**	NS	NS	*	*	NS	NS	NS	*	**	**	**	**	NS	**	NS
Nitrogen (N)			**	**	**	**	**	**	NS	NS	**	NS	*	**	**	**	**	**	**	**	NS	**	**
T × R			NS	**	**	NS	NS	**	NS	NS	**	NS	NS	**	NS	NS	**	**	**	**	*	**	NS
T × N			NS	**	NS	*	**	**	*	NS	NS	NS	NS	**	NS	NS	NS	**	**	**	NS	**	NS
R × N			NS	**	*	**	**	**	NS	NS	**	NS	NS	**	NS	**	**	**	**	**	NS	**	NS
T × R × N			NS	**	NS	**	**	**	NS	NS	**	NS	NS	**	NS	**	**	**	**	**	*	**	NS

CT, conventional tillage; MT, minimum tillage; SS, sorghum stover; GL, glyricidia loppings; NR, no residue; N_0, N_{30}, N_{60} and N_{90}, nitrogen levels (kg ha^{-1}). NS, non-significant at $P > 0.05$. OC, organic carbon (g kg^{-1}); EC, electrical conductivity (dS m^{-1}); N, P, K, available nitrogen, phosphorus and potassium (kg ha^{-1}); Ca, Mg, exchangeable calcium, magnesium (cmol kg^{-1}); S, Zn, Fe, Cu, Mn and B, available sulphur, zinc, iron, copper, manganese and boron (μg g^{-1}); MBC, microbial biomass carbon (μg g^{-1} of soil); DHA, dehydrogenase activity (μg TPF 24 h^{-1} g^{-1}) (TPF, triphenyl formazan); MBN, microbial biomass nitrogen (kg ha^{-1}); BD, bulk density (mg kg^{-1}); HC, saturated hydraulic conductivity (cm h^{-1}); MWD, mean weight diameter (mm); available water % (w/w).

* Significant difference at $P = 0.05$.

** Significant difference at $P = 0.01$.

Table 4
Results of principle component analysis (PCA) of soil quality indicators based on 24-land management treatments

PC's	PC1	PC2	PC3	PC4	PC5
Eigen value	5.0	2.7	1.5	1.4	1.1
% of variance	33.8	17.8	10.1	9.4	7.1
Cumulative %	33.8	51.6	61.7	71.1	78.2
Factor loading/eigen vector					
Variable					
EC	0.029	0.048	*0.680*	*−0.547*	−0.036
Organic carbon	*0.837*	0.328	−0.198	−0.144	0.014
Available N	*0.823*	−0.319	0.138	−0.120	0.071
Available P	0.404	0.486	−0.407	−0.501	−0.067
Available K	−0.012	*0.719*	−0.307	0.023	0.115
S	−0.204	0.048	0.371	0.113	*0.768*
Cu	0.162	0.539	0.033	*0.542*	−0.192
Mn	0.623	−0.664	−0.060	0.052	−0.111
B	0.603	0.172	−0.208	−0.004	0.541
Dehydrogenase	0.662	0.152	0.099	*0.565*	0.099
Microbial biomass C	*0.896*	−0.049	−0.161	−0.155	−0.057
Microbial biomass N	*0.872*	−0.309	−0.057	0.109	0.020
Bulk density	−0.604	−0.396	−0.464	0.260	−0.014
Hydraulic conductivity	0.165	*0.787*	0.399	0.130	−0.245
MWD	0.560	−0.223	0.375	0.266	−0.197

Italic face factor loadings are considered highly weighted within 10% of variation of the absolute values of the highest factor loading in each PC.

(0.05–0.14 dS m^{-1}) and hence eliminated from the MDS. The DTPA-Cu was also eliminated because of low treatment variation (0.6–0.8 $\mu g\ g^{-1}$). Although DHA was found as a highly weighted variable under PC4, it could not be retained because of its higher correlation with MBC (r = 0.50, significant at P = 0.05) and N (r = 0.42, significant at P = 0.05). Available S was another variable, which was qualified under PC5 and was considered under MDS because occurrence of frequent deficiencies of sulphur in dryland Alfisol (critical limit <10 $\mu g\ g^{-1}$). Andrews et al. (2002a) and Dalal and Moloney (2000) reported that choice among well-correlated variables could also be based on the practicability of the variables. Hence, one could use the options to retain or drop the variables from the final MDS considering the ease of sampling, cost of estimation and logic and interpretability. Considering these reports, options were utilized to retain or eliminate the variables from the MDS. Hence, the final MDS consisted of MBC, N, K, HC and S. The set of indicators chosen earlier for Eutric Fluvisols by Andrews et al. (2002b) varied with crops. When all the above indicators, that were retained in the MDS were regressed as independent variables with data on management goal as dependent variables, the coefficient of determination (R^2) with SYI, average yield of sorghum and average yield of castor were 0.41, 0.42 and 0.51, respectively (Table 6).

Multiple regressions revealed that N and HC significantly influenced all three management goals, while the effect of S was significant only on SYI. Available K and MBC had significant influence on average castor yield.

3.4. Soil quality index

Tillage did not influence SQI significantly (Table 7). Main effects of residue and nitrogen levels on SQI were significant. Many interactions were also significant. Application of gliricidia loppings was superior to sorghum stover and no residue in maintaining higher SQI values. Increasing N levels also helped in maintaining higher SQI values. The application of gliricidia loppings at all levels of nitrogen proved to be quite effective in maintaining soil quality under CT, but not under MT with N_0. Among the combination of 24 treatments, the SQI

Table 5
Correlation matrix for highly weighted variables under PC's with high factor loading

Variables	Organic carbon	Nitrogen	Microbial biomass carbon	Microbial biomass nitrogen
PC1 variables				
Pearson's correlation				
Organic carbon	1.000	0.479*	0.846**	0.550**
Nitrogen	0.479*	1.000	0.625**	0.829**
Microbial biomass carbon	0.846**	0.625**	1.000	0.763**
Microbial biomass nitrogen	0.550**	0.829**	0.763**	1.000
Correlation sums	2.875	2.933	3.234	3.142
	Potassium	Hydraulic conductivity		
PC2 variables				
Potassium	1.000	0.334		
Hydraulic conductivity	0.334	1.000		
	Electrical Conductivity			
PC3 variables				
Electrical conductivity	1.000			
	Electrical conductivity	Copper	Dehydrogenase activity	
PC4 variables				
Electrical conductivity	1.000	−0.104	−0.203	
Copper	−0.014	1.000	0.319	
Dehydrogenase activity	−0.203	0.319	1.000	
Correlation sums	1.217	1.423	1.522	
	Sulphur			
PC5 variables				
Sulphur	1.000			

[*] Significant difference at $P = 0.05$.
[**] Significant difference at $P = 0.01$.

ranged from 0.90 to 1.27. Highest SQI was obtained in CTGLN_{90} (1.27) followed by CTGLN_{60} (1.19) and MTSSN_{90} (1.18). Lowest SQI value was obtained under MTNRN_{30} (0.90) followed by MTNRN_{0} (0.94), suggesting relatively less aggradative effect of these treatments.

Averaged across tillage and N levels, application of sorghum stover and gliricidia loppings resulted in SQI values of 1.12 and 1.13, whereas with no residues, it was 0.99 (Fig. 1). Averaged across tillage and residues, SQI increased with the increasing levels of N. The contribution of individual indicators towards SQI was 32, 31, 17, 16, 4% for N, MBC, K, HC and S, respectively.

In the present study, the contribution of available N towards SQI was substantial. Available soil N plays a dominant role in maintaining the yield of dryland crops. It helps in increasing the vegetative growth as well as root biomass. This in-turn enhances the organic matter in soil. Coming to the

Table 6
Results of multiple regressions of the minimum data set (MDS) components using management goal attributes at different probability (*P*) levels

Goal or function	R^{2**}	Most significant MDS variables	*P*
Sustainable yield index	0.411	N, HC, S	>0.000, >0.000, >0.035
Average sorghum yield	0.420	N, HC	>0.000, >0.001
Average castor yield	0.507	N, K, MBC, HC	>0.000, >0.016, >0.049, >0.000

N, K, S: available nitrogen, potassium, sulphur; MBC: microbial biomass carbon; HC: saturated hydraulic conductivity.
[**] Significant at $P = 0.01$ level.

Table 7
Effect of different land management treatments on soil quality index

N levels (kg ha^{-1})	Conventional tillage (CT)			Minimum tillage (MT)		
	SS	GL	NR	SS	GL	NR
N_0	1.02	1.10	0.95	1.12	0.99	0.94
N_{30}	1.07	1.12	0.97	1.11	1.11	0.90
N_{60}	1.17	1.19	1.01	1.13	1.15	1.01
N_{90}	1.16	1.27	1.02	1.18	1.17	1.10
Tillage (T)				NS		
Residue (R)				**		
Nitrogen (N)				**		
T × R				**		
T × N				NS		
R × N				**		
T × R × N				**		

SS, sorghum stover; GL, glyricidia loppings; NR, no residue; N_0, N_{30}, N_{60} and N_{90}, nitrogen levels (kg ha^{-1}), NS, non-significant at $P > 0.05$.

** Significance at $P = 0.01$.

role of MBC in improving SQI, soil microorganisms are the driving force behind soil organic matter transformations, such as mineralization and immobilization of organic constituents. These transformations are the basis of plant decomposition, soil aggregation, soil tilth and nutrient availability (Smith et al., 1993). There are reports that MBC is strongly influenced by management practices and system perturbations (Smith and Paul, 1990) and it provides an indication of soil's ability to store and recycle nutrients and energy. It also serves as a sensitive indicator of change and in organic matter levels and equilibria (Gregorich et al., 1994). The contribution of HC to SQI is likely derived from this soil's hard setting tendencies, crust formation and poor water retention. Available K is important for osmotic regulations. Potassium provides much of the osmotic pull that draws water into plant roots. Plants that are K deficient are less able to withstand water deficit mostly because of their inability to make full use of available water. Malfunctioning of stomata due to a deficiency of this nutrient has been related to lower rates of photosynthesis and less efficient use of water, which is a discouraging feature for moisture stress situations in drylands. Further, tillage practices are known to influence K availability by modifying other factors such as oxygen or aeration, temperature, soil moisture and positional availability of applied K. There is evidence that K availability

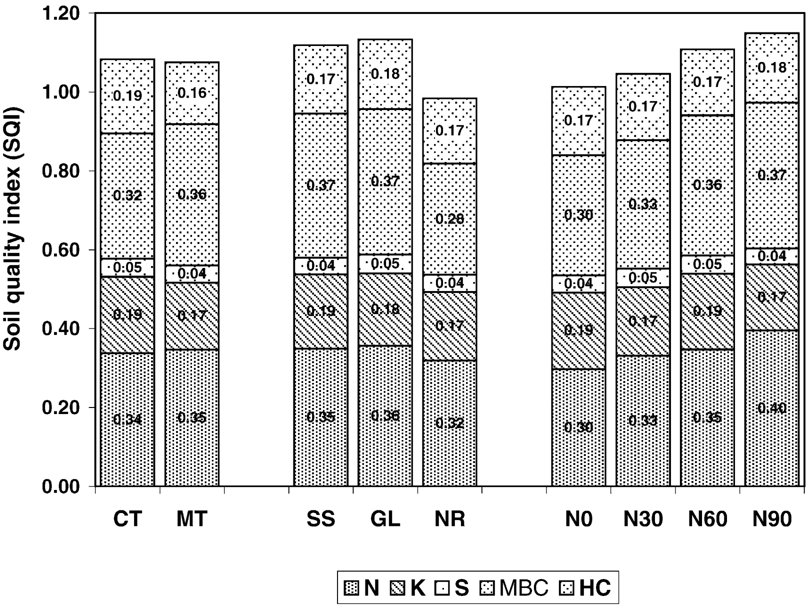

Fig. 1. Average effect of tillage, residues and N levels on soil quality index and the individual contribution of each of the key indicators. Note – CT: conventional tillage; MT: minimum tillage; SS: sorghum stover; GL: glyricidia loppings; NR: no residue; N_0, N_{30}, N_{60} and N_{90}: nitrogen levels (kg ha^{-1}).

under minimum tillage or zero tillage is lower because of increased compaction, less aeration, low temperature and positional availability of K applied on the surface (Tisdale et al., 1985). Despite medium soil test values (<290 kg ha^{-1}) and no application of K fertilizer in the present study, K emerged as a key indicator contributing 17% towards SQI.

4. Summary

Among the various treatments, CTGLN$_{90}$ had the highest SQI. This treatment was found most promising from the viewpoint of sustainability, maintaining higher average yield levels and better soil quality in dryland Alfisols under sorghum–castor rotation. When SYI was considered, CT remained superior to MT. These Alfisols suffer from hard setting tendencies and low infiltration of water because of compact surface. To maintain yield as well as soil quality in these tropical Alfisols, primary tillage along with organic residue and N application is recommended.

Acknowledgements

Authors are thankful to Dr. J.F. Parr and Dr. J.F. Power of United States Department of Agriculture (USDA) for providing the funds and technical suggestions from time to time for the project in the initial years of field experiments during 1995–1996 under Indo-US collaborative programme. Thanks are also due to National Agricultural Technology Project authorities (NATP – World Bank) for supporting the project financially since 2000. Authors are also thankful to former Director Dr. H.P. Singh and present Director Dr. Y.S. Ramakrishna of CRIDA, Hyderabad for facilitating the research program during the period of the study.

References

Acton, D.F., Gregorich, L.J., 1995. Understanding soil health. In: Acton, D.F., Gregorich, L.J. (Eds.), The Health of Our Soils – Toward Sustainable Agriculture in Canada. Centre for Land and Biological Resources Research, Research Branch, Agriculture and Agri-Food, Canada, Ottawa, ON, pp. 5–10.

Andrews, S.S., Mitchell, J.P., Mancinelli, R., Larlen, D.L., Hartz, T.K., Horwarth, W.R., Pettygrove, G.S., Scow, K.M., Munk, D.S., 2002a. On farm assessment of soil quality in California's Central Valley. Agron. J. 94, 12–23.

Andrews, S.S., Karlen, D.L., Mitchell, J.P., 2002b. A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agric. Ecosyst. Environ. 90, 25–45.

Arshad, M.A., Coen, G.M., 1992. Characterization of soil quality: physical and chemical criteria. Am. J. Alter. Agric. 7, 25–31.

Berger, K.C., Truog, E., 1944. Boron tests and determination for soils and plants. Soil Sci. 57, 25–36.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1, Physical and Minerological Methods, Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI, pp. 364–367.

Brejda, J.J., Moorman, T.B., Karlen, D.L., Dao, T.H., 2000. Identification of regional soil quality factors and indicators. I. Central and Southern High Plains. Soil Sci. Soc. Am. J. 64, 2115–2124.

Cassel, D.K., Nielsen, D.R., 1986. Field capacity and available water capacity. In: Klute, A. (Ed.), Methods of Soil Analysis, Part I, Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI, pp. 901–924.

Dalal, R.C., Moloney, D., 2000. Sustainability indicators of soil health and biodiversity. In: Hale, P., Petrie, A., Moloney, D., Sattler, P. (Eds.), Management for Sustainable Ecosystems, Centre for Conservation Biology. The University of Queensland, Brisbane, pp. 101–108.

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. Soil Sci. Soc. Am., Inc, Madison, WI, USA, pp. 3–21.

Doran, J.W., Sarrantonio, M., Liebig, M.A., 1996. Soil health and sustainability. Adv. Agron. 56, 1–54.

El-Swaify, S.A., Pathak, P., Rego, T.J., Singh, S., 1985. Soil management for optimized productivity under rainfed condition in the semi arid tropics. Adv. Soil. Sci. 1, 1–64.

El-Swaify, S.A., Singh, S., Pathak, P., 1987. Physical and conservation constraints and management components for SAT Alfisols. In: Alfisols in the Semi-arid Tropics: A Consultants' Workshop Held at ICRISAT Centre, India from December 1–3, 1983, pp. 33–48.

Ericksen, P.J., McSweeney, K., 2000. Fine scale analysis of soil quality for various land uses and landforms in central Honduras. Am. J. Alt. Agric. 14, 146–157.

Gee, G.W., Bauder, J.W., 1986. Particle size analysis. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. Physical and Minerological Methods, Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI, pp. 404–408.

Ghosh, P.K., Dayal, D., Mandal, K.G., Wanjari, R.H., Hati, K.M., 2003. Optimization of fertilizer schedules in fallow and groundnut-based cropping systems and an assessment of system sustainability. Field Crops Res. 80, 83–98.

Granatstein, D., Bezdicek, D.F., 1992. The need for a soil quality index: local and regional perspectives. Am. J. Alt. Agric. 7, 12–16.

Gregorich, E.G., Carter, M.R., Angers, D.A., Monreal, C.M., Ellert, B.H., 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil. Sci. 74, 367–385.

Hanway, J.J., Heidel, H., 1952. Soil analyses methods as used in Iowa State College Soil Testing Laboratory. Iowa Agric. 57, 1–31.

Hillel, D., 1980. Fundamentals of Soil Physics. Academic Press, New York.

Hornung, M., 1993. Defining soil quality for ecosystems and ecosystem functioning. Integrated Soil and Sediment Research: A Basis for Proper Protection. In: Eijsackers, H.J.P., Hamers, T. (Eds.), Proceedings of The First European Conference on Integrated Research for Soil and Sediment Protection and Remediation (EUROSOL), Maastricht, The Netherlands, September 1–12, 1992, Kluwer Academic Publishers, Dordrecht, pp. 201–211.

Howard, P.J.A., 1993. Soil protection and soil quality assessment in the EC. Sci. Tot. Env. 129, 219–239.

Hussain, I., Olson, K.R., Wander, M.M., Karlen, D.L., 1999. Adaptation of soil quality indices and application to three tillage systems in southern Illinois. Soil Till. Res. 50, 237–249.

Jackson, M.L., 1967. Organic matter determinations for soils. In: Soil Chemical Analysis, Prentice Hall, New Delhi.

Jenkinson, D.S., Ladd, J.N., 1981. Microbial biomass in soil: measurement and turnover. In: Paul, E.A., Ladd, J.N. (Eds.), Soil Biochem. 5, pp. 415–457.

Jenkinson, D.S., Powlson, D.S., 1976. The effects of biocidal treatments on metabolism in soil. V. A method for measuring soil biomass. Soil Boil. Biochem. 8, 209–213.

Jones, O.R., Allen, R.R., Unger, P.W., 1990. Tillage systems and equipment for dryland farming. Adv. Soil Sci. 13, 89–125.

Karlen, D.L., Eash, N.S., Unger, P.W., 1992. Soil and crop management effects on soil quality indicators. Am. J. Alter. Agric. 7 (1/2), 48–55.

Karlen, D.L., Parkin, T.P., Eash, N.S., 1996. Use of soil quality indicators to evaluate conservation reserve program sites in Iowa. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. SSSA Special publication no. 49. Soil Sci. Soc. Am, Madison, WI, USA, pp. 345–355.

Karlen, D.L., Stott, D.E., 1994. A framework for evaluating physical and chemical indicators of soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. Soil Sci. Soc. Am., Inc, Madison, WI, USA, Special publication 35, pp. 53–72.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., Jordahl, J.L., 1994a. Crop residue effects on soil quality following 10-years of no-till corn. Soil Till. Res. 31, 149–167.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., Jordahl, J.L., 1994b. Long term tillage effects on soil quality. Soil Till. Res. 32, 313–327.

Klute, A., 1965. Laboratory measurement of hydraulic conductivity of saturated soil. In: Black, C.A. (Ed.), Method of Soil Analysis. Part I, Agronomy 9. Am. Soc. Agron. Inc, Madison, WI, USA, pp. 210–211.

Lanyon, L.E., Heald, W.R., 1982. Magnesium, calcium, strontium and barium. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties, Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI, pp. 247–262.

Larson, W.E., Pierce, F.J., 1994. The dynamics of soil quality as a measure of sustainable management. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. SSSA. Spec. Publ. 35. SSSA and ASA, Madison, WI, pp. 37–51.

Lenhard, G., 1956. Die dehydrogenase-activitat des Bodens als Mass fur die mikroorganis-mentatigkeit im Boden. Zeitschrift fur Pflanzenernaehr. Dueng und Bodenkd. 73, 1–11.

Lewandowski, A., Zumwinkle, M., Fish, A., 1999. Assessing the soil system: a review of soil quality literature. Minnesota Dept. of Agriculture, Energy and Sustainable Agriculture Program, St. Paul.

Lindsay, W.L., Norvell, W.A., 1978. Development of a DTPA soil test for zinc, iron, manganese and copper. Soil Sci. Soc. Am. J. 42, 421–428.

Nortcliff, S., 2002. Standardization of soil quality attributes. Agric. Ecosyst. Environ. 88, 161–168.

Olsen, S.R., Cole, C.U., Watanabe, F.S., Deen, L.A., 1954. Estimation of available phosphorus in soil by extracting with sodium bicarbonate. USDA circular 939, Washington.

Palm, C.A., Swift, M.J., Woomer, P.L., 1996. Soil biological dynamics in slash-and-burn agriculture. Agric. Ecosys. Environ. 58, 61–74.

Parr, J.F., Papendick, R.I., Hornick, S.B., Meyer, R.E., 1992. Soil quality: attributes and relationship to alternative and sustainable agriculture. Am. J. Alter. Agric. 7, 5–11.

Prasad, R.N., Biswas, P.P., 1999. Soil Resources of India. In: Fifty Years of Natural Resource Management Research, Natural Resource Management Division, Indian Council of Agricultural Research, New Delhi, pp. 13–30.

Rasmussen, P.E., Collins, H.P., 1991. Long-term impacts of tillage, fertilizer and crop residue on soil organic matter in temperate semi arid regions. Adv. Agron. 45, 93–134.

Rhoades, J.D., 1982. Soluble salts. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2, Chemical and Microbiological Properties. Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI, pp. 635–655.

Shukla, M.K., Lal, R., Ebinger, M., 2004. Soil quality indicators for reclaimed mine soils in southeastern Ohio. Soil Sci. 169 (2), 133–141.

Singh, R.P., Das, S.K., Bhaskara Rao, U.M., Narayana Reddy, M., 1990. Towards Sustainable Dryland Agricultural Practices, Technical Bulletin. Central Research Institute for Dryland Agriculture, Hyderabad, India, pp. 1–106.

Singh, H.P., Sharma, K.L., Venkateswarlu, B., Vishnumurthy, T., Neelaveni, K., 1998. Prospects of Indian agriculture with special reference to nutrient management under rainfed systems. In: Proceedings of the Long Term Soil Fertility Management through Integrated Plant Nutrient Supply, National Workshop held during April 2–4, 1998 at IISS, Bhopal, pp. 34–54.

Smith, J.L., Elliott, L.F., 1990. Tillage and residue management effects on soil organic matter dynamics in semi arid regions. Adv. Soil Sci. 13, 69–85.

Smith, J.L., Papendick, R.I., Bezdicek, D.F., Lynch, J.M., 1993. Soil organic matter dynamics and crop residue management. In:

Blaine Metting, Jr., F. (Ed.), Soil Microbial Ecology – Applications in Agricultural and Environmental Management. Environmental Sciences Department, Washington, pp. 65–94.

Smith, J.L., Paul, E.A., 1990. The significance of soil microbial biomass estimations. In: Bollag, G.M., Stotzky, G. (Eds.), Soil Biochemistry, vol. 6. Marcel Dekker, New York, pp. 357–396.

Subbaiah, B.V., Asija, G.C., 1956. A rapid procedure for determination of available nitrogen in soils. Curr. Sci. 25, 259–260.

Tisdale, S.L., Nelson, W.L., Beaton, J.D., 1985. Soil Fertility and Fertilizers. Macmillan, New York, pp. 67–68, 270–271.

van Bevel, C.H.M., 1949. Mean weight diameter of soil aggregates as a statistical index of aggregation. Soil Sci. Soc. Am. Proc. 14, 20–23.

Wander, M.M., Bollero, G.A., 1999. Soil quality assessment of tillage impacts on Illinois. Soil Sci. Soc. Am. J. 63, 961–971.

Williams, C.H., Steinbergs, A., 1959. Soil sulphur fractions as chemical indices of available sulphur in soil Australian soils. Aust. J. Agric. Res. 10, 340–352.

Yoder, R.E., 1936. A direct method of aggregate analysis and study of the physical nature of erosion losses. J. Am. Soc. Agron. 28, 337–351.