Journal of Agricultural Science (2006), **144**, 249–259. © 2006 *Cambridge University Press*
doi:10.1017/S0021859606006046 *Printed in the United Kingdom* First published online 6 April 2006

Carbon sequestration potential and sustainable yield index for groundnut- and fallow-based cropping systems

P. K. GHOSH[1]*, M. C. MANNA[1], D. DAYAL[2] AND R. H. WANJARI[1]

[1] *Indian Institute of Soil Science, Nabibagh, Berasia Road, Bhopal 462 038, India*
[2] *National Research Centre for Groundnut, Junagadh 362 001, India*

(*Revised MS accepted 7 February 2006*)

SUMMARY

Soil organic carbon storage encompasses both soil productivity and environmental capabilities. The influence of fertilizer (nitrogen and phosphorus) levels (0 NP, 0·5 NP, 1·0 NP (recommended standard) or 1·5 NP) on total system productivity, sustainable yield index and soil organic carbon storage in Vertisols (Typic Haplustert) under groundnut and fallow-based cropping systems were examined in a field experiment over 6 years. The aim was to identify a system that provided an acceptable balance between total system productivity and soil organic carbon restoration. The experiment comprised two rainy season crops (groundnut or fallow) and five post-rainy season crops (wheat, mustard, chickpea, sunflower or summer groundnut), each post-rainy season crop with four levels of NP fertilizer. The total system productivity was 130% higher in the groundnut-based than in the fallow-based system and was in the order: groundnut–groundnut > groundnut–chickpea > groundnut–wheat > groundnut–mustard > groundnut–sunflower. The sustainable yield index was highest in the groundnut–groundnut system. The gross C input was relatively higher in the groundnut-based system but the C loss rate was greater. The amount of residue needed per ha per year to compensate for loss of soil organic carbon was estimated to be 4·3 t in the fallow-based and 7·6 t in the groundnut–based cropping system. Though the total system productivity was greater in groundnut–groundnut and groundnut–chickpea systems, soil organic carbon declined. The groundnut–wheat system contributed more C, particularly root biomass C, than other systems, improved the restoration of soil organic carbon and maintained total system productivity. It was concluded that current fertilizer recommendations are adequate for maintaining yields in groundnut-based systems but the addition of crop residues at regular intervals along with fertilizer is necessary to maintain restoration of soil organic carbon.

INTRODUCTION

Understanding long-term soil organic carbon (SOC) changes in various ecosystems is of prime importance because it directly affects soil quality and serves as a major repository of plant nutrients (Bandaranayake *et al*. 2003). Above-ground biomass produced in agricultural or natural ecosystems is either removed from the system or remains on the soil surface. The most significant change in SOC results from the incorporation of above-ground biomass and surface litter into the soil, which leads to rapid decline of SOC when soil moisture and temperature are favourable for surface litter decomposition (Capriel 1991). This results in a reduction of the nutrient supply due to lower microbial activity and soil fertility, with consequences for soil physical properties, and impacts on global atmospheric CO_2 levels. These changes in SOC, in turn, lead to increasing dependence on inorganic fertilizers, risk of erosion, lower crop yields and ultimately global warming.

Promoting soil C sequestration is an effective strategy for reducing atmospheric CO_2 and improving soil quality (Lal *et al*. 1999). Indeed, quantification of SOC in relation to various crop management practices is of importance in identifying sustainable systems for C sequestration in soils and increasing crop productivity in semi-arid and sub-tropical environments. Various crop management practices such as tillage, cropping system and fertilization influence potential C sequestration and storage in

* To whom all correspondence should be addressed. Email: pkg@iiss.ernet.in

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Table 1. *Initial soil analysis prior to the initiation of the study*

Physico-chemical properties	Chemical composition of soil
Available N (kg/ha)	122
OC (g/kg)	5·28
Available K (kg/ha)	320
Available P (kg/ha)	8·10
EC (dS/m)	1·35
$CaCO_3$ (g/kg)	21·40
pH_w (1:2)	7·70
Available (DTPA[a]) Zn (g/kg)	21·60
Available (DTPA[a]) Fe (g/kg)	0·32
Exchangeable Mg^{2+} (mmol kg/soil)	14·6
Exchangeable Ca^{2+} (mmol kg/soil)	150
Cation exchange capacity (mmol (+) kg/soil)	375

[a] Diethyl triamine penta acetic acid.

soil. Swarup (1998) reported that under intensive cropping and imbalanced fertilizer use, particularly application of N alone, SOC declined in rice–wheat–jute, soybean–wheat, soybean–wheat–maize fodder and rice–wheat–cowpea fodder systems. This was associated with declines in yield. Balanced use of NPK and green manuring may increase SOC (Ghosh & Sharma 1996).

Since organic materials supplied by the roots are decomposed rapidly in such systems, it is difficult to measure the magnitude of organic debris deposition in soil by plant roots during the growth period. Keith *et al*. (1986) reported in a study with ^{14}C that rhizodeposition during the growing season of wheat was 0·3 of the total C accumulated in above-ground biomass. There is a lack of quantification of the mass of below-ground residue C produced by plant roots from various crops under fallow and cultivated land management systems.

In India, groundnut (*Arachis hypogaea* L.)-based cropping systems may incorporate successive groundnut crops or wheat (*Triticum aestivum* L.), sunflower (*Helianthus annuus* L.), chickpea (*Cicer arietinum* L.) or mustard (*Brassica juncea*) (Singh 1994; Reddy *et al*. 2001). There are no published reports quantifying rhizodeposition in groundnut, chickpea and sunflower, although some studies have been done on other crops including wheat (Jenkinson & Rayner 1977; Lucas *et al*. 1977). In groundnut-based cropping systems, above-ground biomass removal is common practice. Fertilizer scheduling in groundnut-based cropping systems might maintain or restore SOC. Therefore, the present study attempts (i) to quantify C input through different cropping systems with different levels of fertilizer NP, and (ii) to examine the effect of C input of various cropping systems on changes in SOC and their potential for C sequestration.

MATERIALS AND METHODS

Experimental site

The experimental site is located at Junagadh, Gujarat, India (70°36′E and 21°31′N, 60 m asl). The climate of the region is semi-arid with a mean annual rainfall of 844 mm confined to the period June to September, with practically no rainfall during October to May. The average temperature from April to June is 37–44 °C with a mean of 41 °C. The soil is a Vertisol (Vertic-Ustochrept) (Soil Survey Staff 1975), highly calcareous and slightly alkaline (pH 7·7). The P fixation capacity ranges from 16·4–20·7 mg/kg P of phosphorus applied at 21·8 mg/kg (Akbari *et al*. 1981). The initial soil fertility status is given in Table 1.

Treatments and crop culture

The experiment was conducted for 6 consecutive years (1992/93–1997/98). The experiment comprised two rainy season crops (groundnut or fallow) and five post-rainy season crops (wheat, chickpea, sunflower, mustard or summer groundnut), each post-rainy season crop with four levels of NP fertilizer (0 NP, 0·5 NP, 1·0 NP (the standard recommendation) or 1·5 NP). The experimental layout was a factorial randomized block design with three replications. The 40 individual treatment combinations were randomly allocated to plots within blocks in the first year, and remained on the same plots throughout the 6 years. The size of each plot was 4×6 m. All the post-rainy season crops were grown under irrigated conditions, whereas rainy season groundnut was rainfed. The cultivation procedures, including tillage and irrigation, followed those normally practised in the area (Table 2). No tillage was carried out in fallow plots during the rainy season. However, the management practices followed for all the winter and summer crops were the same in both the fallow-based system and the groundnut-based system. Urea (464 g N/kg) and single superphosphate (70 g P/kg) were the sources of N and P, respectively. N and P were applied as a single basal dose except for wheat, where half of the N was retained and applied at crown root initiation stage (about Zadoks' Growth Stage 14; Zadoks *et al*. 1974). Potassium fertilizer was not applied to any treatment because of the high amount of soil available K at the start of the experiment (Table 1). Crops were hand-weeded during growth and weed biomass did not differ between treatments. Grain yield was recorded at the end of each crop in the rainy as well as the winter season each year, from

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Table 2. *Management practices used for different crops*

Crops	Season	Sowing time	Tillage	Full recommended fertilizer dose (kg/ha) N	P	Irrigation	Harvesting
Groundnut	Rainy	Last week of June	One summer ploughing with two ploughings before sowing by tractor-drawn cultivator	12·5	11	Rainfed	Oct
Groundnut	Summer	1st two weeks of Jan	Two ploughings by tractor-drawn cultivator	25·5	22	10 irrigations at 10 day intervals	May
Wheat	Winter	3rd week of Nov	Two ploughings by tractor-drawn cultivator	120	36	Flooded three times: at crown root initiation (21 days after sowing, DAS), maximum tillering (55 DAS) and ear emergence (100 DAS)	Mar
Mustard	Winter	2nd week of Oct	Two ploughings by tractor-drawn cultivator	30	18	Two irrigations: one at pre-flowering (50 DAS) and one at pod formation (70 DAS)	Feb
Sunflower	Winter	2nd week of Oct	Two ploughings by tractor-drawn cultivator	40	18	Two irrigations: one at pre-flowering (47 DAS) and one at heading stage (62 DAS)	Jan
Chickpea	Winter	2nd week of Oct	Two ploughings by tractor-drawn cultivator	20	18	Two irrigations: one at pre-flowering (35 DAS) and one at pod formation (51 DAS)	Feb

a net plot size of 3×4 m. Crops were harvested manually by sickle and yield was recorded. Grain yields of winter crops were converted into groundnut equivalent yields (GEY) on a financial value basis as GEY = (yield of post-rainy season crops × unit price of post-rainy season crops/unit price of groundnut pods). The market value of different crops per kg seed/grain is given in Table 3. Yield of rainy season groundnut and GEY of post-rainy season crops were added to determine total system productivity (TSP). The GEY of the fallow crop was taken as 0·0 so the TSP of the fallow-based system was the GEY of post-rainy season crops. Yield data were used for calculating sustainable yield index (SYI) as $SYI = (y - \sigma_{n-1})/y_m$ (Singh *et al.* 1990), where y is the mean yield, σ_{n-1} the standard deviation and y_m the maximum yield. In the concept of SYI, low values of standard deviation suggest sustainability of the system. If the standard deviation is large, SYI will be low indicating unsustainable management practice.

Table 3. *The market value (Rs) per kg seed of different crops*

Year	Crops Groundnut	Wheat	Mustard	Chickpea	Sunflower
1992/93	18·3	7·2	10·1	16·7	9·1
1993/94	18·0	7·0	10·3	16·3	9·3
1994/95	17·8	6·8	9·8	17·0	10·0
1995/96	18·0	7·0	9·8	16·4	9·6
1996/97	17·9	7·1	10·0	16·1	9·5
1997/98	18·0	7·0	10·0	16·5	9·5

Soil sampling and analysis

After the harvest of post-rainy season crops, soil samples were collected from 0–150 mm and 150–300 mm depths, sieved (2 mm mesh), dried at 105 °C and analysed for total organic carbon (Walkley & Black 1934). Carbon gain or loss was calculated from the difference between initial and final value. C content (kg/ha) at 0–150 and 150–300 mm depths were calculated by multiplying C concentrations (g/kg soil) by bulk density. As bulk density was not significantly affected by treatments at the beginning and end of the experiment, the average value was used to calculate C contents for a

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Table 4. *Composition of different crops at harvest* (S.D.)

Crops	Leaf C content (g/kg)	Stubble biomass C (g/kg)	Root biomass C (g/kg)	Stubble biomass N (g/kg)	Root biomass N (g/kg)	Lignin in stubble (g/kg)	Lignin in root (g/kg)	Cellulose in stubble (g/kg)	Cellulose in root (g/kg)	Root C/N ratio	Stubble C/N ratio	Contribution of stubble left after harvest (g/m²)
Wheat	–	463 (28)	461 (11)	5 (0·8)	5·7 (0·2)	68 (5)	69 (3)	336 (13)	312 (11)	81·9	86·9	83 (15)
Mustard	460 (11)	459 (19)	468 (9)	4 (0·7)	4·6 (0·3)	91 (6)	98 (2)	367 (21)	321 (18)	99·8	108·2	125 (21)
Chickpea	–	468 (17)	423 (8)	7 (0·3)	8·0 (0·4)	83 (3)	93 (6)	331 (11)	302 (13)	58·5	61·2	50 (23)
Sunflower	410 (13)	397 (16)	369 (11)	6 (0·6)	6·2 (0·5)	89 (8)	107 (3)	311 (12)	301 (10)	72·1	75·6	100 (22)
Groundnut	–	419 (13)	404 (8)	8 (0·3)	8·7 (0·3)	75 (6)	81 (6)	376 (21)	353 (8)	53·9	59·7	–

Values are expressed on oven dry weight basis, ±S.D. (D.F. = 2).

treatment. The bulk density of the soil at the end of the experiment was 1·29–1·32 and 1·31–1·35 Mg/m³ at 0–150 and 150–300 mm depths, respectively.

Plant sampling and analysis

The total stubble biomass left over in the field after harvest and below-ground biomass from each plot was estimated. An area of 0·2 × 0·2 m was excavated to a depth of 300 mm with a narrow, flat-bladed shovel and handsaw. Soil containing roots was gently rotated and dispersed through tap water, then passed through a series of sieves to collect coarse roots (>4 mm diameter), medium roots (2–4 mm diameter), small roots (1–2 mm diameter) and fine roots (0·25–1 mm diameter) without attempting to differentiate live and dead roots. Coarse root fractions (>0·25 mm) were removed from the sieves manually, using forceps. Roots were then dried at 65 °C to a constant weight, weighed and passed through a 0·150 mm sieve for carbon analysis (Brown & Thilenius 1976; Anderson & Ingram 1993).

An area of about 1 m² (1·66 × 0·6 m) of field was selected between two rows and leaf fall was collected on nylon net (4 mm mesh) in weeks 1–6, 6–9 and 9–12 of crop growth. The collected material was cleaned with tap water. Weight was recorded after drying to constant weight at 65 °C and the carbon content was determined.

Samples of stubble were collected at harvest from a 1 m² area at three locations of each treatment and C input was estimated on C content basis. The above-ground stubble biomass left on the surface varied from 50 ± 23 g/m² in chickpea to 125 ± 21 g/m² in mustard (Table 4).

The C input into the soil was calculated based on observed C content in various plant parts. The C content in leaf, root and shoot biomass was estimated using dry combustion at 550 °C as described by Poincelot (1972). The contribution of leaf-fall carbon into soil was computed for mustard and sunflower only, because other crops (wheat, chickpea and groundnut) supplied only small amounts of leaf to the ground.

Bronson *et al.* (1998) estimated root exudates to represent 0·15 g/g of above-ground biomass at maturity with a C concentration of 360 and 330 g/kg biomass in unfertilized and fertilized treatments, respectively. These values were assumed in the present study when calculating the total rhizodeposition derived from different cropping systems.

The pre-emergence herbicide was used every year uniformly to all the treatments to control weeds. During the crop growth period in both groundnut-based and fallow-based systems, the seasonal weeds were much reduced. Since there was no difference between treatments in weed biomass, the few weeds were removed and incorporated into soil, and the

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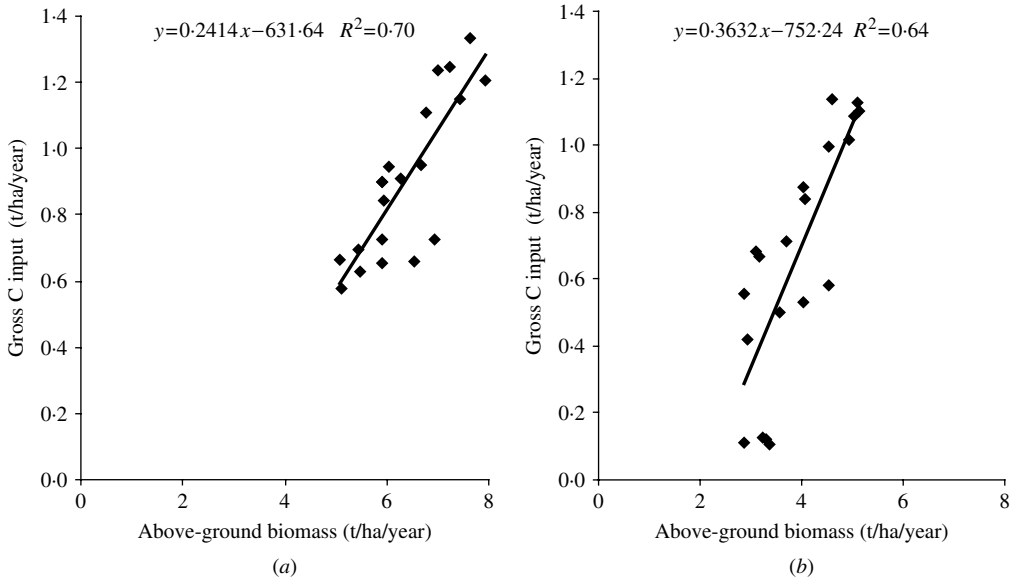


Fig. 1. Gross C input in relation to total above-ground biomass in (*a*) groundnut-based and (*b*) fallow-based cropping systems.

contribution of weed biomass to SOC is ignored in the present paper.

To estimate the annual rate of changes in SOC, it is necessary to know the amount of organic C present in the soil at the beginning of the experiment. In order to establish a relationship between C addition and SOC storage in a given soil under two cropping systems, a simple linear regression equation was fitted as $dC_s/dt = hA - kC_s$ (Jenkinson 1988), where dC_s/dt is losses or gains from initial value over time (t) in 0–300 mm soil depth, A is the annual C input, h is the humified SOC after decomposition of added biomass and k is the decay rate constant.

Nitrogen concentration in plant samples was determined by the H_2SO_4-H_2O_2 method as described by Kuo *et al.* (1997). Total N was determined by the standard method as described by Bremner & Mulvaney (1982). Lignin and cellulose were determined by the method of Rowland & Roberts (1994).

Statistical analysis

Since the experimentation was for 6 years, the pooled data analysis was carried out over the years. It showed that year × treatment interaction was significant, enabling a yield trend analysis to be conducted. To determine yield trends (slope) over the years and to test the hypothesis that yield trends throughout the experimentation period are not significantly different from zero, a linear regression analysis as $Y = a + bt$ for all 6 years' data for individual treatment were carried out, where Y is the yield (t/ha), a is a constant, t the year, and b the slope or magnitude of any yield trend. The P-value indicates the level of significance of the observed yield changes. Similarly, to explore the effect of above-ground biomass on C input, a linear regression was computed for both systems as $Y = a + bX$, where Y is the gross C input, a is the intercept, b the slope and X the above-ground biomass (Fig. 1). Analysis of variance (Gomez & Gomez 1984) was performed to determine the effects of treatment.

RESULTS

Yield and sustainability

In general, yields of all the post-rainy season crops were higher in the fallow-based than the groundnut-based system. However, total system productivity (TSP) was 130 % higher in the groundnut-based than fallow-based (Table 5). The sustainable yield index (SYI) did not differ between rainy season crops of groundnut or fallow. Among the crops, summer groundnut had significantly higher SYI than all other crops. The lowest SYI was in mustard. The yield, TSP and SYI of post-rainy season crops increased significantly ($P \leqslant 0{\cdot}05$) with increasing level of NP fertilizer up to the full recommended level, beyond which yield declined.

The only system where groundnut yield was significantly affected by fertilizer was groundnut-summer groundnut at the 1·5 NP level (–0·083 t/ha/year, $P = 0{\cdot}003$) and fallow-summer groundnut at the 1·0 NP (−0·057 t/ha/year, $P = 0{\cdot}015$) and 1·5 NP

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Table 5. *Yields, total system productivity (TSP), groundnut equivalent yield (GEY) and sustainable yield index (SYI) of different crops and cropping systems*

Treatments	Pod yield of groundnut (t/ha)	Post-rainy season crop yield (t/ha)	TSP in terms of GEY (t/ha)	SYI
Rainy season crop				
Groundnut based	1·20	1·1	2·06	0·46
Fallow based	–	1·2	0·90	0·49
Mean	1·20	1·2	1·48	0·48
S.E. (478 D.F.)	–	0·14	0·266	0·015
Post-rainy season crop				
Wheat	1·20	1·8	1·4	0·50
Mustard	1·26	0·9	1·3	0·37
Chickpea	1·26	1·0	1·7	0·42
Sunflower	1·32	0·8	1·1	0·39
Summer groundnut	1·17	1·3	1·9	0·70
Mean	1·24	1·2	1·5	0·48
S.E. (478 D.F.)	0·28	0·20	0·22	0·013
Fertilizers NP levels (proportions of recommended amounts)				
0 NP	0·40	1·17	1·11	0·37
0·5 NP	0·57	1·40	1·43	0·47
1·0 NP	0·74	1·55	1·65	0·52
1·5 NP	0·82	1·52	1·73	0·53
Mean	0·63	1·41	1·48	0·47
S.E. (478 D.F.)	0·062	0·211	0·105	0·012

levels ($-0{\cdot}116$ t/ha/year, $P<0{\cdot}001$). There was no significant decline in any other crop under either of the systems (Table 6).

Chemical composition of crops

The chemical composition of the C input is presented in Table 4. Nitrogen concentration was higher in legume stubble biomass than cereal and oilseeds stubble biomass (Table 4). The lowest N content was in mustard stubble biomass. Root N contents also followed a similar trend. In general, N content in stubble biomass was higher than root N but C content did not vary much. There were no significant correlations ($r=0{\cdot}17$, $P>0{\cdot}05$) between nitrogen and lignin content. It was observed that the lignin/nitrogen ratio in roots was higher than that in shoots but the reverse was the case for carbon/nitrogen ratios.

Plant derived soil C-input

The mean above-ground biomass was greatest in the groundnut-mustard system. In the fallow-based system, the above-ground biomass was determined by only the irrigated post-rainy season crops. Application of fertilizers significantly increased the total above-ground biomass. Like yield and TSP, significant responses to applied fertilizer NP were observed up to 1·0 NP in the groundnut-based system. However, in the case of the fallow-based system, the above-ground biomass increased significantly ($P\leqslant 0{\cdot}05$) with increasing rate of NP fertilizer up to 1·5 NP.

Below-ground gross C-input

In a 6-year continuous cropping system, the annual C input in the groundnut-based system was relatively higher than in the fallow-based system (Table 7). Across the fertilizer treatments, the estimated annual C input in the groundnut-wheat system was 1115 kg/ha/year. The total annual C input was slightly higher in the groundnut-mustard system than the groundnut-wheat system, but root biomass and rhizodeposition contributed more to C input in the latter to improve soil organic carbon (SOC). In the unfertilized treatment, the total C input in the groundnut-wheat system was 30% lower than the treatment receiving 120 kg N and 36 kg P/ha (Table 7). Among the groundnut-based systems, the groundnut–chickpea system contributed the least annual C input. On average, contribution of C input from the groundnut-based system was 0·24 ($r=0{\cdot}80$, $P\leqslant 0{\cdot}01$) of the total above-ground biomass while in the fallow-based system it was 0·36 ($r=0{\cdot}83$, $P\leqslant 0{\cdot}01$, Fig. 1). Because of this, the total gross C input biomass was about 12% higher in the fallow-based

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Table 6. *Yield trends of post-rainy season crops under varying NP levels in groundnut and fallow-based systems*

		Groundnut-based				Fallow-based			
			Rate of yield change				Rate of yield change		
Crops	Fertilizer treatments	Initial value (t/ha)	Magnitude (t/ha/year)	*t*	*P*	Initial value (t/ha)	Magnitude (t/ha/year)	*t*	*P*
Wheat	0 NP	1·35	−0·029	1·35	0·19	1·88	−0·034	1·49	0·15
	0·5 NP	1·64	−0·036	1·21	0·24	2·33	−0·051	1·46	0·16
	1·0 NP	2·11	−0·074	2·07	0·05	2·43	−0·053	1·62	0·12
	1·5 NP	2·09	−0·033	0·74	0·47	2·51	−0·048	0·89	0·39
Mustard	0 NP	0·93	−0·045	1·00	0·33	0·82	0·004	0·08	0·93
	0·5 NP	0·97	−0·004	0·09	0·93	0·96	−0·001	0·03	0·98
	1·0 NP	1·01	−0·028	0·64	0·54	1·01	0·020	0·42	0·68
	1·5 NP	1·12	−0·036	0·84	0·41	1·03	0·040	0·95	0·36
Chickpea	0 NP	1·08	−0·071	1·57	0·13	1·23	−0·050	1·065	0·30
	0·5 NP	1·19	−0·082	2·46	0·05	1·38	−0·082	1·509	0·16
	1·0 NP	1·12	−0·066	2·03	0·06	1·19	0·022	0·316	0·76
	1·5 NP	1·17	−0·085	1·63	0·12	1·19	−0·048	1·127	0·27
Sunflower	0 NP	0·53	0·019	0·764	0·45	0·54	0·03	1·215	0·24
	0·5 NP	0·70	0·009	0·294	0·77	0·69	0·03	1·031	0·32
	1·0 NP	0·74	−0·016	0·733	0·47	0·75	0·03	0·855	0·40
	1·5 NP	0·77	−0·001	0·023	0·98	0·67	0·04	1·724	0·10
Groundnut	0 NP	1·01	0·006	0·391	0·70	1·13	−0·041	1·998	0·06
	0·5 NP	1·30	−0·019	0·964	0·35	1·35	−0·039	2·040	0·06
	1·0 NP	1·40	−0·017	0·784	0·44	1·53	−0·057	2·704	0·015
	1·5 NP	1·83	−0·083	3·54	0·003	1·88	−0·116	7·830	<0·001

system than the groundnut-based system and thus restored C to a higher level than the groundnut-based system. The effect of gross C input on SOC change was greater in the groundnut-based than the fallow-based system, as was evident from the greater R^2-value in the groundnut-based system (Fig. 2).

DISCUSSION

Yield decline could occur due to many factors such as decline of SOC and associated nutrients, imbalanced fertilizer use, insect pests, soil types, climate, crop management practices (Dawe *et al*. 2000), genotype and genotype × environment interaction (Sharma *et al*. 2003). In the present study, SOC in both the groundnut-based system and the fallow-based system had a significant effect on yield ($R^2 = 0{\cdot}86$, $P \leqslant 0{\cdot}05$). However, fallowing fields in the rainy season results in reduced cropping intensity. It was observed that declines in yield were more pronounced in chickpea and summer groundnut in both groundnut and fallow-based system (Table 6). Furthermore, the TSP was greater in the groundnut–groundnut and groundnut–chickpea systems (Table 5), but SOC declined. The retention of SOC depends upon the quantity as well as the quality of chemical composition (lignin/nitrogen ratio, carbon/nitrogen ratio, cellulose, hemi-cellulose, etc.) of plant roots and shoots biomass, and varies widely as a function of climate and soil type (Parton *et al*. 1987). In the present study, the average carbon/nitrogen and lignin/nitrogen ratios in the groundnut–groundnut and groundnut–chickpea systems were relatively lower than those in the other three systems (Table 4). In general, the decomposition rate is much faster in the narrow carbon/nitrogen ratio than the wider ratios of the materials. This is one of the reasons why the SOC storage was not higher in groundnut–chickpea and groundnut–groundnut systems than groundnut–wheat, groundnut–mustard and groundnut–sunflower systems.

It was assumed that the whole amount of biomass C from leaf fall, stubble biomass left in the field and root mass and rhizodeposition remained in the 0–300 mm surface layer. The small amount of weed biomass was not uniform within the experimental plot, and also, succulent and young weeds are decomposed faster than old and dried ones. Therefore, the value of C input through weed biomass was ignored while constructing C balance in both the systems. The average annual below-ground gross C input added to the soil varied largely due to variation in above-ground biomass, which was influenced by different fertilizer NP levels. This resulted in additional C input over unfertilized plots. In all the treatments, the degree of SOC change depended upon the annual rate of NP fertilization. The change in SOC in 0–300 mm soil depth was positively correlated

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Table 7. *Effect of continuous cropping for 6 years and different fertilizer treatments on root biomass C, rhizodeposition C, stubble C and leaf-fall C*

Parameters	Wheat	Mustard	Chickpea	Sunflower	Summer groundnut
Root biomass C (kg/ha/year)					
Groundnut-based					
0 NP	466	394	291	356	298
0·5 NP	614	493	348	414	364
1·0 NP	635	567	379	462	384
1·5 NP	687	609	383	412	404
Mean	600	516	350	411	363
S.E. (78 D.F.)	1·8	5·2	1·1	0·9	0·5
Fallow-based					
0 NP	501	373	33·5	246	262
0·5 NP	598	467	36·3	291	323
1·0 NP	615	573	37·7	305	330
1·5 NP	621	533	39·1	339	357
Mean	584	486	36·6	295	318
S.E. (78 D.F.)	0·9	1·9	0·3	10·0	0·4
Rhizodeposition C (kg/ha/year)					
Groundnut-based					
0 NP	319	318	296	322	277
0·5 NP	335	368	209	312	292
1·0 NP	392	347	270	299	343
1·5 NP	359	377	293	331	353
Mean	351	353	277	316	316
S.E. (78 D.F.)	1·1	1·5	20·3	0·6	13·5
Fallow-based					
0 NP	217	219	18·1	155	158
0·5 NP	244	224	14·1	153	176
1·0 NP	250	228	15·9	158	199
1·5 NP	254	252	16·3	182	224
Mean	241	231	16·1	162	189
S.E. (78 D.F.)	3·2	2·1	0·40	0·3	0·6
Above-ground biomass C (kg/ha/year)					
Groundnut-based					–
0 NP	116	101	44·1	102	–
0·5 NP	159	183	64·2	112	–
1·0 NP	180	202	44·3	113	–
1·5 NP	200	215	51·2	120	–
Mean	164	175	50·9	112	–
S.E. (78 D.F.)	1·0	0·5	0·76	2·4	–
Fallow-based					–
0 NP	154	161	55·1	95	–
0·5 NP	174	191	60·2	167	–
1·0 NP	223	211	74·1	124	–
1·5 NP	227	212	64·2	117	–
Mean	195	194	63·4	126	–
S.E. (78 D.F.)	0·7	2·3	0·27	2·5	–
Leaf-fall C (kg/ha/year)					
Groundnut-based					
0 NP	–	83	–	66	–
0·5 NP	–	107	–	71	–
1·0 NP	–	121	–	73	–
1·5 NP	–	134	–	87	–
Mean	–	111	–	74	–
S.E. (78 D.F.)	–	1·5		2·5	
Fallow-based					
0 NP	–	85	–	61·1	–
0·5 NP	–	115	–	71·2	–
1·0 NP	–	126	–	81·3	–
1·5 NP	–	129	–	76·2	–
Mean	–	113	–	72·4	–
S.E. (78 D.F.)		0·7		0·34	

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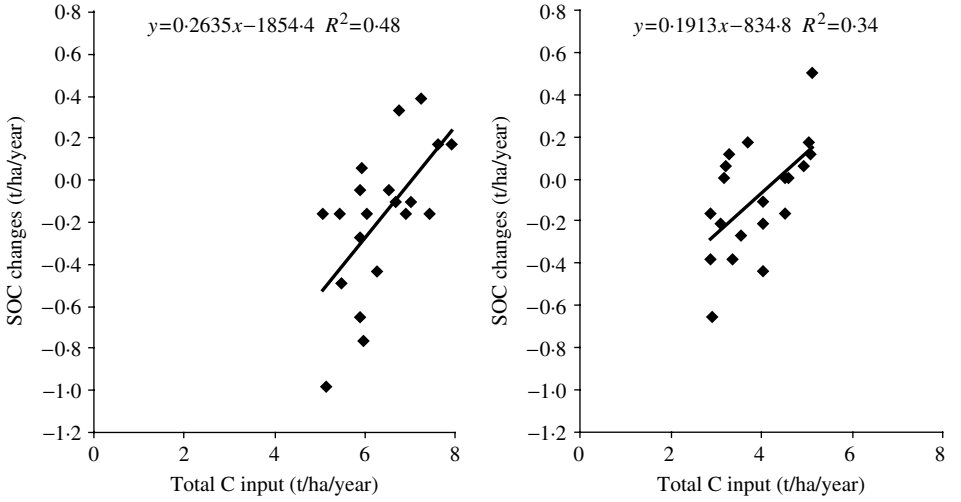


Fig. 2. Change in SOC ($dC_s/dt = hA - kC_s$) in relation to total C input in (*a*) groundnut-based and (*b*) fallow-based cropping systems (1992/93–1997/98) ($n = 20$).

with the gross C input in both the systems (Fig. 2). The linear relationship between change in SOC and added C input in soil has also been reported by others (Buyanovsky *et al.* 1987; Parton *et al.* 1996; Buyanovsky & Wagner 1998) and termed the carbon storage fraction constant.

From the above regression equation, it was observed that in this Vertisol under subtropical conditions the value of the humification rate constant (h) of annually added biomass C was 0·26 for the groundnut-based system and 0·19 for the fallow-based system, both close to the value (0·2) reported by Buyanovsky *et al.* (1987). The intercept of the equation reflects the annual loss of C from the native soil organic matter and suggests that the C losses during 6 years of different cropping systems from the native SOC were 1854 and 835 kg C/ha/year in the groundnut and fallow-based systems, respectively (Fig. 2). This suggests that the SOC in the latter was more resistant to decomposition than the former. Further, under the traditional fallow-crop system, soil fertility is regenerated and soil moisture is conserved, as was observed by Jones & Sinclair (1989). The amount of biomass C required to maintain equilibrium in the SOC content of the soil was estimated as 7637 kg C/ha/year for the groundnut-based and 4353 kg C/ha/year for the fallow-based system.

In the USA, C inputs from 200 to 2000 kg C/ha/year were required to maintain SOC content equilibrium in the 0–300 mm soil layer (Rasmussen & Collins 1991; Rasmussen & Albrecht 1998) while Larson *et al.* (1972) reported that in continuous corn cultivation in Iowa, 2000 kg of residue C/ha/year was required to maintain SOC. Standley *et al.* (1990) also reported that annual retention of about 4·0 t/ha of sorghum residue was necessary to maintain or slightly increase surface carbon levels in Vertisols of the summer rainfall zone of Australia. The present results suggest that the higher amount of C input required in subtropical soils is due to the higher loss rate (Fig. 2).

Overall, gross C input is relatively higher in the groundnut-based than the fallow-based system but the loss rate is much higher. This indicates that with more intensive cultivation, the SOC restoration process is reduced. Loch *et al.* (1987) also reported that SOC in the top 0–100 mm of virgin soils of Vertisols of Australia was reduced to half over a 10-year period of continuous groundnut cropping. The SOC content is influenced by the quantity of biomass returned to the soil. Thakur *et al.* (1995) reported that the removal of nearly all crop residues in intensive rice–wheat and rice–maize systems had contributed to the decline in SOC in Asian countries. However, in a few isolated cases, small increases in SOC have been reported in rice–wheat systems where residue is removed. Rice–upland crop rotations such as rice–wheat or rice–maize systems generally have a lower SOC than sole rice systems (Cheng 1984; Nambiar 1994).

In the present study, increased residue production through fertilizer application to crops has proved to be successful in preventing SOC decline. The positive effects of NP fertilization under the groundnut–wheat system added significantly more crop residue inputs to the soil, resulting in increased SOC. This ultimately helps in sequestering atmospheric CO_2 into SOC by

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increasing plant growth and subsequently returning more organic C to the soil. Similar results were also reported by Heenan *et al.* (1995) in the sandy loam soils of moist southeast Australia. Thus, increasing organic matter inputs via agricultural management could increase SOC. If the initial level of SOC is below the capacity of a specific soil to store it, then SOC levels may increase linearly with increasing input levels. The present results clearly show that application of even 1·5 times the recommended amounts of N and P fertilizer could not produce enough C in the groundnut-based cropping system. Even if the above-ground biomass of all crops is removed, these production levels are not sufficient to supply enough C input to surpass the quantity of C input required to maintain equilibrium in SOC content. Thus, for an intensive cropping system, external sources of decomposed organic matter addition would be a better option. Svensson *et al.* (2004) suggested that a blend of two-thirds of mineral nitrogen and one-third compost probably would be the most efficient nutrient management practice for sustaining productivity of high intensive oat–barley crop rotation in Sweden. The present study will assist in understanding how land use management strategies sustain soil quality.

The conclusion from the present work is that the fallow-based system restored more SOC compared to the intensive cropping system but had a lower total system productivity. Under an intensive cropping system, above-ground biomass removal is more common in farmers' practices, because the transitional gap between two crops is limited. In this situation, external sources of decomposed organic matter addition are more important. Though the TSP was greater in groundnut–groundnut and groundnut–chickpea rotations, these lose SOC. Farmers may, therefore, mine their soils of carbon to produce the greatest biomass. The groundnut–wheat system produced more biomass and C, and improved the restoration of SOC without compromising TSP.

We are grateful to the Director, NRCG for giving constant encouragement in conducting the study, Dr K. K. Pal, Scientist (SS), NRCG and also Dr K. S. Murthy, Animal Scientist, Gujarat Agricultural University, Junagadh for helping in the analysis of various chemical components in roots and other plant parts. We also thank Dr Abhishek Rathore for helping in the additional statistical analysis.

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