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Review

Managing natural resources of watersheds in the semi-arid tropics for improved soil and water quality: A review

K.L. Sahrawat *, S.P. Wani, P. Pathak, T.J. Rego

Global-Theme Agroecosystems, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India

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ABSTRACT

Soil, water and production systems constitute the most important natural resources of a watershed in the rainfed agro-ecosystem; and for sustainability of the production systems they need to be in harmony with the environment. To learn from the past research, a review is made of literature on the impact of natural resource management practices on soil and water quality in the semi-arid tropical regions of India. The results from long-term on station field experiments show that an integrated use of soil and water conservation practices with balanced plant nutrition can not only sustain increased productivity but also maintain soil quality at the watershed or catchment level. Natural resource management practices that conserve soil and water also help to maintain surface and groundwater quality. The changes in soil and water quality, as impacted by natural resource management practices, need to be monitored and assessed on a continuing basis as the outcome of such research offers valuable opportunity for the implementation of corrective management practices, as and when needed.
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1. Introduction

Soil, water, vegetation and production systems constitute the most important natural resources of a watershed in an agro-ecosystem. The importance of water shortage cannot be over-emphasized for the rainfed production systems in the semi-arid tropical regions (CAWMA, 2007; Pathak et al., 2009). Apart from water shortages, vegetation cover, biomass production and productivity of the farming systems in the SAT regions are also constrained by low soil fertility (Zougmore et al., 2003; Rego et al., 2007; Sahrawat et al., 2007; Twomlow et al., 2008a). From this, it follows that for sustained productivity both water shortage and nutrient problems have to be simultaneously addressed in an integrated management strategy (Wani et al., 2003; Zougmore et al., 2003; Rego et al., 2007).

Good soil quality is essential not only for increased productivity, but also for the agro-ecosystem to provide its services and benefits derived from the regulation of ecosystem processes. Soil also plays a key role in providing agro-ecosystem supporting services such as nutrient cycling and primary productivity (de Groot et al., 2002; Carpenter, 2002; Wani et al., 2005). These agro-ecosystem benefits cannot be derived from a degraded land resource base. Thus, maintaining the soil quality is of paramount importance and critical for the soil to perform its production and

* Corresponding author. Tel.: +91 40 30713071x2529; fax: +91 40 30713074.
E-mail address: k.sahrawat@cgiar.org (K.L. Sahrawat).

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environment-related functions on a sustainable basis (Katyal, 2003; Wani et al., 2005; Twomlow et al., 2008a).

For sustained productivity, the maintenance of soil fertility on a long-term basis is a prerequisite. For sustained soil fertility, it is essential that organic matter and nutrients removed in harvest or produce plus those lost through physical, chemical and biological processes are compensated through external addition on a regular basis such that organic matter status is maintained and nutrient balances are not negative in the longer term. Moreover, the maintenance of soil organic matter level at a threshold level, which depends on the soil type and climatic factors, is of critical importance for maintaining the physical, chemical and biological integrity of the soil, and to perform its agricultural productivity and environmental functions on a sustainable basis (Pathak et al., 2005; Bationo et al., 2008; Twomlow et al., 2008a).

Agricultural activities as part of the natural resource management (NRM) practice impact soil and water quality at the watershed or catchment level (Wani et al., 2003; Twomlow et al., 2008a). The negative effects on soil quality that lead to soil degradation can be broadly classified in two categories. One negative effect is caused by soil loss by water and wind erosion (den Biggelaar et al., 2004), and the second negative effect takes place due to deterioration in physical, chemical and biological properties of the soil (Poch and Martinez-Casanovas, 2006). The causes of physical, chemical and biological deterioration include loss of organic matter, waterlogging, salinization and alkalization of the soil, and the contamination of water resources. It has been observed that the intensification of production systems without adequate investment to sustain the system, results in the loss of fertility (Katyal, 2003; Pathak et al., 2005). The effects of loss of soil fertility are manifested as reduced yields due to reduced soil quality (Carpenter, 2002; Lal, 1997, 2004; den Biggelaar et al., 2004).

However, it is not necessary that agricultural practices always have a negative impact on soil quality and productivity. It is possible through quality soil and water and nutrient management practices to improve or maintain soil quality and sustain productivity at the same time. The objectives of this paper are to review and discuss results from long-term field research, with emphasis on the ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) experience, relating to the impact of improved soil, water and nutrient management practices on soil and water quality at the watershed/catchment level with emphasis on the Indian semi-arid tropics (SAT).

The changes in soil quality are monitored using a range of physical (soil erosion, depth, aggregation and aggregate stability, bulk density, infiltration, total and air-filled porosity, compaction, hydraulic conductivity), chemical (pH, organic C, total N, electrical conductivity, cations and acidity, available macro- and micronutrients) and biological (microorganisms, microbial biomass and activity, respiration, mineralizable N, microbial biomass C and N, earthworm and termite biomass) characteristics (Pathak et al., 2005).

ICRISAT has adopted an integrated genetic and natural resource management (IGNRM) approach to enhance agricultural productivity in rainfed areas, and this approach is based on a powerful integrative strategy of enhancing agricultural productivity. This approach maximizes synergies among the disciplines of NRM, crop improvement, social sciences; along with people's empowerment through capacity building measures (e.g. see Twomlow et al., 2008b). ICRISAT has learnt that converging different agrotechnologies at field level have greater impact on agricultural productivity in the farmers' fields than did compartmentalized evaluation of individual technologies. This was achieved through adoption of an integrated watershed management approach that is holistic in nature to realize the desired results of enhancing productivity, reducing land degradation and protecting the environment—a real win–win strategy for alleviating rural poverty in the rainfed areas of the semi-arid tropical regions (Wani et al., 2007, 2009).

2. Improved soil, water, and nutrient management for agricultural systems

The underlying principle of improved or quality management for sustaining productivity and soil and water quality under rainfed conditions in the semi-arid tropics (SAT) is based on exploiting the synergy between soil and water conservation practices and integrated nutrient management (INM) practice (supply of nutrients through mineral and organic sources) at the watershed level (Wani et al., 2003; Sahrawat et al., 2006; Bationo et al., 2008).

Under an integrated watershed management strategy in the Indian SAT, soil and water conservation measures are carried out following a detailed reconnaissance survey of the watershed. This is followed up by the implementation of appropriate landform treatment such as broad-bed and furrow (BBF), contour planting for *in situ* soil and water conservation; construction of soil and water conservation structures and tanks for water storage. The various soil and water conservation practices to be implemented depend on the amount and the distribution of rainfall, slope and soil type, especially soil profile depth (affects water holding capacity) and texture, especially clay content and clay type, which greatly influence water holding capacity, water infiltration rate and hydraulic conductivity, impacting water runoff and soil erosion (Pathak et al., 2005).

The harvested water stored in tank is used for supplemental irrigation of the crop during the growing season to save the crop and enhance productivity (Pathak et al., 2009). The harvested water can also be used to extend cropping intensity by cropping in both the rainy and post-rainy seasons, especially on Vertisols with higher water holding capacity through use of improved crop cultivars, and use of organic (use of organic matter through compost and legumes) and mineral sources (chemical fertilizers) to supply plant nutrients (Zougmore et al., 2003; Pathak et al., 2005, 2009).

ICRISAT has been conducting NRM research at its farm in Patancheru, Andhra Pradesh (India) which typifies a semi-arid tropical climatic environment. The two major semi-arid tropical soil types – Vertisols and Alfisols – are represented at the farm. The rainy season begins in June and ends in early October. However, the rains during the month of June, at the end of sowing of crops, are unstable and a wide variation is observed in the onset of the rainy season by the south-west monsoon. Also, during the rainy season, the amount and distribution of the rains vary widely.

In 1973, ICRISAT developed a set of small Vertisol watersheds (varying in area from 2.5 to 16 ha) at its Patancheru farm. This was a part of the approach to NRM, which was based on the strategy that if land was properly graded and the seedbed prepared, in advance of the monsoon rains, in such a way that the rainwater was given enough opportunity to infiltrate into the soil, the crop-growing season would be secure against water deficits. Moreover, grassed waterways were laid out in small watershed units, so that when heavy rains are received, the water does not stagnate in the field, but is safely guided through the furrows and grassed waterways to the dug-out water tanks or reservoirs. These tanks or reservoirs were strategically located in a series to capture most of the surface runoff. These watersheds on Vertisols have been used to conduct research to gain insight into the climatic variability effects on rainfed agricultural production options (improved and traditional) for sustaining crop productivity (ICRISAT, 1989).

These watersheds have been used to evaluate the effects of the semi-arid tropical climate on alternate methods of soil and water conservation and agronomy on crop productivity. For example, in the improved watershed-based technology treatment, the land was cultivated and prepared to a graded broad-bed and furrow (BBF) system. The rainy season crop was sown in the dry bed prior to the onset of monsoon rains; and two crops were grown annually in a rotation. The crops were: maize followed by chickpea in year 1, and sorghum intercropped with pigeonpea in year 2. The crops were planted on the graded broad-bed, 105 cm wide. Each broad-bed was separated by a furrow, 45 cm wide. The fertilizer management involved the application of 80 kg N and 40 kg P_2O_5 per ha. Under the traditional technology treatment, the seedbed was kept flat, and one crop, either sorghum or chickpea was grown during the post-rainy season utilizing the stored soil moisture in the profile. No mineral fertilizers were added; and farmyard manure was added at 10 t ha^{-1} every 2 years.

The long-term (1976–2006) results showed that under the improved management treatment, the two-crop yields consistently exceeded 4.5 t ha^{-1}, while in the traditional management treatment; the average yield over the period was 0.9 t ha^{-1}. Because of the improvement of the soil quality with time in the improved management treatment, the two-crop yields increased at an average rate of 82 kg ha^{-1} y^{-1}, while in the traditional management system, the yield increased at an average rate of 23 kg ha^{-1} y^{-1} (Wani et al., 2007). The carrying capacity of the improved system was rated at 21 persons ha^{-1} y^{-1} as compared to 4.6 persons ha^{-1} y^{-1} in the traditional management system (Wani et al., 2007).

Equally important, the soil quality improved due to higher amount of C sequestration under the improved management treatment as compared to the traditional systems. It was found that after 24 years of cropping, the soil under the improved system contained 46.8 t C ha^{-1} in the 0–120 cm profile depth as compared to 39.5 t C ha^{-1} found in the soil profile under traditional management treatment (Wani et al., 2007).

It was concluded that there is a need to prioritize the prevalent production systems that enhance C sequestration in the soil for the sustainable maintenance of agricultural productivity and environmental quality. The capture of atmospheric carbon dioxide and storing in the soil profile is a win–win proposition because C sequestration not only improves soil quality but also maintains environmental quality by mitigating global warming (Lal, 1999, 2002, 2007; Wani et al., 2007).

3. Agricultural practices and soil quality

The degradation of soil and water resources, especially in the developed countries has clearly brought home the message that these natural resources are finite and that the mismanagement of soil resource can have adverse effects on environmental quality including surface and groundwater quality and global warming (Lal, 2007). Indeed, the environmental concerns have focused attention on the development of NRM practices that conserve soil and water resources, sustain productivity and maintain environmental quality.

The adverse effects of agricultural practices as a part of NRM on soil quality occur when farming systems are intensified, without due consideration to the conservation of soil and water resources, through non-judicious use of agricultural chemicals, especially pesticides and mineral fertilizers (Singh and Singh, 2003; Sahrawat et al., 2005). The adverse effects on the soil quality also take place when land in the sensitive ecosystems such as semi-arid and arid regions with porous soils are used for intensified production systems disregarding soil and water conserving practices in NRM (Lilburne et al., 2004).

Soil quality is generally used to refer to the capacity of a soil to perform its production and environment-related functions: to produce healthy and nutritious crops, resist erosion and reduce the impact of environmental stresses on plants, soil biota, and human and animals (Doran and Zeiss, 2000). Several soil physical, chemical and biological properties/parameters are used as indicators of soil quality (Sanchez et al., 2003; Sojka et al., 2003; Pathak et al., 2005). The goal is to use the various soil indicators to develop agricultural management practices that maintain or enhance productivity, and maintain soil and water quality, and catchment health.

Maintaining soil quality for various diverse uses is a complex problem, but it is agreed that the use of soil quality indicators with threshold values (Dexter and Zoebisch, 2006) can help in developing management practices that sustain productivity and maintain environmental quality (Doran and Parkin, 1994; Arshad and Martin, 2002; Karlen et al., 1997, 2003; Lal, 2004; Pathak et al., 2005). Recent research on soil quality in relation to agricultural practices suggests that the degradation of top soils is usually reversible, while degradation of sub-soils is rather more difficult to reverse or in some instances may even be irreversible (Dexter and Zoebisch, 2006).

Importantly, the complementarities between conservation and productivity objectives make watershed or catchment development an attractive option and an entry point for implementing agricultural and rural development activities in the semi-arid areas of India (Kerr, 2002; Wani et al., 2005).

Attempts have also been made to develop a land quality index specifically for dryland crops such as sorghum in the semi-arid tropical regions of India (Mandal et al., 2001). Such focused research is important and needs encouragement as this fosters the development of a sustainable system with proper choice of crop and natural resource management practices in an integrated way.

Several definitions of soil quality have been proposed keeping in view diverse production and environment-related uses of soil. For the purpose of this paper, the definition proposed by a committee of the Soil Science Society of America and Karlen et al. (2003) being 'the fitness of a specific kind of soil, to function within its capacity and within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation' has been adopted as this definition seems appropriate and inclusive for assessing the impact of agricultural practices on soil and water quality.

In this section, the results with examples from the long-term field experiments, on the impact of various agricultural practices (improved vs. traditional) on soil physical, chemical, and biological properties, are discussed.

3.1. Changes in soil physical properties

A long-term experiment (1975–1998) was conducted at the ICRISAT farm in Patancheru to evaluate the impact of improved (broad-bed and furrow land treatment, cropping during rainy and post-rainy seasons with the implementation of soil and water conservation practices and integrated nutrient management) and traditional (cultivated rainy season fallow, post-rainy season cropping on flat land configuration) management practices on physical characteristics and productivity of Vertisols. The results (Table 1) showed that after 23 years of imposition of the treatments, clay content decreased and gravel content increased in the surface (0–10 cm) soil layer under traditional compared to improved management. Other physical characteristics such as bulk density, total and air-filled porosity, penetration resistance and cumulative infiltration were also more favorably poised under improved than under traditional management practices (Table 1).

Table 1
Effects of long-term (1975–1998) landform treatment on physical properties of Vertisols at the ICRISAT farm in Patancheru, India (ICRISAT, unpublished results).

Soil properties	Improved management		Traditional management
	Broad-bed	Furrow	Flat
Clay (%)	51		46
Silt (%)	22		21
Fine sand (%)	16		15
Coarse sand (%)	12		17
Gravel (%)	5		15
Bulk density ($g\,cm^{-3}$)	1.2	1.5	1.5
Total porosity (%)	52.1	39.5	41.5
Air-filled porosity (%)	41.0	33.0	32.0
Penetration resistance (MPa)	1.1	9.8	8.5
Sorptivity (mm $30\,min^{-1}$)	121.2	100.6	88.5
Cumulative infiltration in 1 h (mm)	347.2	205.7	264.7

Table 3
Organic C and total N of semi-arid tropical Vertisols in 1998 after 24 years of cropping under improved and traditional systems in watersheds at the ICRISAT farm in Patancheru, India (adapted from Wani et al., 2003).

Soil property	System	Soil depth (cm)		Standard error
		0–60	60–120	
Organic C ($t\,ha^{-1}$)	Improved	27.4	19.4	0.89
	Traditional	21.4	18.1	
Total N ($kg\,ha^{-1}$)	Improved	2684	1928	156.6
	Traditional	2276	1884	

The decrease in the quality of soil physical parameters (texture and other physical properties) of Vertisols under traditional management might have been, at least in part, due to greater soil loss by erosion (El-Swaify et al., 1985) as shown in Table 2. Soil loss by erosion results in not only in the loss of finer soil fraction, but also leads to loss of organic matter and other dissolved plant nutrients (Karanam et al., 2008). Moreover, the loss of soil chemical fertility and organic matter becomes a source of offsite pollution due to contamination by sediments and chemicals (Sahrawat et al., 2005, 2006).

3.2. Changes in soil chemical properties

Soils in the SAT regions have relatively low contents of organic matter compared to their counterparts in the temperate or humid tropical regions. Moreover, the traditional farming practices followed by farmers in the dryland systems of the SAT regions do not help to maintain sufficient organic matter levels (El-Swaify et al., 1985; Reddy et al., 2003; Sahrawat et al., 2006).

Soil organic matter contents directly or indirectly impacts the productivity and soil quality. Wani et al. (2003) reported the results of a long-term experiment conducted in Vertisol watersheds to determine changes in soil organic C and total N status. It was found that organic C and total N contents were significantly higher in the soil profile (0–120 cm depth) under improved management than under traditional management practices (Table 3).

In another long-term experiment at the ICRISAT Center, Rego and Rao (2000) reported that soil N concentration in the surface (0–15 cm) layer of a Vertisol increased by 125 $mg\,N\,kg^{-1}$ of soil in 12 years under pigeonpea-based cropping systems that had no input of external N. On the other hand, in the traditional (rainy season fallow, post-rainy season sorghum) and non-legume based cropping systems, total N concentration declined to levels below the baseline of total N level (550 $mg\,N\,kg^{-1}$). The results of this long-term study demonstrated the potential of legume-based cropping systems to increase productivity and maintain total soil N levels in the Vertisols (Rego and Rao, 2000).

The results of these long-term experiments show that improved management practices not only reduced soil loss by erosion (Table 2), but also increased accumulation of greater amounts of organic matter (organic C and total N) in the soil profile (Table 3), resulting in sustained increase in crop productivity (Wani et al., 2003). Equally important, these results have implications for fertility improvement and maintaining environmental quality by sequestering C. For example, under the improved catchment management system, the soil contained 46.8 $t\,C\,ha^{-1}$ in the 0–120 cm soil profile as compared to the traditional management practices that contained 39.5 $t\,C\,ha^{-1}$. This amounts to a gain of about 7.3 $t\,C\,ha^{-1}$ over the 24-year period ending in 2000 (Wani et al., 2003, 2007).

Lal (1999) analyzed the contribution of various agricultural practices to C sequestration in the farming systems. Some of the recommended practices that contribute to C sequestration in a system are summarized in Table 4. Evidently, afforestation and reforestation, followed by the restoration of eroded or degraded soils have the largest potential to sequester C in soils. Practices such as conservation tillage with mulch farming, compost and manuring, water conservation, and integrated nutrient management along with precision farming practices all make contribution to C sequestration in soils (Lal, 1999).

3.3. Changes in soil biological properties

In addition to changes in organic matter quantity and quality, potentially mineralizable soil N, soil properties such as microbial population and biomass, earthworm biomass and activity, and soil respiration serve as sensitive indicators of the impact of agricultural practices. Potentially mineralizable N in soil represents the active fraction of organic matter that contributes to the

Table 2
The long-term (1974–1982) effects of improved and traditional management practices on runoff and soil loss in Vertisol watersheds at ICRISAT farm in Patancheru, India (based on El-Swaify et al., 1985).

Year	Improved management			Traditional management		
	Rainfall (mm)	Runoff (% rainfall)	Soil loss ($t\,ha^{-1}$)	Rainfall (mm)	Runoff (% rainfall)	Soil loss ($t\,ha^{-1}$)
1974	811	14.3	1.30	811	27.5	6.60
1975	1041	15.6	1.39	1055	24.0	5.21
1976	687	10.6	0.98	710	33.3	9.20
1977	585	0.2	0.07	586	9.0	1.68
1978	1125	24.3	2.93	1117	36.7	9.69
1979	690	10.6	0.70	682	29.6	9.47
1980	730	15.9	0.97	688	24.1	4.58
1981	1126	29.5	5.04	1126	38.6	11.01
1982	615	1.6	0.20	615	3.3	0.70
Mean	823	13.6	1.51	821	25.1	6.46

Table 4
Recommended management practices for carbon sequestration in soils (adapted from Lal, 1999).

Management practice	Potential rate of soil C sequestration ($t\,ha^{-1}\,y^{-1}$)
Conservation tillage with Mulch farming	0.1–0.5
Compost and manuring	0.05–0.5
INM/precision farming	0.1–0.4
Cropping systems with improved cultivars	0.05–0.4
Water conservation	0.05–0.3
Afforestation/reforestation	0.8–3.0
Restoration of eroded/degraded soils	0.3–1.0

Table 5
Selected biological properties of semi-arid tropical Vertisols in 1998 after 24 years of cropping under improved and traditional systems in watersheds at ICRISAT Center, Patancheru, India (adapted from Wani et al., 2003).

Property	System	Soil depth (cm)		SE
		0–60	60–120	
Soil respiration ($kg\,C\,ha^{-1}$)	Improved	723	342	7.8
	Traditional	260	98	
Microbial biomass C ($kg\,C\,ha^{-1}$)	Improved	2676	2137	48.0
	Traditional	1462	1088	
Microbial biomass N ($kg\,N\,ha^{-1}$)	Improved	86.4	39.2	2.3
	Traditional	42.1	25.8	

production of mineral N and is influenced by cropping systems, especially inclusion of legumes in the system (Wani et al., 1995).

Generally, soil biological properties are positively influenced by the soil organic matter status of the soil. For example, in a long-term experiment on Vertisols, it was found that soil under improved management practices compared to that under traditional management, not only had higher accumulation of organic C and N (Table 3), but microbial biomass C and N and soil respiration values were also greater under improved than in traditional system (Table 5). The results also demonstrated that under improved cropping systems, which integrate soil and water conservation practices with nutrient management, there was increased C sequestration in the soil profile in the longer term (Wani et al., 2007).

Cultivation and other agricultural activities also greatly influence soil biological properties, especially earthworm number, microbial biomass C and N. Measurements made on Vertic Inceptisols in cultivated field and natural vegetation area at the ICRISAT farm and the adjacent farmers' fields showed that organic C, microbial biomass C and N and earthworm numbers were higher in the soil under natural vegetation and in farmers' fields than in the cultivated field (Table 6).

Soil and crop management practices including cultivation and application of agrochemicals, especially herbicides and other pesticides greatly affect earthworm biomass and their functions in improving soil physical and chemical fertility (Reddy et al., 1995; Sahrawat et al., 2006). Soil biological degradation can be restored through the recycling of crop and other organic wastes and by soil and crop management practices that enhance inputs of organic matter (use of crop rotations with legumes, and cover crops) to soil, reduced tillage and through the use of beneficial soil microorganisms (Aslam et al., 1999; Ortas, 2006).

Table 6
Selected soil biological parameters of Vertic Inceptisols under cultivation and natural vegetation, Patancheru, India (ICRISAT, unpublished results).

Parameter	Uncultivated Area	Cultivated field	Farmer's field
Organic C ($g\,C\,g^{-1}$ soil)	6.1	5.5	5.5
Biomass C ($mg\,C\,kg^{-1}$ soil)	270	220	240
Biomass N ($mg\,N\,kg^{-1}$ soil)	42	35	38
Earthworm (no. m^{-2})	44	13	Not done

4. Agricultural practices and water quality

The changes in water quality are monitored and assessed using a number of aesthetic (color, odor, floating matter), physical (turbidity, dissolved solids, sediment load, suspended organic and inorganic materials), chemical (pH, electrical conductivity, dissolved oxygen, chemical oxygen demand, nitrate, phosphate, fluoride, pesticides and other toxic compounds, heavy metals) and biological parameters (pathogens, cynobacteria, biomass, biological oxygen demand, phytoplankton) of water (Sahrawat et al., 2005).

Relatively less attention has been paid to the impact of agricultural practices on water quality. However, limited research indicates that water quality cannot be maintained without implementing soil and water conservation practices. Water quality is highest in the undisturbed or natural agro-ecosystem and is affected by agricultural activities such as soil loss, use of plant production and protection chemicals and fertility management practices (Sahrawat et al., 2005, 2006).

Suitable surface landform treatments such as imposition of broad-bed and furrow landform have been found to reduce soil loss, water runoff and loss of nitrate-N in runoff water (Table 7).

The potential of nitrate loss in light-textured or porous soils under intensive irrigated agriculture is indeed high. For example, during 1999, monitoring of water samples from shallow hand pumps in the four blocks of the Ludhiana district in Punjab, India, with high and low use of N fertilizers, showed that several water samples contained nitrate-N greater than the World Health Organization (WHO, 1970) limit of 10 mg nitrate-N L^{-1}. Water samples collected from blocks with high N fertilizer use had higher concentration of nitrate-N than those collected from areas with low N fertilizer use (Singh and Singh, 2003).

Kundu et al. (2008) made an inventory of nitrate-N enrichment in the surface and groundwater samples in the Hooghly district of West Bengal, India; the Hooghly district has intensive farming with high rates of fertilizer use, especially N fertilizer. Surface and groundwater samples were collected from 412 sites capturing a range of fertilizer use, soil characteristics, production systems and soil and crop management practices. The results showed that despite the use of fairly high N fertilizer, the nitrate-N in the groundwater was well below the permissible limit of World Health Organization (10 mg nitrate-N L^{-1}). This was attributed to the relatively high clay content in the soil profile. Moreover, there was an indication of possible build up of nitrate-N in shallow aquifers where the soils were light in texture.

The results reported by Kundu et al. (2008) reinforce the conclusion that the potential contamination of groundwater with nitrate is high in the light-textured, porous soils as shown by the results reported from other parts of India (Bajwa et al., 1993; Srinivasa Rao, 1998; Singh and Singh, 2008).

Table 7
Landform, flat versus broad-bed and furrow (BBF) effects on water runoff, soil and nitrate loss in Vertic Inceptisols at the ICRISAT farm in Patancheru during the 1998 rainy season, June through September (ICRISAT, unpublished results).

Parameter	Landform treatments	
	Flat	BBF
Water runoff (mm)	287	226
Soil loss ($t\,ha^{-1}$)	5.4	3.1
Nitrate-N loss ($kg\,ha^{-1}$)	13.3	9.3

In a long-term (1981–1990) study, Murthy et al. (2000) monitored the chemical composition of rainwater in the highly industrialized and polluted Patancheru (near Hyderabad, Andhra Pradesh). Results showed that on an average, the rainfall at Patancheru contributed, per ha, 5.8 kg N, 0.4 kg P, 4.8 kg S, 1.7 kg Ca, 1.7 kg Mg and 1.0 kg Na annually. The results show the impact of environmental conditions on the contamination of rainwater with N, S and basic cations and addition of these nutrients to the soil.

Clearly, in upland (arable) production systems, the nitrification of soil and fertilizer-derived ammonium converts relatively immobile ammonium to highly mobile nitrate, which is liable to loss by leaching and denitrification, resulting in the degradation of environmental quality (Galloway et al., 2008; Singh and Singh, 2008). In such cases, the inhibition or retardation of nitrification in the soil reduces the contamination of surface and groundwater with nitrate, by reducing the movement of nitrate in runoff water and through leaching, especially in the porous soils (Sahrawat, 1989; Subbarao et al., 2006).

5. Discussion and conclusions

The bringing of lands from natural ecosystems to agricultural ecosystems, generally depletes the soil organic C pool in the dryland soils of the semi-arid tropical regions. However, the adoption of resource conserving management practices has the potential to maintain or even in some cases to enhance soil organic C and soil quality. Also, the resource management practices followed for agricultural production impact soil and water quality. For sustainable productivity, soil quality as assessed by physical, chemical and biological parameters need to be maintained. Under dryland agriculture, sustainable productivity can be achieved by improved management practices that integrate soil and water conservation with integrated nutrient management at a watershed or catchment level.

Recent research conducted by ICRISAT and its partners and others in the semi-arid tropical region of India, indicates that increased productivity can be sustained and soil quality maintained in the longer term by following improved management practices (Pathak et al., 2005; Sahrawat et al., 2006). Soil and water conservation practices also help in reducing the loss of chemicals in runoff and in maintaining water quality (Sahrawat et al., 2005).

There is need to intensify research for generating information on the long-term impacts of agricultural practices on the contamination of surface and groundwater with various chemical pollutants. The monitoring of soil and water quality in various production systems is not only important for sustaining agricultural productivity but also offers opportunity for the timely implementation of corrective measures through appropriate soil, water and nutrient management practices for checking or reversing the degradation of natural resources and maintaining environmental quality (Lal, 1997; Wander et al., 2002; Lilburne et al., 2004; Sahrawat, 2006; Galloway et al., 2008). The monitoring and assessment of systems are also a prerequisite for developing modeling approaches to understand the impacts and consequences of diverse management systems for planning and implementation (Turner et al., 2007).

The adoption of a holistic approach to dryland agriculture in which soil and water conserving practices are integrated with integrated nutrient management at the watershed or catchment level has the potential to sustainably enhance agricultural productivity by maintaining soil quality. Also, through the convergence of related purposes, multiple benefits can be achieved from the investments made in the watershed development program. The sequestration of atmospheric carbon dioxide in the soil is a win–win strategy because the sequestration of C improves soil quality, enhances productivity on one hand and maintains environmental quality on the other (Wani et al., 2007). For sustainable rural development in the semi-arid tropical regions, agriculture plays a pivotal role and for dryland agricultural development maintaining catchment health (through soil and water conservation and fertility management) is a prerequisite. Improved watershed/catchment health is a win–win strategy for sustainable rural development.

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