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Soybean–chickpea rotation on Vertic Inceptisols I. Effect of soil depth and landform on light interception, water balance and crop yields

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Abstract

Vertic Inceptisols are prone to land degradation because of excessive run-off and soil erosion during the rainy season. Productivity of soybean-based systems on these soils needs to be improved and sustained by better management of natural resources, particularly soil and water. During 1995–1997 a field study was conducted in Peninsular India on a Vertic Inceptisol watershed to study the effect of two soil depths, namely shallow (<50 cm soil depth) and medium-deep ($\geq$50 cm soil depth) and two landform treatments, namely flat and broadbed-and-furrow (BBF) systems, on productivity and resource-use efficiency of soybean–chickpea rotation (soybean in rainy season followed by chickpea in post-rainy season). Soybean grown on flat landform on medium-deep soil had a higher leaf area index and more light interception compared to the soybean grown on the BBF landform. This resulted in an increase in mean seed yield for the flat landform (2120 kg ha^{-1}) compared to the BBF landform (1870 kg ha^{-1}). However, the landform treatments on shallow soil did not affect soybean yields. The soybean yield was higher on the medium-deep soil (1760 kg ha^{-1}) than on the shallow soil (1550 kg ha^{-1}) during 1995–1996, but were not different during 1996–1997. In both years chickpea yields and total system productivity (soybean + chickpea yields) were greater on medium-deep soil than on the shallow soil. Total run-off was higher on the flat landform (25% of seasonal rainfall) than on the BBF landform (20% of seasonal rainfall). This concomitantly increased profile water content (10–30 mm) of both soils in BBF compared to the flat landform treatment during 1995–1996, but not during 1996–1997. Deep drainage was higher in the BBF landform than in flat, especially for the shallow soil. Across landforms and soil depths, water use (evapotranspiration) by soybean–chickpea rotation during 1996–1997 ranged from 496 to 563 mm, which accounted for 54–61% of the rainfall. These results indicate that while the BBF system is useful in decreasing run-off and increasing infiltration of rainfall on Vertic Inceptisols, there is a need to increase light use by soybean on BBF during the rainy season to increase its productivity. A watershed-based farming system needs to be adopted to capture significant amount of rain water lost as run-off and deep drainage. The stored water can be used for supplemental irrigation to increase productivity of soybean-based systems leading to overall increases in resource-use efficiency, crop productivity, and sustainability.

Keywords: Soybean (Glycine max L.); Chickpea (Cicer arietinum L.); Water balance; Crop yields; Vertic Inceptisol; Watershed

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1. Introduction

In India the land area under soybean cultivation has increased exponentially from 0.03 Mha in 1971 to 5.6 Mha in 1997 (Singh, 1997). Soybean as an oilseed crop has good economic value and farmers are expanding soybean-based agriculture in Central India on Vertisols and Vertic Inceptisols. Vertic Inceptisols, which occur in association with Vertisols in a toposequence, occupy about 60 Mha area in India (Sehgal and Lal, 1988). These soils have similar physical and chemical properties as the Vertisols, except that these are shallower (depth of black soil material) and somewhat lighter in texture and occur on slopes not exceeding 5%. These soils have low to medium available water-holding capacity (100–200 mm plant extractable water) which varies with soil depth. Annual rainfall in Central India, where these soils occur, varies from 750 to 1500 mm with almost 80% received from June until September. Total rainfall during these four months often exceeds the water requirement of crops grown during the rainy season. Because of their location in toposequence, Vertic Inceptisols are prone to severe land degradation. Major constraints for crop production on these soils are a high run-off of rain water and associated soil erosion, depletion of nutrients and beneficial organisms leading to decline in crop productivity. There is an urgent need to manage the natural resources of Vertic Inceptisols in the region, particularly rainfall, to control soil erosion and to improve rainfall-use efficiency.

Various land surface management practices (e.g. tillage, ridges and furrows, broad-bed and furrows, etc.) for Vertisols have been investigated in India to control the flow of excess rain water, thereby minimizing soil erosion and increasing infiltration. During 1975–1980, Pathak et al. (1985) studied the influence of four land management systems on annual run-off and soil loss from the Vertisol watersheds. In their study, the system of broadbed-and-furrows (BBF) with field bunds reduced the average annual run-off to one-third and soil loss to one-eleventh when compared to traditional flat landforms. In a subsequent study, Srivastava and Jangwad (1988) measured run-off and soil loss on two small agricultural watersheds on a Vertisol for 12 years. One of the watersheds had an improved management system that included double cropping and BBF system as a landform treatment. The other watershed had a traditional management system characterized by fallow during the rainy season followed by a crop during the post-rainy season on a flat land configuration. The improved system lost only 13.7% of rainfall as run-off compared to 24.1% run-off in the traditional system. Soil loss in the improved system amounted to 1.46 Mg ha^{-1} year^{-1} while it was 6.4 Mg ha^{-1} year^{-1} in the traditional system. In a higher rainfall region of Central India, Gupta and Sharma (1994) studied the influence of four land configuration treatments on in situ conservation of rain water during 1988–1991 on a Vertisol. The mean annual run-off across four years was 10% of seasonal rainfall in the traditional flat system compared to only 4% in the improved landform treatment of raised and sunken bed. The seasonal soil loss was 329 kg ha^{-1} in the traditional landform treatment compared to only 192 kg ha^{-1} in the improved system.

While improved landform systems have been reported to decrease run-off and soil erosion, concomitant yield improvements of crops have not been achieved in various field studies. One of the possible reasons could be that improvements in the use of some resources or resource protection was done at the cost of sacrificing the use of other resources, important for maintaining or increasing the productivity of crops grown on these systems. At the research farm of the International Crops Research Institute for the semi-Arid Tropics (ICRISAT), we studied the crop productivity and resource use of a soybean–chickpea crop rotation on two landforms (BBF and flat) and two soil depths (shallow and medium-deep) at watershed scale on a Vertic Inceptisol, to identify the reasons for the failure to achieve yield increases despite the improvements in resource conservation and use. The objective of this paper is to evaluate the effect of the landform treatments and soil depths on the water balance, light interception, and yield of the soybean–chickpea rotation on the Vertic Inceptisol.

2. Materials and methods

2.1. The field experiment

This study was part of a larger study on natural resource management conducted at a watershed scale at the ICRISAT Center, Patancheru (17°32′N latitude,

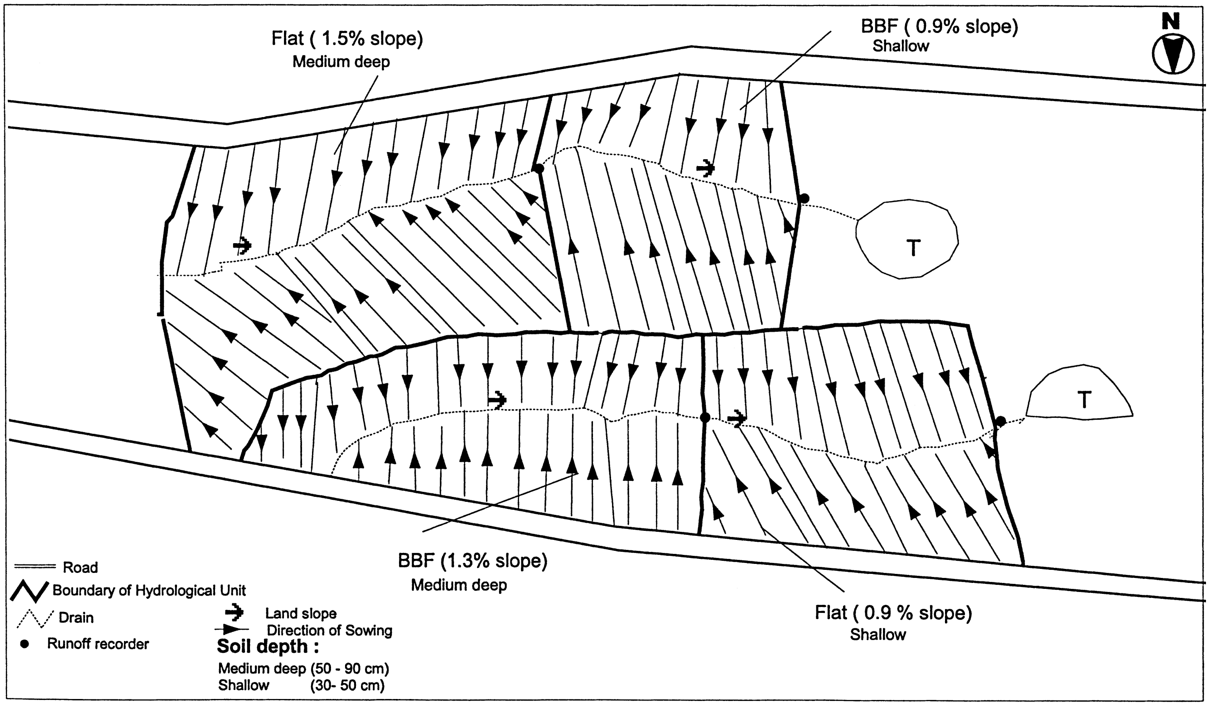

Fig. 1. A plan of the watershed showing four hydrological units, their slope and soil depth, and direction of sowing of crops in each hydrological unit.

78°16′E long., and 540 m elev.), Andhra Pradesh, India. On the basis of a topographical survey a small watershed of 4.7 ha was designed and developed (Fig. 1). The general slope of the land was less than 2%. The watershed had two drainage ways to discharge approximately 0.18 $m^3 s^{-1} ha^{-1}$ of peak run-off rate. The soil was a Vertic Inceptisol, which is classified as the member of the fine, montmorillonitic, isohyperthermic family of paralithic Vertic Ustopepts. The soil profile in the watershed varied in depth from 30 to 90 cm, underlaid by a relatively coarse weathered material locally known as "murrum". This coarse material holds water and can be penetrated by roots for water uptake. Because of the natural variability in soil depth (the depth of the black soil material), the whole watershed area was divided into shallow (<50 cm soil depth) and medium-deep (≥50 cm soil depth) blocks. Effective soil depth, in terms of depth of water extraction by plant roots, was 110 cm in the shallow and 125 cm in the medium-deep blocks. Each block was further divided into two parts to which two landform treatments were assigned. The landform treatments were broadbed-and-furrow (BBF) and flat systems. The width of the bed in the BBF landform was 1.0 m with 0.5 m wide furrows on either side of the bed. The whole watershed thus consisted of four hydrological units arising from the factorial combination of two soil depths and two landforms, which were: (1) flat shallow, (2) BBF shallow, (3) flat medium-deep, and (4) BBF medium-deep. The size of each hydrological unit was different ranging from 0.75 to 1.27 ha. Because of physical restrictions besides their natural occurrence, these hydrological units were not replicated. These hydrological units were further partitioned into 6–8 subplots, ranging in size from 0.07 to 0.20 ha, and treated as replications. Sowing of crops in the BBF system was done on a 0.8% grade, while in the flat system it was done along the contour lines. Detailed observations on various aspects of crop growth and resource use were recorded on these subplots in each hydrological unit.

2.2. Agronomic management

2.2.1. 1995 Season

Before the beginning of the rainy season in 1995 the field plots were ploughed and prepared to flat and BBF landforms as required for each hydrological unit. Single super phosphate was broadcast and incorporated into the soil on 25 June 1995 to provide 18 kg P ha^{-1}. The cropping system followed was a soybean–chickpea crop rotation, that is, soybean was sown during the rainy season and chickpea during the post-rainy season. Soybean (cv. PK 472) seeds treated with *Bradyrhizobium japonicum* were sown in all subplots of each hydrological unit on 26 June 1995 with an animal-drawn planter. In the flat landform, row spacing was 37.5 cm and plant population after thinning was 30 plants m^{-2}. In the BBF landform, four rows of soybean were sown on each bed (33.3 cm row spacing) keeping the same plant population level as in the flat landform. The crop was intercultivated with the animal drawn equipment and weeded manually for four times during the season. The crop was intensively protected from weeds, insect pests and diseases. The soybean crop matured on 15 October 1995 and was harvested on 20 October 1995.

Chickpea seeds treated with *Bradyrhizobium spp*. were sown on 30 October 1995 with an animal-drawn planter. In both the landforms the row spacing was 50 cm and plant population was 10 plants m^{-2}. In BBF three rows of chickpea were sown on each bed. Cultivars sown were ICCV 2 (a short-duration kabuli type with cream colored seed testa) on the shallow soil and ICCC 37 (a medium-duration desi type with dark-brown seed testa) on the medium-deep soil. The plots were intercultivated twice and hand weeded three times during the season. The crop was harvested on 12 February 1996 to determine total biomass and seed yields.

2.2.2. 1996 Season

Fields were cultivated and prepared to flat and BBF landforms during the 1996 summer season much before the onset of the rainy season. Soybean (cv. PK 472) seeds treated with *B. japonicum* were sown on 26 June 1996 just after the onset of the monsoon season. Row-spacing and plant population in each treatment were the same as in 1995 season. Single super phosphate was broadcast and incorporated into the soil prior to sowing to provide 18 kg P ha^{-1}. The crops were intensively protected from weeds, insect pests, and diseases during the season. The crop was harvested on 9 October 1996.

Chickpea (cv. ICCC 37) seeds treated with *Bradyrhizobium spp*. were sown on 14 October 1996 after harvesting soybean directly without any land cultivation. Row-spacing for the flat landform treatment was 37.5 cm and plant population was 23 plants m^{-2}. In the BBF treatment four rows of chickpea were sown on each bed (row-spacing of 33.3 cm) and the plant population was same as in flat landform. The crop was intensively protected from weeds, insect pests, and diseases. Chickpea was harvested on 24 January 1997.

2.3. Measurements

Climatic data were recorded daily from the class 'A' agrometeorological observatory situated adjacent to the watershed including rainfall, maximum and minimum temperatures, and solar radiation. Additionally, rainfall was recorded with two raingauges (one recording and the other nonrecording) placed in the middle of the watershed area.

To determine the interception of photosynthetically active radiation (PAR) by soybean and chickpea, observations on incident light were taken both at the canopy surface and below the crop canopy at ground level with a line quantum sensor (LI-COR instruments, USA). These observations were taken at 2–3 spots in each subplot every week on clear days between 13:00 and 14:00 hours close to solar noon. Light interception was calculated as the difference in the amount of energy received above and below the crop canopy, and expressed relative to the amount received above the canopy.

Plant samples were taken at 7–10 days intervals for growth analysis. Plants were harvested from at least 0.50 m^2 area in each subplot, then brought to laboratory for growth analysis. In case the subplot size was too large, composite samples were taken from 2 to 3 spots in the subplot and then subsampled for growth analysis. Leaf area of each subsample determined using a leaf area meter (LI-COR instruments, USA). Leaf area index (LAI) was calculated as total leaf area per sample divided by the sampled area.

To monitor changes in soil water content, three neutron probe access tubes were installed in each subplot. These tubes were located on the diagonal transect of each subplot to have representative sampling of soil water content of each subplot. Total number of access tubes installed in each hydrological unit was at least 18. Neutron probe readings were taken every 7–10 days intervals in each access tube from 30 to 150 cm depth with increments of 15 cm. Water content of the top two soil layers (0–10 cm and 10–22.5 cm) was determined gravimetrically.

Run-off from each hydrological unit was measured with automatic water stage recorders. The height of water passing through a H-flume was continuously recorded on a strip chart, which was later interpreted in terms of total run-off associated with each rainfall event. Run-off was summed to calculate cumulative run-off. Although run-off was recorded in both seasons, the data obtained during 1996–1997 were more reliable than that during the 1995–1996 season, as the watershed subunits and landform treatments were stabilizing during the first year of installation.

Because of the large subplot size, five samples of both rainy and post-rainy season crops were taken from each subplot to determine their yields at harvest maturity. Each year the total area harvested per subplot was 225 m^2. The harvested material was dried in a large hot-air oven at 60°C for a week and then weighed. The harvested material was threshed to separate seed from stalk and weighed to determine seed yield.

2.4. Estimation of water balance components

Because of simultaneous occurrence of run-off and deep drainage during the rainy season the daily water balance components of soybean for each hydrological unit were estimated using the water balance model of Ritchie (1998), a submodel of the soybean and chickpea crop growth models (Boote et al., 1998). The model requires inputs of weather parameters, leaf area index, and soil profile characteristics. The depth of rooting was taken as 110 cm for the shallow soil and 125 cm for the medium-deep soil, which were the maximum depths of water extraction observed during the post-rainy season for the two soils. The extractable water capacity of soil was 132 mm for the flat shallow, 135 mm for the BBF shallow, 170 mm for the flat medium-deep, and 190 mm for the BBF medium-deep blocks. Total water retention capacity at the drained upper limit (DUL) was 365 mm for the flat shallow, 368 mm for the BBF shallow, 508 mm for the flat medium-deep, and 540 mm for the BBF medium-deep soils. The differences in water retention between the BBF medium-deep and flat medium-deep soils occurred at depths below 95 cm, which had no significant effect on growth of crops in either season.

During the post-rainy season there was no surface run-off and deep drainage and the chickpea crop grew on stored profile moisture with little rain during the post-rainy season. Water use (evapotranspiration) by the chickpea crop was equal to profile water depletion from its sowing to harvest, plus any rainfall during the crop growth period. However, soil evaporation was estimated using the model of Ritchie (1998) to partition observed evapotranspiration into soil evaporation and crop transpiration.

2.5. Analysis of data

The yield data for soybean and chickpea obtained at final harvest were analyzed using the analysis of variance method (ANOVA). For this the four hydrological units were treated as different locations, and the data were analyzed by following the procedure of multi-location analysis. Whereas, the data on LAI, light interception, and soil water were analyzed for each sampling date separately as per the following linear additive random effects model:

$$Y_{ijk} = \mu + S_i + L_{(i)j} + E_{ijk},$$

where Y_{ijk} is the dependant variable, μ the general mean, S_i the effect of soil depth i, $L_{(i)j}$ the effect of landform j within soil depth i, and E_{ijk} is random residual, $i = 1,2$; $j = 1,2$; $k = 1, \ldots 6–8$.

Each effect in the model, except μ, was assumed to be a normally distributed random variable. The BLUPs (best linear unbiased predictors) of the mean effects of different factors and their standard errors (SEd) were used to construct Figs. 2–5.

3. Results and discussion

3.1. Weather

Rainfall during both 1995 and 1996 was above the long-term average (800 mm). Total rainfall received

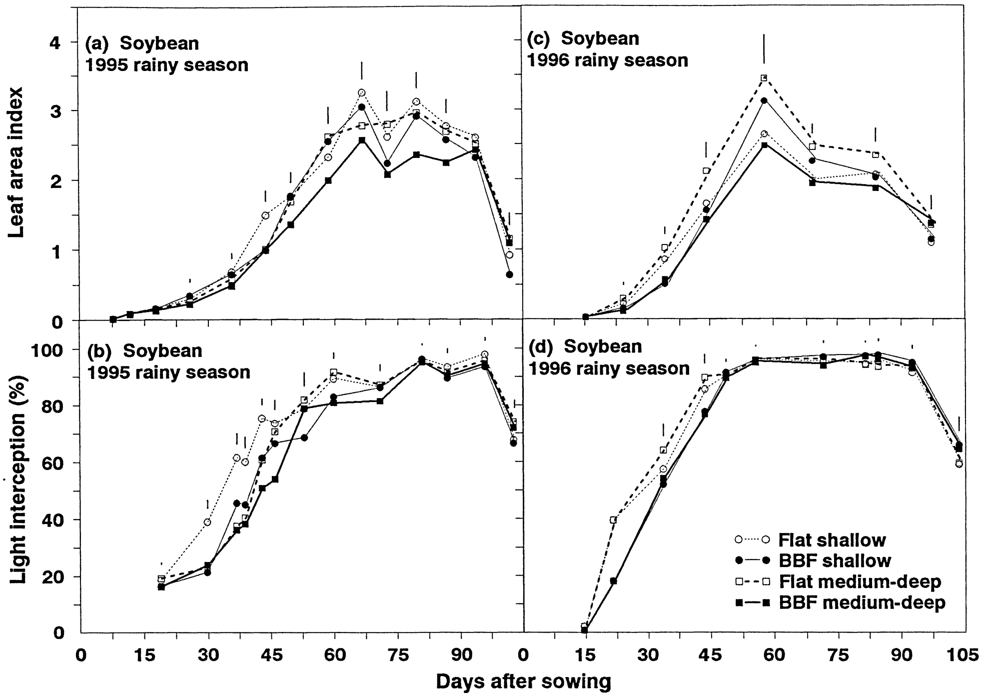

Fig. 2. Effect of landform treatments and soil depth on (a) leaf area index; (b) light interception by soybean during 1995–1996 post-rainy season; (c) leaf area index; (d) light interception during 1996–1997 post-rainy season. Vertical bars above the data points are the standard error of difference.

from June to December was 1121 mm during 1995 and 1017 mm during 1996. In 1995, total monthly rainfall in June, July, August, and October was more than the long-term average rainfall; whereas in 1996 it was more than the long-term average for the months of July and August only (Table 1). Higher rainfall in a given month was generally associated with less solar radiation, low maximum and minimum temperatures, and less open-pan evaporation. During both years soybean did not suffer any significant water deficits and chickpea grew under the conditions of receding soil moisture.

3.2. Leaf area index and light interception

During 1995, the leaf area index (LAI) of soybean was similar in all treatments up to 40 DAS (Fig. 2a). After 40 DAS, LAI was lower in BBF on the medium-deep soil compared to that in the flat landform. Similar trends were also seen in the shallow soil after 60 DAS, but the differences in LAI between flat and BBF landforms were relatively less. Maximum LAI of 3.2 was observed in the flat landform on shallow soil. Light interception closely followed LAI (Fig. 2a). The crop on the flat landform always intercepted more light (PAR) compared to the crop on the BBF landform on both soils until maximum ground cover was achieved. Until 50% flowering (38 DAS) cumulative PAR interception on the BBF was 86–90% of that on the flat landform across soil types, which increased to 95% of light interception on flat at physiological maturity (110 DAS)(data not presented). Greater LAI and light interception on shallow soil could be attributed to better aeration compared to that of the medium-deep soil, resulting in better crop growth.

In 1996, the LAI of soybean was greater throughout the season on the flat landform compared to the BBF landform on the medium-deep soil (Fig. 2c). The highest LAI of 3.5 was observed on the flat landform on medium-deep soil. On shallow soil, LAI was greater on flat landform compared to BBF prior to achieving the maximum LAI. At later stages, LAI was greater on BBF than on the flat landform. Similar differences were observed in light interception by

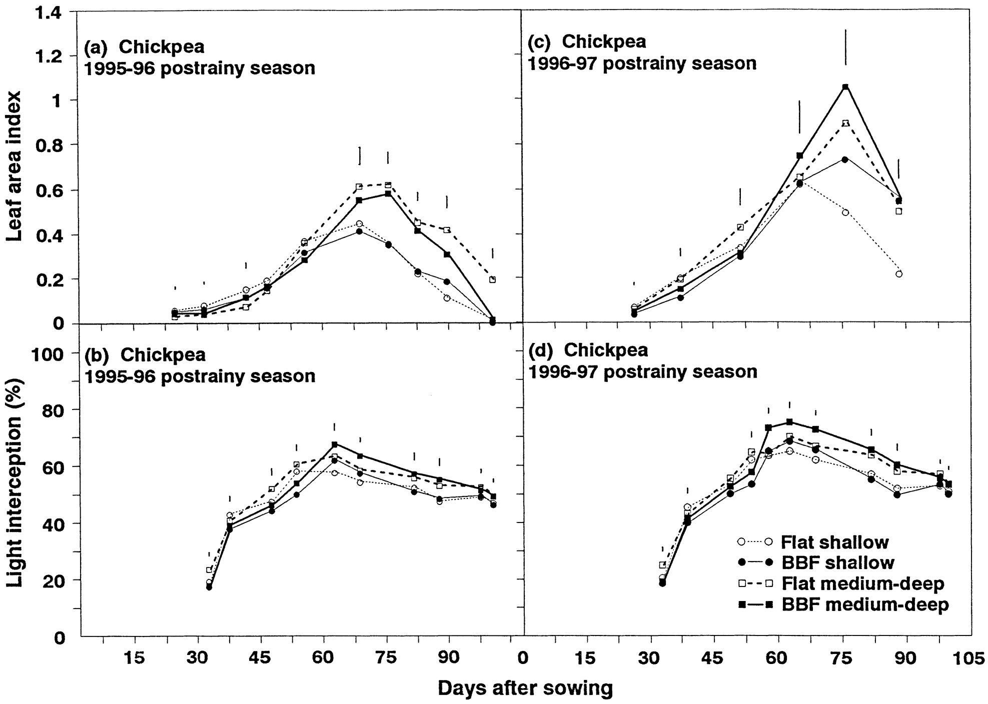

Fig. 3. Effect of landform treatments and soil depth on (a) leaf area index; (b) light interception by chickpea during 1995–1996 post-rainy season; (c) leaf area index; (d) light interception during 1996–1997 post-rainy season. Vertical bars above the data points are the standard error of difference.

soybean as in the LAI (Fig. 2d). Soybean intercepted more light on the flat landform than on the BBF landform on both shallow and medium-deep soils during the initial phase of its growth until 60 DAS when 95% of PAR was intercepted. Later the differences among treatments in light interception were not significant. Cumulative intercepted PAR by soybean was greater on the flat than on the BBF landform for both soil depths. Until 50% flowering (37 DAS), cumulative PAR interception by soybean on BBF was 86–90% of that on flat landform on both soil depths, which increased to between 94% and 97% of interception on flat at physiological maturity (DAS 106)(data not presented). Less light interception on BBF landform is because of unequal spacing between rows. Each bed had four rows of soybean separated by a 0.5 m wide furrow between the beds, which caused more light to be transmitted to the soil surface. On the flat landform the spacing between rows was the same resulting in less loss of light and more interception by the crop canopy. Because water availability was not limiting crop growth on either soil during the rainy seasons, crop growth was directly proportional to the amount of light intercepted.

In the initial phase, when water availability was not limiting chickpea growth, both LAI and light interception were greater on the flat landform on both soil types during both years (Fig. 3). After flowering, both LAI and light interception were influenced more by soil type (water availability in the soil) than by landform treatment (Fig. 3a–d). More LAI and greater light interception was observed on the medium-deep soil than on the shallow soil. Across treatments percent light interception ranged from 60% to 70% during 1995–1996 season and 65–75% during 1996–1997 season. Cumulative PAR intercepted by the crop at the end of the season on shallow soil was about 92% of that on the medium-deep soil in both seasons (data not presented).

The above results indicated that during the rainy season radiation interception is the major determinant of crop yields of soybean grown in Peninsular India;

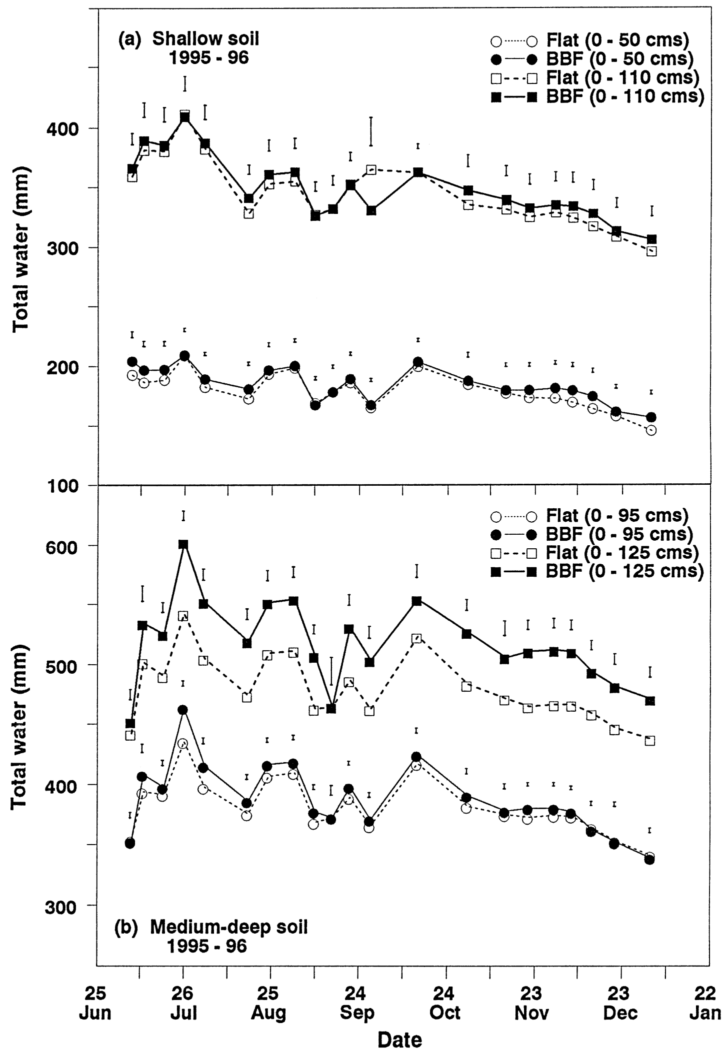

Fig. 4. Effect of landform treatments on soil water changes in the top 50 cm and top 110 cm soil depth in the shallow soil (a) and top 95 cm and top 125 cm soil depth in the medium-deep soil (b) during the 1996–1997 season. Vertical bars above the data points are the standard error of difference.

while soil water availability determines the yield of chickpea during the post-rainy season. Thus to sustain yields of soybean-based systems in the semi-arid tropics we need to develop management practices which will maximize light use in the rainy season and water-use efficiency in the post-rainy season.

3.3. Soil moisture dynamics

Although soil moisture observations were taken up to the maximum soil depth at each monitoring location, the changes in soil moisture observed during the season in the various treatments are presented up to 110 cm depth for the shallow soil and up to 125 cm depth for the medium-deep soil as these depths represent the maximum depth of water extraction by plant roots at the end of post-rainy season. As soil variability in water retention characteristics increased with soil depth in each treatment (hydrological unit), the data on soil water changes have also been presented for the top 50 cm uniform soil layer for the shallow soil and for the top 95 cm uniform soil layer for the medium-

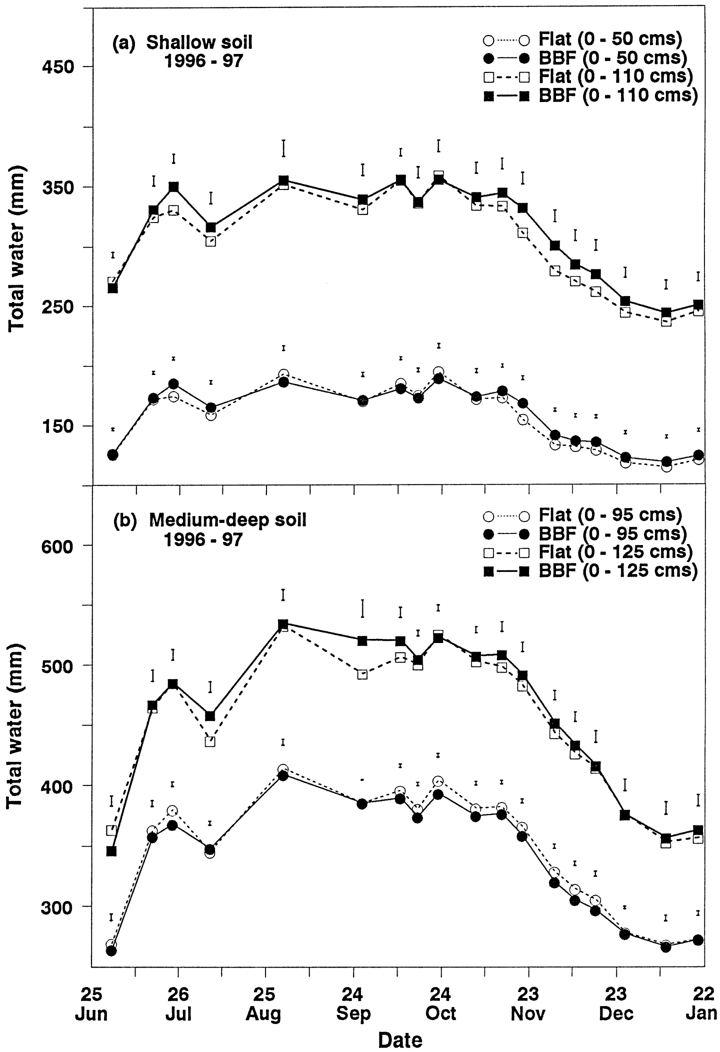

Fig. 5. Effect of landform treatments on soil water changes in the top 50 cm and top 110 cm soil depth in shallow soil and top 95 cm (a) and top 125 cm soil depth in medium-deep soil (b) during the 1995–1996 season. Vertical bars above the data points are the standard error of difference.

deep soil for proper comparison of the treatment effects on soil water changes (Fig. 4a and b). During 1995, with the onset of the rainy season in late June, the soil profile started recharging in early July. In late July (26 July) the soil profiles were recharged above their drained upper limit and were close to fully saturated. Total water retained in the shallow soil was 410 mm, while the medium-deep soil profile retained 540 mm in the flat and 600 mm in the BBF treatment. In both soils, the soil profile under BBF landform often retained more water than under flat landform. Differences in water retention between treatments during the rainy season ranged from 10 to 30 mm in the top uniform soil layer, especially in the medium-deep soil (Fig. 4b). This showed that BBF landform helped to reduce run-off and conserve more water in the soil profile than the flat system. Greater differences in soil water retention between flat and BBF system in the whole soil profile (0–125 cm) of the medium-deep soil are due to the treatment effect and

Table 1
Long-term mean monthly rainfall, total rainfall and mean monthly values of other climatic elements during 1995 and 1996

Month	Mean monthly rainfall (mm)	Year	Total rainfall (mm)	Open-pan evaporation (mm per day)	Maximum temperature (°C)	Minimum temperature (°C)	Solar radiation (MJ m^{-2} per day)
June	118	1995	136.2	10.6	35.5	25.0	20.1
		1996	87.1	8.0	35.2	24.1	19.0
July	174	1995	252.0	4.6	30.1	22.8	15.2
		1996	211.3	5.9	31.7	23.0	17.5
August	196	1995	245.6	4.7	30.2	22.8	17.8
		1996	450.8	3.5	28.9	22.1	13.3
September	164	1995	112.9	4.5	30.2	22.1	17.7
		1996	161.4	4.0	29.9	22.0	17.4
October	95	1995	361.0	3.9	29.1	20.4	14.0
		1996	83.6	4.5	29.1	20.4	15.4
November	23	1995	13.0	4.6	29.3	16.2	18.2
		1996	22.4	4.5	29.2	15.3	16.7
December	4	1995	0	4.2	28.4	13.9	16.6
		1996	0	4.2	27.7	13.2	15.0
January	7	1996	0	5.1	29.6	15.4	17.3
		1997	11.4	4.3	27.2	14.0	16.0
February	5	1996	0	6.6	31.4	16.8	19.1
		1997	0	6.3	31.6	13.7	20.4

also due to the differences in soil water retention below 95 cm soil depth between the two soils. During the post-rainy season after sowing of chickpea (30 October 1995), soil water was depleted gradually until the crop was harvested in January 1996. The soil at harvest of chickpea crop retained some extractable soil water capacity because of poor crop stand during the post-rainy season.

In 1996, soil water content at sowing of rainy season crops was close to the lower limit of water extraction both for shallow (229–233 mm) and medium-deep soils (338–350 mm), except for the seedbeds, which had reached air dry water content. Soil water accretion commenced with the onset of rainfall and the shallow soil was close to field capacity by 24 July (30 DAS) while medium-deep soil was at field capacity by 31 August (66 DAS) (Fig. 5a and b). In both soils, the differences in water retention between BBF and flat in the top uniform soil layers were not consistent. Also the differences in water retention between the two systems in the whole soil profile (0–125 cm) of medium-deep soil were not as large as in 1995 season, which is attributed to the differences in the amount and pattern of rainfall between the two years (Table 1). High rainfall early in 1995 season brought the medium-deep soil to above the drained upper limit earlier in the season, and the differences in water retention between the flat and BBF persisted throughout the season. Whereas in 1996 the medium-deep soil, especially under the BBF system, was filled to the drained upper limit once only in late August. There was practically no limitation of soil water availability to soybeans during the 1996 growing season. The soil water content at the time of chickpea sowing (14 October) was at field capacity in both the shallow and medium-deep soils. During the end of October, 53 mm rainfall was received and the soils were again recharged to their field capacity. Afterwards the chickpea crop grew on stored water. The fields were depleted of available water by 9 January 1997 (87 DAS). Depletion of water by chickpea was much faster during 1996–1997 season because of better crop establishment and growth than during the 1995–1996 post-rainy season.

Table 2
Cumulative rainfall (mm) and cumulative run-off (mm) observed in various treatments during 1996 rainy season

Date	Rainfall	Treatment				Means			
		Flat shallow	BBF shallow	Flat medium-deep	BBF medium-deep	Flat	BBF	Shallow	Medium-deep
		Cumulative run-off (mm)							
12 July	91	9	8	8	6	9	7	9	7
14 July	131	16	15	12	6	14	11	16	9
11 August	319	35	31	35	27	35	29	33	31
24 August	500	73	53	74	73	74	63	63	74
26 August	545	94	62	94	95	94	79	78	95
28 August	588	105	67	112	114	109	91	86	113
30 August	699	176	119	226	193	201	156	148	210
17 September	810	187	125	239	212	213	169	156	226
3 October	920	200	134	259	232	230	183	167	146
		Run-off as % of rainfall							
		22	15	28	25	25	20	18	27

3.4. Surface run-off

The 1996 rainy season was characterized by a large number of medium-intensity long-duration storms. Therefore, relatively high run-off were recorded in all treatments. Of the several run-off events recorded during the season, four run-off events that occurred in the month of August accounted for a major portion of seasonal run-off (Table 2). On average, total run-off from the medium-deep soil was 27% of seasonal rainfall; whereas on shallow soil it was 18% of seasonal rainfall. Average run-off for the flat landform treatment was 25% of rainfall and from BBF it was 20% of rainfall. Although more run-off was observed on the medium-deep soil than on the shallow soil, the differences in run-off between flat and BBF were more for shallow soil (22% in flat and 15% in BBF of seasonal rainfall) than for the medium-deep soil (28% in flat and 25% in BBF of seasonal rainfall). These results show that BBF landform helps in decreasing run-off and increasing infiltration on Vertic Inceptisols. However, the effect of the BBF landform was more dominant for the shallow soil than for the medium-deep soil. This might be caused by a higher infiltration capacity of shallow soil than that of medium-deep soil. Pathak et al. (1985) and Srivastava and Jangwad, (1988) have shown that run-off and soil loss were remarkably small in the BBF landform treatment, compared to the flat landform treatment in a long term Vertisol watershed study.

3.5. Simulated components of water balance

In 1996, rainfall received from sowing to harvest of the soybean crop was 920 mm. Mean simulated run-off for the medium-deep soil (251 mm) was more than that for the shallow soil (175 mm) (Table 3). Similarly the simulated run-off for the flat landform (239 mm) was more than for BBF (187 mm). Simulated run-off for all treatments was very similar to the total measured run-off at the end of season (Tables 2 and 3). On the shallow soil, total run-off was 23% of seasonal rainfall for the flat landform and 15% of seasonal rainfall for the BBF landform treatments. Similarly, on the medium-deep soil, total run-off was 30% of seasonal rainfall on the flat landform and 25% on the BBF landform. Deep drainage was greater in the shallow soil (29% of seasonal rainfall for the flat landform and 36% of seasonal rainfall for the BBF landform) than in the medium–deep soil (19% in flat and 18% in BBF). Thus total water loss as run–off plus deep drainage amounted to 51–52% for the shallow soil and 43–48% for the medium-deep soil. As soil water availability during the 1996–1997 season was not limiting for crop growth, the total water use (evapotranspiration) by soybean across treatments was the same and accounted for 39% of rainfall. Soil profiles were near field capacity at the time of soybean harvest. Substantial losses of rainfall as deep drainage and run-off on both soil types have implications for conjunctive use of water for improving resource-use efficiency and

Table 3
Effect of treatments on water balance components (mm) of soybean–chickpea rotation at ICRISAT Center, Patancheru 1996–1997[a] (all components were simulated unless specified (see footnote))

Water balance component	Treatments				Means			
	Flat shallow	BBF shallow	Flat medium-deep	BBF medium-deep	Flat	BBF	Shallow	Medium-deep
Soybean (rainy season)								
Run-off (R)	207 (23)[b]	142 (15)	272 (30)	231 (25)	239 (26)	187 (20)	175 (19)	251 (27)
Deep drainage (D)	271 (29)	327 (36)	172 (19)	165 (18)	221 (24)	246 (27)	299 (32)	168 (18)
Soil evaporation (Es)	167 (18)	171 (19)	165 (18)	170 (18)	166 (18)	170 (18)	169 (18)	187 (18)
Transpiration (Ep)	192 (21)	187 (20)	195 (21)	188 (20)	193 (21)	188 (20)	190 (21)	192 (21)
Change in soil water content	+84 (9)	+93 (10)	+118 (13)	+166 (18)	+101 (11)	+130 (14)	+88 (10)	+142 (15)
Water loss (R+D)	478 (52)	469 (51)	443 (48)	396 (43)	460 (50)	433 (47)	473 (51)	420 (46)
Water use (Es+Ep)	359 (39)	358 (39)	359 (39)	358 (39)	359 (39)	358 (39)	358 (39)	359 (39)
Chickpea (post-rainy season)								
Soil evaporation (Es)	72	72	77	75	75	74	72	76
Change in soil water content[c]	−91	−85	−151	−148	−121	117	88	150
Water use (Es+Ep)[c]	144	138	204	201	174	170	141	203
Transpiration[d]	72	66	127	126	100	96	69	127

[a] Total rainfall was 920 mm during rainy season and 53 mm during post-rainy season.
[b] Numbers in parentheses are the water balance components as percentage of seasonal rainfall.
[c] Observed data.
[d] Observed water use minus simulated soil evaporation.

sustainable crop production. We need to manage both deep drainage and surface run-off water to conserve soil, enhance water and nutrient-use efficiency and so to increase crop productivity on Vertic Inceptisols.

During the 1996–1997 post-rainy season rainfall was 53 mm. There was practically no run-off or deep drainage during this cropping season. Chickpea grew on residual stored soil water to meet its demand for transpiration. Total water use by chickpea was higher on the medium-deep soil (201–204 mm) than on the shallow soil (138–144 mm) (Table 3). Soil evaporation formed a significant proportion of total water loss, ranging from 72 to 77 mm across treatments. These results indicated that crop yields during the post-rainy season could be increased by decreasing soil evaporation and by increasing soil water extraction to the maximum possible extent. Total water use during the 1996–1997 season by soybean–chickpea rotation was 52% of rainfall for the shallow soil and 58% for the medium-deep soil. The remaining rainfall was lost either as surface run-off or deep drainage.

3.6. Crop yields

During the 1995–1996 season, the soil depth had a significant effect on seed yield of soybean. Yield was significantly higher on the medium-deep ($1760\ kg\ ha^{-1}$) than on the shallow soil ($1550\ kg\ ha^{-1}$) (Table 4). Seed yield was also greater on the flat ($1880\ kg\ ha^{-1}$) than on BBF landform ($1650\ kg\ ha^{-1}$) for the medium-deep soil, but these differences were not significant for the shallow soil. Response of total dry matter to soil depth and landform treatments was the same as for seed yield. Total dry matter and seed yields of chickpea and soybean+chickpea were greater on medium-deep soil than on shallow soil. Landform did not affect total dry matter (TDM) and seed yields of chickpea for either soil depth. However, the system productivity for TDM and seed yield, i.e., the sum of soybean and chickpea yield, was greater on flat landform than on BBF on the medium-deep soil.

During the 1996–1997 season, soil depth did not affect TDM and seed yields of soybean (Table 4). Seed yield of soybean was significantly higher ($P < 0.01$) on the flat landform ($2360\ kg\ ha^{-1}$) than on BBF ($2080\ kg\ ha^{-1}$) for the medium-deep soil. However, these differences were not significant for the shallow soil. The landform treatments did not affect TDM production on any soil type. Similarly, both TDM and seed yields of chickpea were not affected by landform treatments on either soil type. Seed yield of chickpea

Table 4
Total dry matter and seed yields of soybean and chickpea and the system (soybean + chickpea) total productivity during the 1995–1996 and 1996–1997 seasons

Treatment	Seed yield (kg ha^{-1})			Total dry matter (kg ha^{-1})		
	Soybean	Chickpea	Soybean + Chickpea	Soybean	Chickpea	Soybean + Chickpea
1995–96 Season						
Flat medium-deep	1880	580	2460	4600	1180	5780
BBF medium-deep	1650	540	2190	4190	1090	5280
SE	54.6	24.0	54.7	156.3	42.0	154.6
Mean	1760	560	2320	4400	1130	5530
Flat shallow	1530	360	1890	3970	810	4780
BBF shallow	1570	390	1960	3700	900	4600
SE	54.6	46.5	115.6	156.3	93.6	292.6
Mean	1550	380	1930	3840	860	4700
SE for comparing soil depths	32.7			96.0		
1996–97 Season						
Flat medium-deep	2360	1380	3740	4460	2310	6770
BBF medium-deep	2080	1500	3580	4320	2560	6880
SE	73.1	133.4	148.3	154.9	198.9	846.4
Mean	2220	1440	3660	4390	2440	6830
Flat shallow	2260	1020	3280	4210	1820	6030
BBF shallow	2300	990	3290	4570	1840	6410
SE	73.1	133.4	148.3	154.9	189.9	846.4
Mean	2280	1010	3290	4390	1830	6220

was significantly higher ($P < 0.01$) on the medium-deep soil (1440 kg ha^{-1}) than on shallow soil (1010 kg ha^{-1}). Similarly, TDM yield of chickpea was greater on the medium-deep soil (2440 kg ha^{-1}) than on the shallow soil (1830 kg ha^{-1}). Total system productivity for seed yield (sum of soybean and chickpea seed yields) was significantly higher ($P < 0.05$) on the medium-deep soil (3660 kg ha^{-1}) than on the shallow soil (3290 kg ha^{-1}). Similar differences were observed for TDM production of the entire cropping system. The landform treatments did not impact the total system productivity on any soil type.

Relating crop production and transpiration to climate, Monteith (1988) proposed two types of crop growing environments: (i). a light-limited environment, where crop roots have access to abundant supplies of water and hence transpiration proceeds at maximum rate as determined by solar radiation, and (ii). a water-limiting environment where uptake of water by crops depends on size of its root system and the state of water in the surrounding soil. Analyzing monthly values of rainfall and radiation for Hyderabad, Monteith (1988) concluded that during July–September, when most of the rainfall occurs, radiation is the factor limiting crop growth throughout the monsoon period. In most of the years from 1981 through 1987 when rainfall was normal, the total biomass production of sorghum was limited by the amount of light intercepted by the crop canopy. The results of our study with respect to the yields of soybean during the rainy season, also showed that light interception was the main cause for the differences between the landform treatments, especially on the medium-deep soil. Therefore, while the BBF system is a good landform practice for improving surface drainage during high rainfall years and water conservation during low to medium rainfall years, there is a need to improve light use by crops during the rainy season. This could be achieved by adjusting plant populations on the BBF system or by reducing land area under furrows to reduce the loss of light. However, during the post-rainy season, soil water availability was the major factor determining yield of chickpea on the Vertic Inceptisol.

4. Summary and conclusions

The results of the field experiments conducted on the Vertic Inceptisol showed that soybean grown during the rainy seasons on flat landform had more LAI and greater light interception by the crop than that on the BBF landform. These differences in LAI and light interception were statistically significant for the medium-deep soil, but not for the shallow soil. Greater light interception by plants grown on the flat landform resulted in higher soybean yields than the BBF landform for the medium-deep soil, but not for the shallow soil. Chickpea yields were not influenced by landform treatments, but were significantly higher on the medium-deep soil because of more soil water availability than on the shallow soil. A significant proportion of rainfall, i.e., 40–50%, was lost either as surface run-off or deep drainage. The BBF landform decreased run-off, increased infiltration of rainfall into the soil profile, and increased deep drainage for both soil types. Increased infiltration of water in BBF landform often increased soil water content of the medium-deep soil by 10–30 mm, but not for the shallow soil. It is inferred from these results that while the BBF system reduces run-off and increases infiltration, there is a need to maximize light interception and light use by crops grown on the BBF system. Water lost as surface run-off and deep drainage should be conserved and used as supplemental irrigation. This will increase crop productivity as well as resource-use efficiency on Vertic Inceptisols.

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