Sustainability of Soybean-based Cropping Systems on a Vertic Inceptisol: 2. Simulated Yield Gaps, Soil Water Balance and Soil Organic Carbon

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ABSTRACT: Crop simulation models were used to evaluate the long-term effects of improved versus traditional management of a Vertic Inceptisol on the performance of soybean-chickpea sequential (SB-CP) and soybean/pigeonpea intercrop (SB/PP) systems. Traditional management (sowing on flat landform and no crop residues additions) and improved management (sowing on broadbed-and-furrow (BBF) landform and additions of composted crop residues and *Gliricidia* pruning) treatments were applied to shallow and medium-deep phases of the soil in a watershed.

Yield gap between potential rainfed yield and actual yield of cropping systems increased over time. Yield gap of cropping systems with improved management was less as compared to the traditional management on the medium-deep soil; but did not differ much on the shallow soil. Simulated deep drainage of water was more in the shallow soil than medium-deep soil, which was further increased with improved management. Thus, the lack of crop yield response to improved management on the shallow soil could be attributed to greater leaching of soil carbon and other nutrients beyond the rooting zone. In spite of decreasing trends in soil organic carbon (OC) over time, simulated OC retention in the soil was higher with the additions of crop residues and with the SB/PP system as compared to the SB-CP system. Simulations also showed that crop residues additions @ 8 t ha^{-1} yr^{-1} would be required to maintain soil OC at levels observed at the beginning of study. The need for crop residue application can be less if practices such as surface application of crop residues and minimum tillage are adopted.

Keywords: Carbon sequestration, crop residues, crop simulation, semi-arid tropics, yield gaps

In India, land degradation caused by soil erosion by water and nutrient depletion is the major constraint for low productivity of soybean-based cropping systems on Vertic Inceptisols. In part 1 of the series, Singh *et al.*, (2006) have shown that Improved management (sowing on BBF landform and crop residue additions) of the Vertic Inceptisol decreased surface runoff and soil erosion as compared to the traditional management (sowing on flat landform and no crop residue additions). The study also revealed that total biomass productivity of both the soybean-chickpea sequential (SB-CP) and soybean/pigeonpea intercrop (SB/PP) systems decreased with continuous cropping for nine years in both the management treatments. Biomass and grain yield productivity of the SB-CP system was higher with improved management than with traditional management on both the soils. Total grain yield of the SB/PP system marginally increased (4-7%) with improved management over the traditional management. Organic carbon (OC) content of soil also decreased over time, however, improved management as compared to the traditional management and the SB/PP system as compared to SB-CP system helped retain more OC in the soil. Several factors might have caused the decline in productivity of the two systems. These include climatic effects on productivity, decline in soil fertility (secondary and micro-nutrients) with time or yield loss caused by increased incidence of pests and diseases.

Validated crop simulation models provide an opportunity to simulate the potential rainfed yields expected in given agro-environment and help identify factors that could cause yield gaps between the expected and actual yields obtained. In an environment of greater soil and climatic variability, the simulation models also provide an opportunity to evaluate more consistently the long-term effects of cropping systems management on productivity and changes in soil quality under a given set of soil conditions. In this watershed study we used the APSIM suit of simulation models (McCowen *et al.*, 1996) to determine potential yields, yields gaps, soil water and soil carbon balances of two cropping systems to analyze the extent and causes of their yield responses to the soil management treatments on a variable soil. Long-term effects of crop residue additions on maintenance of soil carbon were also investigated.

Materials and Methods

The watershed experiment is described in detail in part 1 of the series (Singh *et al.*, 2007). Briefly, the watershed comprised of four hydrological units: medium-deep soil with improved management, medium-deep soil with traditional management, shallow soil with improved management and shallow soil with traditional management. Improved management comprised of sowing on broadbed-and-furrow landform (BBF) with *Gliricidia* (*Gliricidia sepium* (L.)) grown on graded field bunds (at 0.6 to 0.8% slope) between plots. This treatment received organic matter additions to the soil through composted crop residues of soybean [*Glycine max* (L.) Merr.], chickpea [*Cicer arietinum* (L.)] and pigeonpea [(*Cajanus cajan* (L.) Millsp.] applied at the start of the season and the pruning of *Gliricidia* added to the soil during the cropping season. Traditional management comprised of flat landform with sowing along the graded field bunds. No organic matter was added to this treatment except the additions through natural leaf senescence and roots. The two cropping systems evaluated from 1996 to 2003 were soybean-chickpea sequential (SB-CP) and soybean/pigeonpea intercrop (SB/PP) systems, except during the first year (1995/96 season) when only SB-CP was grown in all the four hydrological units. The amounts of crop residues and fertilizer applied to the treatments are given in part I of the series.

Runoff and soil moisture monitoring

Surface runoff was recorded for each hydrological unit and for each rainfall event using H-flumes installed at the lowest point of each hydrological unit. Cumulative runoff was calculated to calibrate the model for simulation of runoff. Soil moisture changes were recorded at 7-10 day interval for each cropping system in a hydrological unit up to the maximum depth of rooting.

Crop growth analysis and yields at maturity

For growth analysis, plant samples were taken from 0.50 m^2 area in each plot at 7–10 days intervals. In case the plot size was too large, composite samples were taken from 2 to 3 spots in a plot and then sub-sampled for growth analysis. Every year crop yields were determined from five subplots per plot, each measuring 225 m^2. The harvested material was oven dried at 60 °C for 48 hours and then weighed to determine total biomass and grain yield.

Measurement of soil carbon

Soil samples were collected from each plot in June 1995 and again 2002 to study the impact of the different treatments on soil organic carbon. Samples were taken from five random positions per plot at 0-15, 15-30, 30-60 and 60-90 cm soil depths and pooled for each sampling depth per plot for further processing and analysis. Organic carbon content was determined using the dichromate digestion method (Nelson and Sommers, 1996).

Model calibration for crop yields and soil water balance

Crop models of soybean, chickpea and pigeonpea available in the APSIM (Agricultural Production Systems Simulator) software (McCowen *et al.*, 1996) were used to simulate growth and development of crops, crop yields and soil water balance of the SB-CP and SB/PP cropping systems. Using first two years of observed data, the cropping systems were calibrated for growth and development, grain yield and soil water dynamics of the component crops.

Changes were made in the cultivar-specific and soil parameters files such that the simulated results matched the observed data on crop phenology, growth and yield and soil water changes. For SB/PP intercrop system, adjustments were also made in the light extinction coefficients of pigeonpea such that the competition for light for the growth of soybean and pigeonpea was simulated accurately. To simulate soil water balance of the cropping systems, runoff curve number and drainage coefficients in the soil file were calibrated for each soil and management treatment to match simulated runoff with the observed data. After initial calibration of the curve numbers to simulate surface runoff for the 1995/96 to 1999/2000 seasons, the curve numbers had to be readjusted for during 2000/01 to simulate surface runoff for the remaining study period (Table 1). After model calibration, the crop models were applied to simulate crop yields and water balance components (surface runoff, deep drainage, soil water changes in the rooting zone and evapo-transpiration) of cropping systems for all the cropping seasons.

Simulation of potential yields and yield gaps

After calibrating the crop models for soil parameters and crop cultivar-specific coefficients for each management treatment, the models were used to simulate rainfed potential yields of component crops of cropping systems. These simulations were performed for both the cropping systems and soil management treatments. All the crop and soil management data and the initial conditions data were input to the project management files of each treatment and cropping systems to simulate potential yields and soil water balance for each season. Potential yields of component crops of each cropping system were summed to arrive at the total potential yield of the cropping systems. Yield gap for the cropping system was calculated as the difference between the total simulated potential yield and the total actual yield observed in the field experiment.

Model calibration for soil carbon changes

To validate the soilN module of APSIM for soil carbon changes (Probert *et al.*, 1998), the actual soil and crop management practices followed from 1995 to 2002, especially the applications of organic and chemical fertilizers were added to the crop management files. Initial contents of soil organic carbon (OC) observed at the beginning of the 1995 season were input to the soil parameters file (Table 2). Changes were made in the initial values of active (fbiom) and inactive (inert) fractions of humus content of soil layers such that the simulated organic carbon matched the observed organic carbon content of the soil observed in 2002. Plots having higher content of initial organic carbon had a rapid decline in OC initially as compared to the plots having low OC. This was achieved by taking larger values of rapidly decomposable humus (fbiom) compared to the inert humus (inert) in the soil parameter file (Table 2). C:N ratio of 16:1 was used for both *Gliricidia* and other crop residues added to the soil.

Simulation of long-term changes in soil carbon

After the model was calibrated, long-term analysis of soil carbon balance was performed for various levels of

Table 1. Physical parameters of the soils of the four hydrological units used as input to crop simulation models.

Treatment	DUL	LL	AWHC	U	CONA	SWCON	CN2*	CN2**
Medium-deep soil								
Improved	529	343	186	6	3.5	0.7	85	73
Traditional	500	324	176	6	3.5	0.7	89	84
Shallow soil								
Improved	353	207	146	6	3.5	0.7	77	72
Traditional	348	207	141	6	3.5	0.7	86	82

DUL = Drained upper limit of water retention (mm) ; LL = Lower limit of water retention (mm)
AWHC = Available water holding capacity of soil (DUL-LL) (mm)
U = Upper limit of stage-1 evaporation (mm); CONA = Drainage coefficient (fraction drained/day)
CN2* = Runoff curve number (unit-less) used for the period 1995/96 to 1999/2000
CN2** = Runoff curve number (unit-less) used for the period 2000/01 to 2003/04

Table 2. Distribution of initial soil organic carbon (OC), fraction of active humus (fbiom) and inert humus (inert) in the soil used for model calibration of soil organic carbon for different treatment.

Treatment	Cropping system	Soil property	Soil depth (cm) 0-10	10-22	22-52	52-82	82-112	112-127
Medium-deep soil								
Improved	SB-CP	% OC	0.56	0.57	0.43	0.33	0.31	0.31
	SB/PP	% OC	0.66	0.65	0.47	0.35	0.33	0.33
		fbiom	0.14	0.14	0.09	0.07	0.05	0.05
		Inert	0.29	0.37	0.59	0.69	0.93	0.93

Table Contd.

Traditional	SB-CP	% OC	0.87	0.77	0.59	0.46	0.42	0.42
	SB/PP	% OC	0.90	0.86	0.65	0.46	0.42	0.42
		fbiom	0.84	0.80	0.77	0.74	0.71	0.71
		Inert	0.09	0.11	0.17	0.39	0.53	0.53
Shallow soil								
Improved	SB-CP	% OC	0.96	0.88	0.73	0.67	0.66	—
	SB/PP	% OC	0.92	0.84	0.62	0.62	0.64	—
		fbiom	0.84	0.80	0.77	0.74	0.71	—
		Inert	0.09	0.11	0.18	0.39	0.53	—
Traditional	SB-CP	% OC	0.73	0.68	0.47	0.38	0.38	—
	SB/PP	% OC	0.87	0.73	0.47	0.38	0.37	—
		fbiom	0.14	0.14	0.11	0.07	0.06	—
		Inert	0.29	0.38	0.48	0.69	0.93	—

organic matter additions through crop residues and *Gliricidia* pruning (C:N ratio 16:1) to evaluate the practice that would sustain or reverse the declining trend of organic carbon in the soil. The organic matter input treatments evaluated were: (1) no application of organic matter; (2) addition of organic matter @ 4 t ha^{-1} every year (i.e., 3.0 t ha^{-1} of crop residue on June 1 + 0.5 t ha^{-1} of *Gliricidia* pruning at 25 days after sowing (DAS) in *Kharif* + 0.5 t ha^{-1} of *Gliricidia* pruning to the second crop at 30 days after the harvest of first crop); and (3) addition of organic matter @ 8 t ha^{-1} every year (6.0 t ha^{-1} of crop residue on June 1 + 1.0 t ha^{-1} of *Gliricidia* pruning at 25 DAS in *Kharif* + 1.0 t ha^{-1} of *Gliricidia* pruning to the second crop at 30 days after the harvest of first crop). Long-term simulations were performed for both the cropping systems on medium-deep and shallow soils assuming initial soil organic carbon content of 58 t ha^{-1} in the top 90 cm soil depth. This amount corresponded to the initial values of soil OC observed for the SB/PP system under traditional management treatment of the shallow soil. Simulated values of organic and biomass carbon status of soil were outputted at the end of May every year, prior to the fresh additions of crop residues at the beginning of the rainy season, to see the changes in these parameters.

Results and Discussion

Validation for crop models for crop growth and soil processes

The validation results showed that the crop growth and grain yield curves of soybean and chickpea in the SB-CP sequential system and soybean and pigeonpea in the SB/PP intercrop system for the 1998-99 season were simulated fairly accurately in the absence of any insect-pests or diseases (Fig. 1a and b). Soil moisture changes in the two cropping systems during the season were also simulated accurately (Fig. 2a and b). These results indicated that the performance of the crop models was satisfactory to assess rainfed potential yields and soil water balance of the two cropping systems. As the models do not incorporate the effects of pests and diseases on crop growth, the crop growth and yields were generally overestimated during seasons when these incidents occurred.

Simulated changes in OC content of medium-deep and shallow soils matched the observed data of the year 2002 for all the treatments, indicating that the model calibration was satisfactory to simulate long-term changes in soil OC for the cropping systems and the management treatments (Fig. 3a and b). The crop models in this study simulated the rainfed potential yield of legumes as determined by agronomic management and weather during the season. As the legume models also simulate biological nitrogen fixation, any nitrogen deficiency in the soil, if it occurred, was compensated by additional nitrogen fixation by legumes in the model.

Simulated potential yields and yield gaps of cropping systems

Simulated potential biomass and grain yields of the cropping systems (sum of the yields of first and second crop) were determined by the soil and crop management practices followed and the prevailing weather conditions

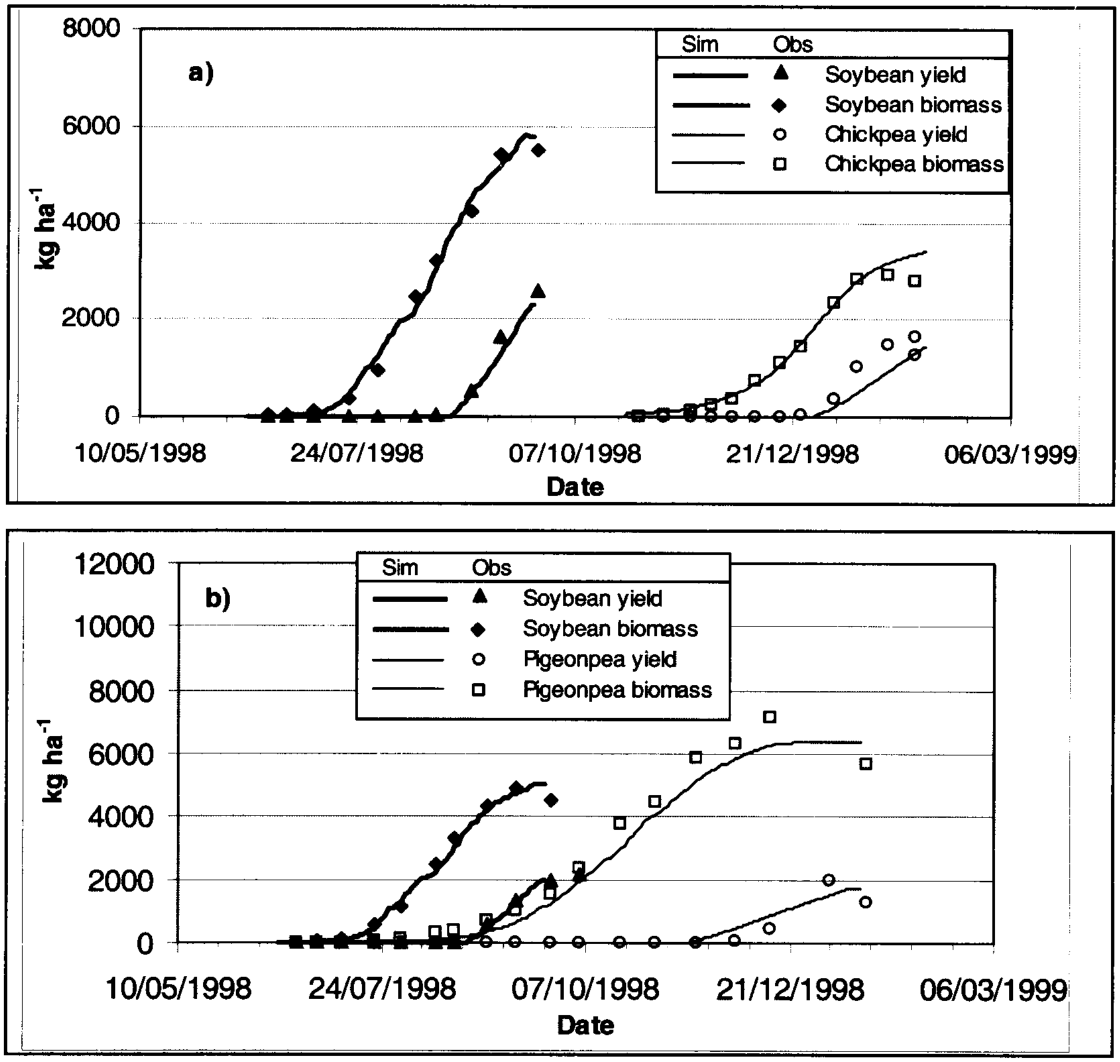
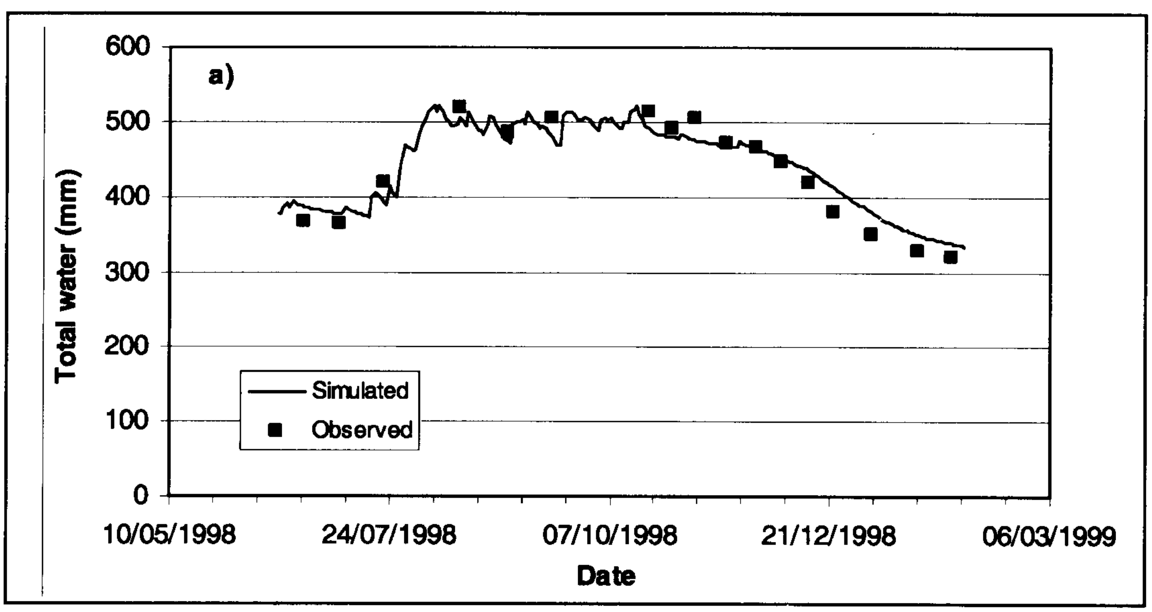


Fig 1. Simulated and observed total biomass and grain yield of a) SB-CP and b) SB/PP systems in the traditional management treatment during 1998-99 season.



(Fig 2a : SB-CP)

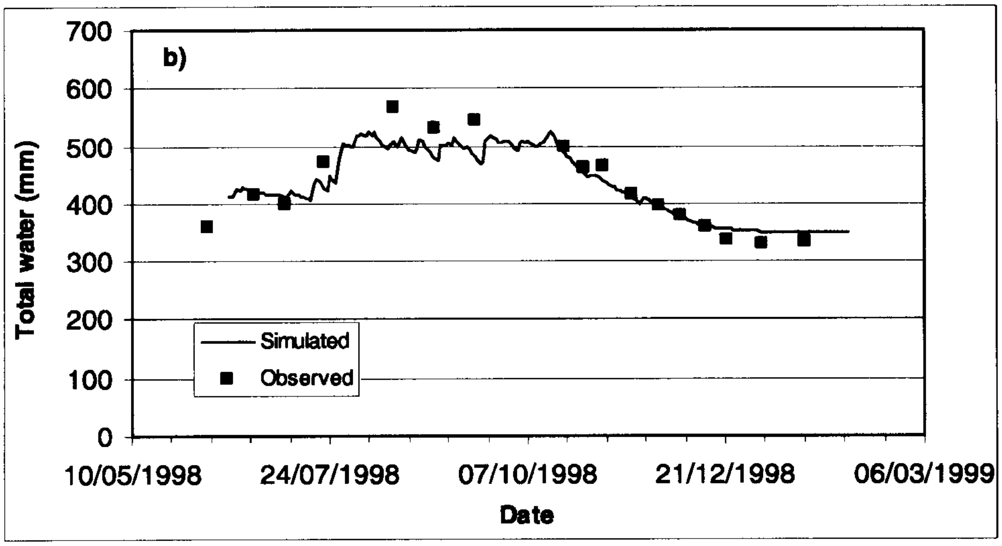


Fig 2. Simulated and observed changes in total soil water under: b) SB/PP systems in the traditional management treatment during 1998-99 season.

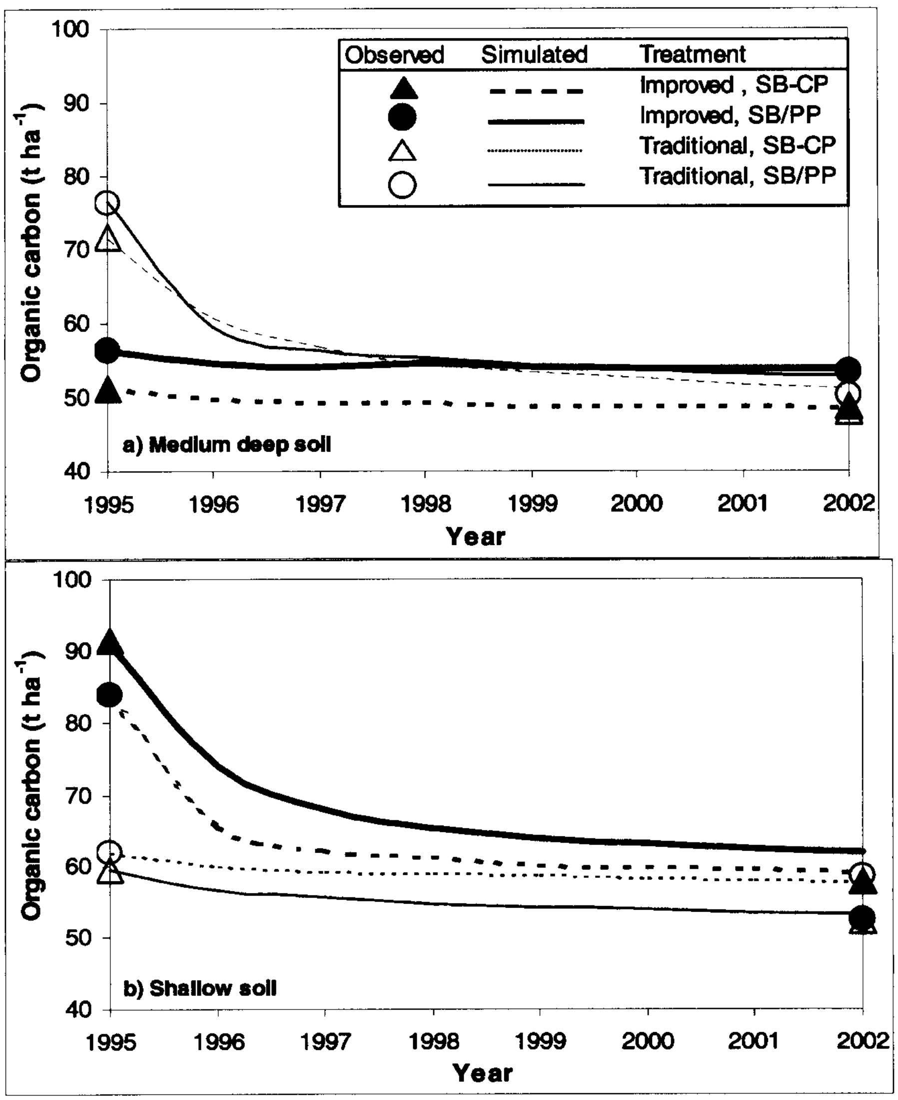


Fig 3. Model validation of changes in soil organic carbon in the top 90 cm soil depth from 1995 to 2002 under various management and cropping system treatments on the two soils.

during the cropping period. Simulated potential biomass yield of the two cropping systems was more during the first three years of study which decreased to lower values during the last three years in both the management treatments and soils (Table 3). However, the simulated grain yields declined only in the case of SB/PP intercrop system because of its longer crop growth duration as compare to the SB-CP sequential systems. The decline in the observed crop yields of the cropping systems over the years was due to the weather effects as well as other factors (declining soil fertility and pests and diseases) limiting yields. Although, the yield gaps between the observed and simulated data existed at the beginning of the experiment, these yield gaps further widened over time for each cropping system and management treatments on both the soils. The difference in yield gaps between improved and traditional management treatments indicated the response to management over

Table 3. Simulated potential yields, observed yields, and yield gap of the two cropping systems in the traditional and improved management treatments during the first three and the last three years of study on the Vertic Inceptisol.

Cropping system	Seasons	Simulated yield Imp.	Simulated yield Trad.	Observed yield Imp.	Observed yield Trad.	Yield gaps Imp.	Yield gaps Trad.
Medium-deep soil							
Total biomass (kg ha^{-1})							
SB-CP	1995/96-1997/98	6670	6580	6340	6170	330	410
SB-CP	2001/02-2003/04	6410	6280	5170	4260	1240	2020
Grain yield (kg ha^{-1})							
SB-CP	1995/96-1997/98	3280	3240	2750	2710	530	530
SB-CP	2001/02-2003/04	3370	3310	2170	1780	1200	1530
Total biomass (kg ha^{-1})							
SB/PP	1996/97-1998/99	8240	8210	8060	7230	180	980
SB/PP	2001/02-2003/04	6760	6840	6190	5600	570	1240
Grain yield (kg ha^{-1})							
SB/PP	1996/97-1998/99	3270	3270	2000	2180	1270	1090
SB/PP	2001/02-2003/04	2800	2840	1780	1710	1020	1130
Shallow soil							
Total biomass (kg ha^{-1})							
SB-CP	1995/96-1997/98	6430	6390	5890	5360	540	1030
SB-CP	2001/02-2003/04	5950	5750	3660	3390	2300	2360
Grain yield (kg ha^{-1})							
SB-CP	1995/96-1997/98	3150	3130	2520	2360	630	770
SB-CP	2001/02-2003/04	3130	3020	1400	1290	1730	1730
Total biomass (kg ha^{-1})							
SB/PP	1996/97-1998/99	7920	7890	7950	6880	0	1010
SB/PP	2001/02-2003/04	6740	6510	5500	5020	1240	1490
Grain yield (kg ha^{-1})							
SB/PP	1996/97-1998/99	3170	3190	2100	2030	1070	1160
SB/PP	2001/02-2003/04	2860	2770	1690	1590	1170	1180

Imp. – improved; Trad. – traditional

time in spite of declining crop yields (Table 3). These results on yield gap analysis indicated that the benefits of improved management were observed only on the medium-deep soil for the two cropping systems. The benefits were larger for the SB-CP systems than for the SB/PP system. There was no advantage of improved management to the productivity of cropping systems on the shallow soil. Thus, on a more heterogenus soil, analysis of potential yields and yield gaps using crop simulation models provide better means to differentiate the treatment effects more realistically than the comparison of actual field data.

Simulated soil water balance of cropping systems

Simulated surface runoff, deep drainage and water use by the cropping systems varied from year-to-year depending upon the amount of rainfall received (Table 4). Shallow soil being somewhat lighter in texture than the medium-deep soil, more deep drainage was estimated for the shallow soil than for the medium-deep soil. It was 58 to 68% higher for the SB-CP system on the shallow soil as compared to the medium-deep soil. Deep drainage was also more in the improved management treatment than the traditional management treatment for both the soils and cropping systems. For the SB-CP system on the medium-deep soil, average deep drainage in the improved management was 21% higher as compared to the traditional management; and on the shallow soil average deep drainage in the improved management was 29% higher as compared to the traditional management. Total water use (evapo-transpiration) by the SB-CP system ranged from 62 to 65% of rainfall received during the growing period, which was not influenced by the management treatments.

As soybean/pigeonpea intercrop (SB/PP) system is of longer duration as compared to the SB-CP system, its total water use (evapo-transpiration) was somewhat more than that of the SB-CP system. It ranged from 65 to 69% of seasonal rainfall across management treatments and soils. Deep drainage in the improved management system as compared to the traditional management was 17% higher for the medium-deep soil and 33% higher for the shallow soil.

Lack of yield response of cropping systems in the improved management treatment on the shallow soil may be attributed to greater deep drainage resulting in leaching

Table 4. Simulated soil water balance components of cropping systems in the improved and traditional management treatments on the shallow and medium-deep soil.

	Rainfall	Water balance components (mm)					
		Surface runoff		Deep drainage		Evapotranspiration	
		Imp.	Trad.	Imp.	Trad.	Imp.	Trad.
Soybean-chickpea system (1995/96-2003/04)							
Medium depth							
Mean	815	160	208	136	112	528	516
Range	436-1254	22-480	40-625	0-302	0-294	461-577	438-557
Shallow depth							
Mean	815	116	100	229	177	512	503
Range	436-1254	10-458	26-583	12-498	0-401	464-548	449-534
Soybean/pigeonpea system (1996/97-2003/04)							
Medium depth							
Mean	782	146	193	112	96	543	534
Range	436-1254	20-480	34-625	0-304	0-308	438-635	424-594
Shallow depth							
Mean	782	112	163	190	143	518	510
Range	436-1254	8-457	21-583	5-477	0-395	456-560	440-553

Imp. – improved; Trad. - traditional

of soluble forms of organic carbon and other nutrients from the rooting zone. Greater amount of deep drainage in the improved management treatment might have further aggravated this problem of leaching. On the medium-deep soil, deep drainage was relatively less than that simulated for the shallow soil. Therefore, greater retention of nutrients in the soil profile resulting in crop response to improved management in spite of decreasing trends in crop yields over time.

Long-term simulation of soil carbon changes

After model calibration, the model was used to check the dynamics of biomass and organic carbon in the soil at various levels of organic matter additions to the two cropping systems on the two soils. The aim was to find out the amount of crop residues to be applied to maintain or to establish the upward trend in the OC status of the soil over the years. Long-term simulation analysis of carbon balance for a period of 28 years showed that both the organic and biomass carbon content of the top 90 cm soil profile decreased with time without applications of crop residues on both the soils (Fig, 4 and 5). However, the rate of decrease of OC was slower for the SB/PP system (-0.27 t ha^{-1} yr^{-1}) than for the SB-CP system (-0.35 t ha^{-1} yr^{-1}) (Fig, 4). This slow rate in case of SB/PP system is due to higher biomass production by the system and contributions through leaf fall and roots to the soil carbon, especially by pigeonpea crop, as compared to the SB-CP system (Fig, 4). Similar, results on increased carbon sequestration were reported by Wani *et al.*, (2003) for the cropping systems that included pigeonpea as the component crop. Progressive additions of crop residues from nil to 8 t ha^{-1} during the cropping period decreased the rate of decrease of organic carbon from – 0.35 t ha^{-1} yr^{-1} to – 0.025 t ha^{-1} yr^{-1} for the SB-CP system on both the soil types. However, for the SB/PP system the rate of change in organic carbon became positive (+0.06 t ha^{-1} yr^{-1} for the medium deep soil and +0.07 t ha^{-1} yr^{-1} for the shallow soil) at 8 t ha^{-1} yr^{-1} application rate of crop residue, indicating the reversal of declining trend in organic carbon of soil. After the initial decline in the biomass carbon the maintenance of biomass carbon in the soil

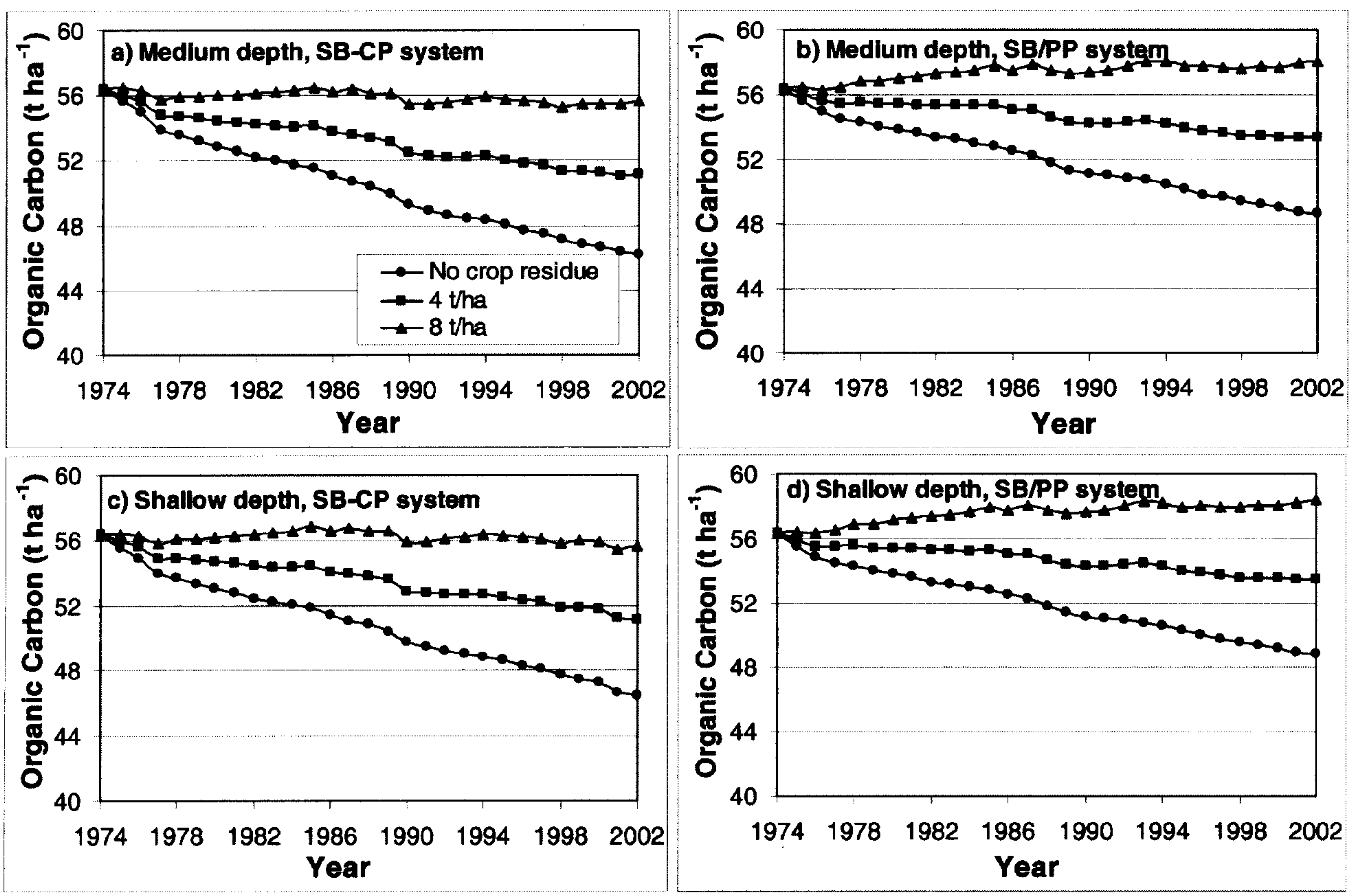


Fig 4. Simulated changes in soil organic carbon in top 90 cm soil profile at various levels of crop residue inputs to two cropping systems on the two soils.

was better than that for the organic carbon. For every 4 t ha^{-1} additions of crop residue per year, the increase on biomass carbon ranged from 0.61 to 0.65 t ha^{-1} of biomass carbon for the SB-CP system and 0.67 to 0.74 t ha^{-1} for the SB/PP system on both the soil types (Fig 5). Crop residue addition at 8 t ha ha^{-1} yr^{-1} rate was able to maintain the biomass carbon in the soil at its original status in the SB-CP system and some accretion in case of SB/ PP system.

These results indicate that crop residue additions @ 8 t $ha^{-1}yr^{-1}$ are required for long-term maintenance of organic and biomass carbon status of the Vertic Inceptisol. Any additional contribution to crop residues through leaf fall or roots by a cropping system would reduce this amount for long-term maintenance of soil OC in the soil. Considering crop residues as fodder needs for the livestock, alternate approach would be to develop practices that would minimize the loss of OC from the soil when limited crop residues are applied to the soil. This would entail surface application of crop residues and minimum tillage that would reduce incorporation of crop residues in the soil resulting in less organic matter decomposition and loss of carbon from the soil. This would reduce such high requirements of residues application to maintain carbon in the soil at higher levels.

Conclusions

Analysis of the potential yields showed that the yields gaps of the two cropping systems increased over time in each management treatment on both the soils. Considering yield gaps with reference to the expected yield (rainfed potential yield) for each treatment, the beneficial effects of improved management for crop yields of the two cropping systems were observed only on the medium deep soil. Lack of response to management on the shallow soil could be because of leaching soil OC, nitrogen and other nutrients beyond the rooting zone because of high deep drainage on the shallow soil as compared to that on the medium deep soil. Long-term simulation analysis showed that SB/PP systems as compared to the SB-CP system retained more OC in the soil which, is attributed to significant amounts

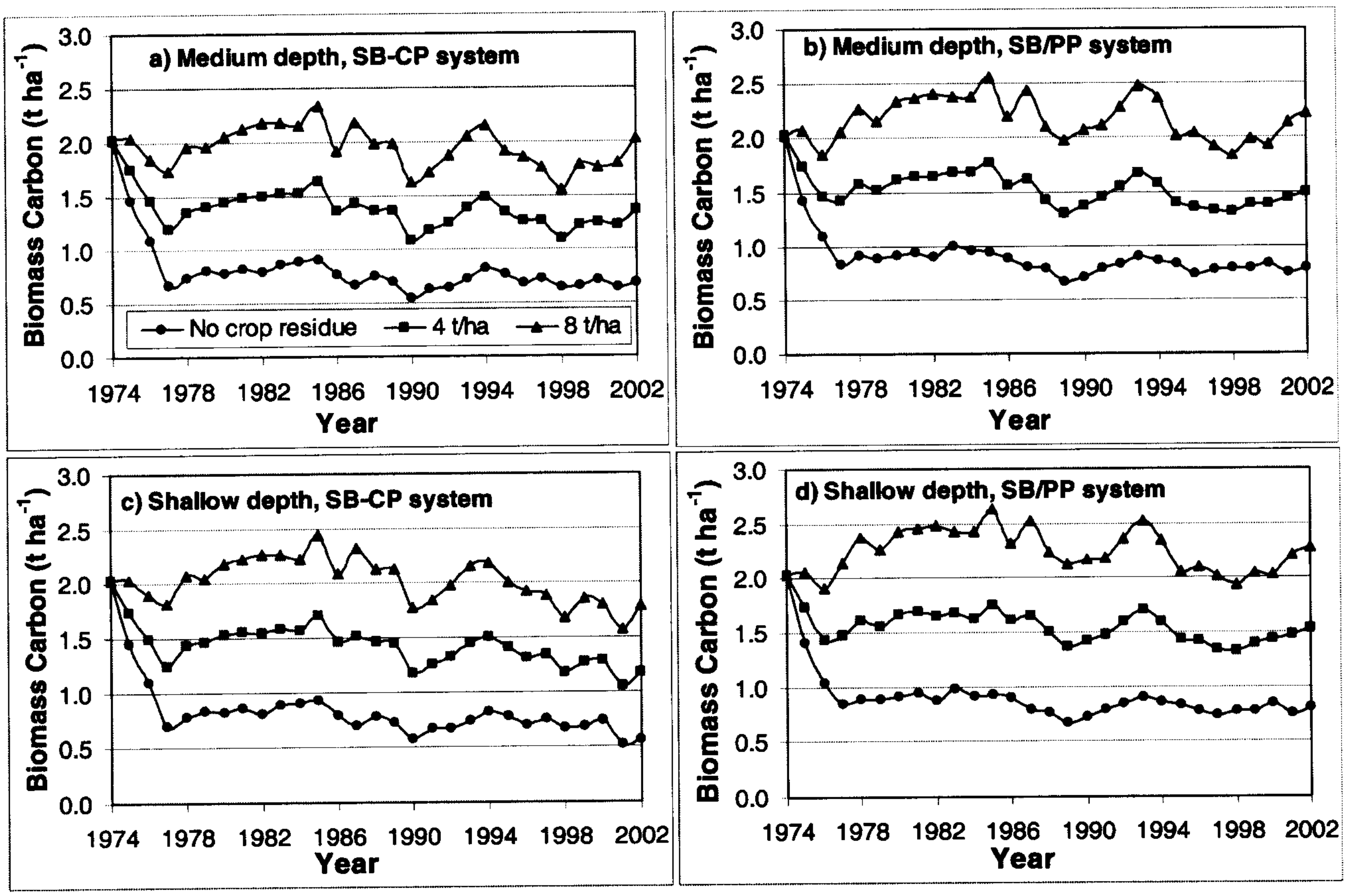


Fig 5. Simulated changes in soil biomass carbon in the top 90 cm soil profile at various levels of crop residue input to two cropping systems on two soils.

of organic matter additions through roots and leaf fall of the pigeonpea crop. To enhance soil quality and sustainability, crop residue additions at the rate of 8 $t ha^{-1} yr^{-1}$ would be needed to maintain or reverse the declining trend of OC due to cropping on these soils. This may be achieved partly through external sources of crop residue additions and partly by increased contributions of roots and leaf senescence to the total organic matter additions to the soil. Surface applications of crop residues and minimum tillage would be further helpful to reduce such high requirements of residue application.

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