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# Soil management and production of Alfisols in the semi-arid tropics. III.* Long-term effects on water conservation and production

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*Abstract*

A calibrated cropping systems model was used to provide long-term biophysical responses of various land managements at two differing semi-arid tropic environments in India. Organic based practices such as farmyard manure or straw amendments and perennial pastures reduced runoff by between 50 and 87%, and are optimum for *in situ* water and soil conservation. A consequence of the reduced runoff was an increase in drainage below the root zone. Furthermore, the detrimental effects of cropping on high slopes and long slope lengths showed that it is not feasible to crop on slopes greater than 5%. Our study did not incorporate farmer preferences for land management, but the results can still be used as an integral part of decision making for optimum land management.

*Keywords:* simulation, runoff erosion.

## Introduction

Soil management can be used to reduce soil erosion and improve crop water supply. However, options that control runoff and reduce soil erosion may also have detrimental effects on an agricultural system. For example, a consequence of higher productivity from improved infiltration and increased soil water may be higher leaching of solutes. Hence, impacts of soil management on the various components of an agricultural system are studied to provide an understanding of the impact of soil management on soil processes. Studies of short duration provide valuable information on these processes but they are often limited by the short climatic period over which the work was conducted and cannot explain the long-term impacts of various soil management options. Simulation modelling is a valuable tool that can extrapolate short-term results to give insight into the impacts of soil management options over the long-term. Probabilistic outputs of

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environmental and production factors can be produced to assist land managers to make decisions on optimum soil management options in their environment.

Large areas of the Alfisols in the semi-arid tropics (SAT) of India are either suffering from land degradation or are subject to degradation through agricultural activities. Smith *et al.* (1992) outlined a project designed to study soil management options to reduce the rate of land degradation on Alfisols and ameliorate degraded soils. In Part I of this series, Littleboy *et al.* (1996*a*) calibrated and validated the cropping systems simulation model PERFECT (Productivity, Erosion, and Runoff, Functions to Evaluate Conservation Techniques). The aim of this paper is to apply PERFECT to identify optimum soil management practices for water conservation, resource protection and productivity for the SAT Alfisols of India.

## Materials and methods

The cropping systems model, PERFECT, was validated using experimental data collected on an Alfisol at ICRISAT in the semi-arid tropics of India. A description of the validation occurs in previous papers (Littleboy *et al.* 1996*a*, 1996*b*). Experimental data were derived from 15 treatments which included a tillage by amendment factorial and perennial pasture treatments. The tillages were zero tillage, shallow tillage to 10 cm, and deep tillage to 20 cm, while the amendments were bare, 15 t/ha farmyard manure (FYM) and 5 t/ha rice straw. The remaining six treatments were perennial grain and pasture species including pigeon pea (*Cajanus cajan*), Cenchrus (*Cenchrus ciliaris*) and Stylosanthes (*Stylosanthes hamata*), either alone or in mixtures. Pigeon pea is a shrubby food legume that grows between 1 and 2 m in height and has a stem thickness of approximately 3–4 cm. Cenchrus is clumpy pasture grass and Stylosanthes is a densely growing pasture legume. A full description of the experimental design is given by Smith *et al.* (1992).

A validated model provides confidence to extrapolate the results of the short-term experiment to long-term trends. Long-term climatic data for Hyderabad (91 years) (18° N, 78° E; 764 mm rainfall) and Anantapur (25 years) (15° N, 77° E, 562 mm rainfall), collated by the meteorological laboratory of ICRISAT, were used for the long-term runs. Hyderabad is regarded as a relatively good SAT environment, while Anantapur is considered a drought prone area.

The effects of a range of other environmental variables, namely slope (2, 5, 10, and 15%), slope length (50 and 150 m) and soil depth (40, 80, and 120 cm) were also considered. PERFECT uses slope and slope length in its erosion algorithms, while soil depth affects the water balance and interactions between the water balance and crop growth. All 15 treatments, two environments, four slopes, two slope lengths and three soil depths were simulated.

Finally, to study the effects of crop/pasture rotations on the system, five varying crop/pasture proportions were simulated. The proportions of Stylosanthes/zero till bare sorghum were 0%/100%, 20%/80%, 40%/60%, 60%/40%, 80%/20% and 100%/0%. These rotations were based on a 5 year cycle, for example, 20%/80% meaning that in every 5 years there was 1 year of Stylosanthes and 4 years of zero tillage bare sorghum. Simulations were undertaken for these crop/pasture rotations for the 80 cm soil depth, 50 m slope length and 80 cm soil depth.

## Results

### *Rainfall*

Average monthly rainfall distributions for the historical rainfall records at Hyderabad and Anantapur are given in Fig. 1. At Hyderabad, 86% of the average annual rainfall of 764 mm falls between June and October, with most occurring in July, August and September. Average annual rainfall at Anantapur is 564 mm and falls mostly between July and October (71%), with the highest average monthly rainfall occurring in September.

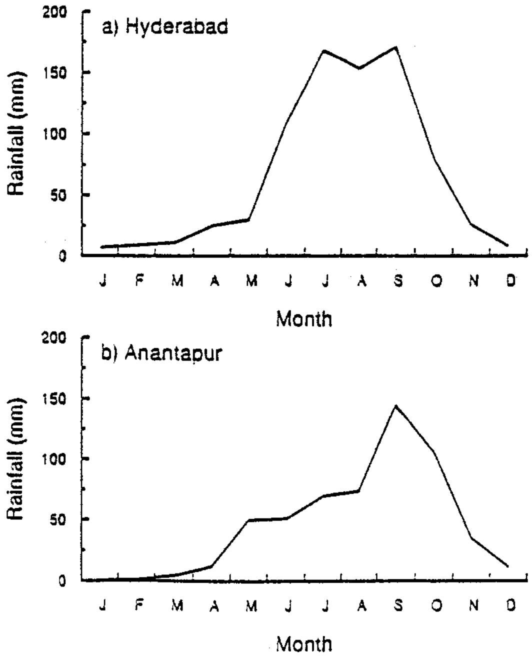


**Fig. 1.** Average monthly rainfall at (*a*) Hyderabad and (*b*) Anantapur.

*Effects of tillage on runoff, drainage, soil loss and yield (Hyderabad and Anantapur)*

*Runoff*

In comparison to zero tillage, median annual runoff at Hyderabad was reduced by 5% with shallow tillage and by 14% with deep tillage (Table 1; zero tillage, bare soil; shallow tillage, bare soil; deep tillage bare soil). At the drier site of Anantapur, the reduction in median annual runoff was larger with 10 and 24% less runoff from shallow and deep tillage treatments respectively.

Shallow and deep tillage in June reduced average monthly runoff at Hyderabad for June and July (Fig. 2). Thereafter, shallow tillage has little effect on runoff, however, deep tillage continues to reduce average runoff for a further one month. At Anantapur, the benefit of tillage, in reducing average monthly runoff, lasts longer due to lower rainfall at this site.

*Drainage*

Median annual drainage increased with deep tillage at Hyderabad, compared with zero tillage and shallow tillage (Table 1), but there was no difference at Anantapur. Highest monthly drainage (data not shown) occurred during August at Hyderabad and during September at Anantapur for all tillage treatments. Drainage at Anantapur was much lower than at Hyderabad (Table 1).

*Soil loss*

Distributions of average monthly soil erosion at Hyderabad showed two peaks (Fig. 3*a*). The largest average monthly soil erosion occurred in September and was similar for all tillages (2·3–2·5 t/ha). In June, however, erosion was highest for zero tillage and least following deep tillage. Erosion at Anantapur was highest for zero tillage in July (Fig. 3*b*). Erosion was also high in May and in September/October, but generally, average monthly erosion rates at this site were lower.

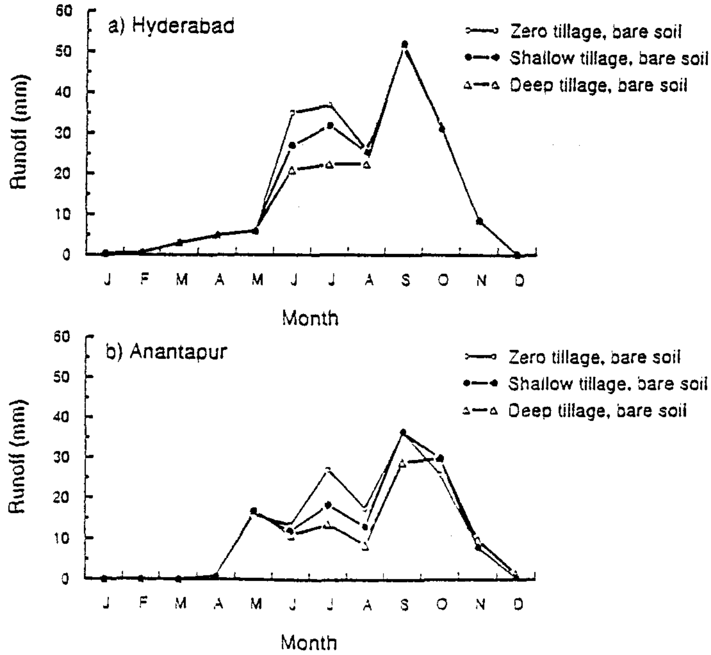


**Fig. 2.** Predicted average monthly runoff for zero, shallow and deep tillage at a 2% slope, 50 m slope length and 80 cm soil depth for (*a*) Hyderabad and (*b*) Anantapur.

Soil erosion at Hyderabad and Anantapur was increased by both increased slope and slope length (Tables 2 and 3). Average annual soil erosion of up to 7 t/ha was predicted for the 2% slope, ranging up to 243 t/ha for a 15% slope at Hyderabad (Table 2). The range at Anantapur was from 3 to 155 t/ha. An increase in slope length from 50 to 150 m doubled erosion regardless of slope (Table 3).

*Yield*

Median sorghum yield (Table 1) at Hyderabad was increased only marginally by tillage and this was due to improved yields at lower probability levels between 0 and 50% (data not shown). Yields at Anantapur were variable and ranged between 4529 and 4936 kg/ha (Table 1).

*Effects of amendment on runoff, drainage, soil Loss and yield (Hyderabad and Anantapur)*

*Runoff*

Median annual runoff was substantially reduced by either straw- or FYM-amendment at both locations. Median annual runoff was 184, 85, and 37 mm for zero tillage bare, FYM- and straw-amended soils, and 136, 75 and 28 mm at Anantapur, respectively (Table 1). The reduction in runoff due to application of organic amendments occurred in each month from June to November (Fig. 4).

**Table 1. Water balance and yield (kg/ha, median) for 21 soil managements on a 2% slope, 80 cm soil depth and 50 m slope length at Hyderabad (median rain 759 mm) and Anantapur (median rain 577 mm)**

RO, runoff (mm); DR, drainage below root zone (mm); ET, evapotranspiration (mm)

| Soil treatment | Hyderabad | | | | Anantapur | | | |
|---|---|---|---|---|---|---|---|---|
| | RO | DR | ET | Yield | RO | DR | ET | Yield |
| Zero tillage, bare soil | 184 | 0 | 575 | 4714 | 136 | 0 | 441 | 4793 |
| Zero tillage + manure | 85 | 81 | 593 | 4966 | 75 | 9 | 493 | 4801 |
| Zero tillage + straw | 37 | 135 | 587 | 4966 | 28 | 52 | 497 | 4529 |
| Shallow tillage, bare soil | 175 | 0 | 584 | 4810 | 122 | 0 | 455 | 4979 |
| Shallow tillage + manure | 84 | 86 | 589 | 4966 | 75 | 3 | 499 | 4802 |
| Shallow tillage + straw | 35 | 136 | 588 | 4966 | 28 | 53 | 496 | 4529 |
| Deep tillage, bare soil | 159 | 16 | 584 | 4942 | 104 | 0 | 473 | 4936 |
| Deep tillage + manure | 78 | 95 | 586 | 4966 | 67 | 8 | 502 | 4780 |
| Deep tillage + straw | 34 | 138 | 587 | 4966 | 24 | 56 | 497 | 4575 |
| Pigeon pea | 99 | 16 | 644 | — | 89 | 0 | 488 | — |
| Pigeon pea + Stylo | 24 | 49 | 686 | — | 27 | 24 | 526 | — |
| Pigeon pea + Cenchrus+Stylo | 31 | 81 | 647 | — | 29 | 26 | 522 | — |
| Cenchrus | 70 | 15 | 674 | — | 67 | 0 | 510 | — |
| Cenchrus + Stylo | 64 | 23 | 672 | — | 70 | 3 | 504 | — |
| Stylo | 24 | 49 | 686 | — | 27 | 24 | 526 | — |
| Rotation 0/100[A] | 184 | 0 | 575 | 4714 | | | | |
| Rotation 20/80 | 150 | 0 | 609 | 4336 | | | | |
| Rotation 40/60 | 105 | 7 | 647 | 3125 | | | | |
| Rotation 60/40 | 82 | 12 | 665 | — | | | | |
| Rotation 80/20 | 48 | 32 | 679 | — | | | | |
| Rotation 100/0 | 24 | 49 | 686 | | | | | |

[A] Rotation of 0% of years Stylosanthes and 100% of years sorghum.

*Drainage*

Median annual drainage was negligible at both sites when no amendment was applied, compared with 81–138 mm at Hyderabad and 3–56 mm at Anantapur, for FYM- or straw-amended soils. Average monthly drainage was greatest with amendments of FYM and straw, and peaked in August and September in Hyderabad, and October in Anantapur.

*Soil loss*

Median annual soil erosion was reduced substantially by amendments at both sites (Tables 2 and 3). For a 2% slope and 50 m slope length, median soil erosion was less than 2 t/ha for FYM- or straw-amended soils but increased to between 29 and 61 t/ha for a slope of 15% and a slope length of 150 m.

*Yield*

There was no difference in crop yields for FYM- and straw-amended soils. Cumulative probabilities for a shallow soil (40 cm) ± straw amendment, and

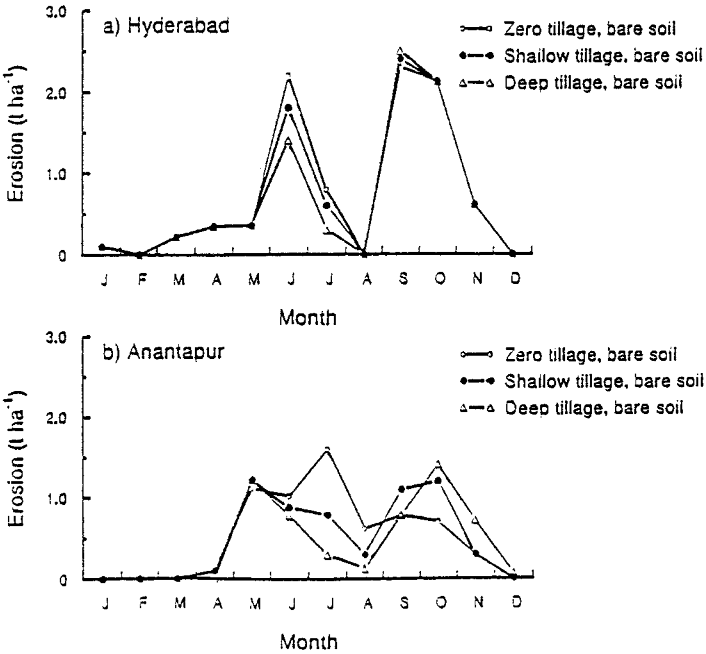


**Fig. 3.** Predicted average monthly erosion for zero, shallow and deep tillage at a 2% slope, 50 m slope length and 80 cm soil depth for (*a*) Hyderabad and (*b*) Anantapur.

**Table 2. Median soil erosion (t/ha) for 21 soil management treatments on various slopes (2, 5, 10, 15%) and slope lengths (50, 150 m) at a 80 cm soil depth at Hyderabad**

| Soil treatment Slope: | 2% | | 5% | | 10% | | 15% | |
|---|---|---|---|---|---|---|---|---|
| Length: | 50 | 150 | 50 | 150 | 50 | 150 | 50 | 150 m |
| Zero tillage, bare soil | 8 | 11 | 24 | 41 | 66 | 125 | 126 | 243 |
| Zero tillage + manure | 2 | 2 | 6 | 10 | 16 | 31 | 31 | 61 |
| Zero tillage + straw | 0 | 0 | 2 | 3 | 5 | 10 | 10 | 20 |
| Shallow tillage, bare soil | 7 | 11 | 23 | 40 | 63 | 120 | 121 | 234 |
| Shallow tillage + manure | 2 | 2 | 5 | 10 | 16 | 30 | 30 | 59 |
| Shallow tillage + straw | 0 | 0 | 2 | 3 | 5 | 10 | 10 | 20 |
| Deep tillage, bare soil | 7 | 9 | 20 | 36 | 57 | 109 | 108 | 210 |
| Deep tillage + manure | 1 | 2 | 5 | 9 | 15 | 30 | 29 | 57 |
| Deep tillage + straw | 0 | 0 | 2 | 3 | 5 | 10 | 10 | 20 |
| Pigeon pea | 0 | 0 | 2 | 2 | 3 | 6 | 6 | 12 |
| Pigeon pea + Stylo | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pigeon pea + Cenchrus + Stylo | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cenchrus | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 |
| Cenchrus + Stylo | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Stylo | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rotation 0/100[A] | 6 | | | | | | | |
| Rotation 20/80 | 4 | | | | | | | |
| Rotation 40/60 | 2 | | | | | | | |
| Rotation 60/40 | 1 | | | | | | | |
| Rotation 80/20 | 0 | | | | | | | |
| Rotation 100/0 | 0 | | | | | | | |

[A] Rotation of 0% of years Stylosanthes and 100% of years sorghum.

medium (80 cm) and deep (120 cm) soils without straw are shown in Fig. 5. The application of straw to the shallow soil improved the yield probability by approximately 50% of the difference between shallow and medium soils without straw.

**Table 3. Median soil erosion (t/ha) for 21 soil management treatments on various slopes (2, 5, 10, 15%) and slope lengths (50, 150 m) at a 80 cm soil depth at Anantapur**

| Soil treatment Slope: | 2% | | 5% | | 10% | | 15% | |
|---|---|---|---|---|---|---|---|---|
| Length: | 50 | 150 | 50 | 150 | 50 | 150 | 50 | 150 m |
| Zero tillage, bare soil | 5 | 7 | 15 | 26 | 42 | 79 | 80 | 155 |
| Zero tillage + manure | 2 | 2 | 6 | 10 | 16 | 31 | 31 | 60 |
| Zero tillage + straw | 1 | 1 | 2 | 5 | 8 | 15 | 15 | 29 |
| Shallow tillage, bare soil | 4 | 6 | 12 | 22 | 35 | 66 | 67 | 129 |
| Shallow tillage + manure | 2 | 2 | 5 | 10 | 16 | 31 | 31 | 60 |
| Shallow tillage + straw | 1 | 1 | 2 | 5 | 8 | 15 | 15 | 29 |
| Deep tillage, bare soil | 3 | 5 | 10 | 18 | 29 | 55 | 56 | 108 |
| Deep tillage + manure | 1 | 2 | 5 | 9 | 14 | 28 | 28 | 54 |
| Deep tillage + straw | 1 | 1 | 2 | 5 | 8 | 15 | 15 | 29 |
| Pigeon pea | 0 | 0 | 1 | 1 | 3 | 5 | 5 | 11 |
| Pigeon pea + Stylo | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pigeon pea + Cenchrus + Stylo | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cenchrus | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 |
| Cenchrus + Stylo | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Stylo | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rotation 0/100[A] | 6 | | | | | | | |
| Rotation 20/80 | 4 | | | | | | | |
| Rotation 40/60 | 2 | | | | | | | |
| Rotation 60/40 | 1 | | | | | | | |
| Rotation 80/20 | 0 | | | | | | | |
| Rotation 100/0 | 0 | | | | | | | |

[A] Rotation of 0% of years Stylosanthes and 100% of years sorghum.

*Effects of perennials on runoff and drainage*

Median annual runoff for pigeon pea was intermediate between bare and FYM amended soils at both sites (Table 1), while runoff from Stylosanthes was similar to straw amended sorghum. At Hyderabad, average monthly runoff from pigeon pea was only slightly lower than from sorghum grown with shallow tillage; while average monthly runoff from Stylosanthes was substantially lower (Fig. 6). A similar result occurred at Anantapur (data not shown).

Average monthly drainage (Fig. 7) was greatest for perennials with Stylosanthes as a component. However, the reduction in runoff from Stylosanthes was not equivalent to the increase in predicted drainage. These differences were due to higher evapotranspiration from the Stylosanthes treatments as shown in Table 1. This trend was evident at both Hyderabad and Anantapur.

*Effects of crop/pasture rotations on runoff and drainage*

Increased proportions of Stylosanthes pasture in the crop/pasture rotation reduced runoff, increased drainage (Table 1) and reduced soil erosion (Tables 2 and 3). Median annual runoff from a rotation of 60% Stylosanthes and 40% zero tillage bare sorghum was similar to FYM amended sorghum but less soil erosion occurred. The decrease in runoff was translated into increased transpiration as well as increased drainage. A comparison of the water balance partitioning for shallow tillage bare, shallow tillage FYM and a rotation of 40% sorghum/60% Stylosanthes is shown in Fig. 8.

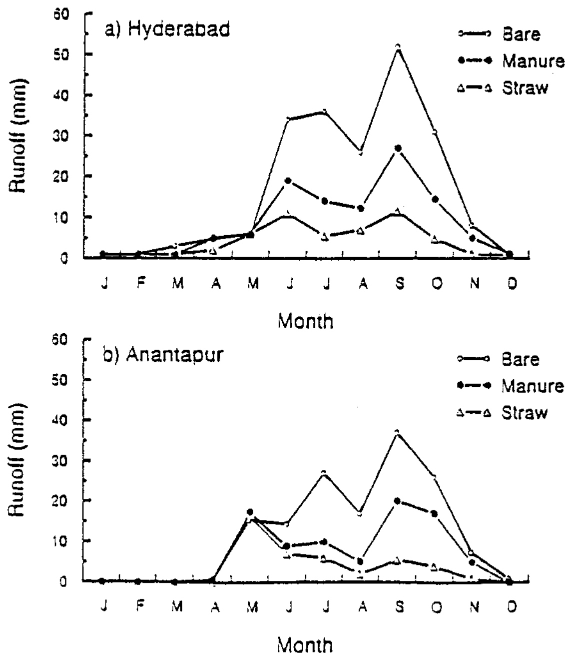


**Fig. 4.** Predicted average monthly runoff for bare, manure- and straw-amended soils under zero tillage at a 2% slope, 50 m slope length and 80 cm soil depth for (*a*) Hyderabad and (*b*) Anantapur.

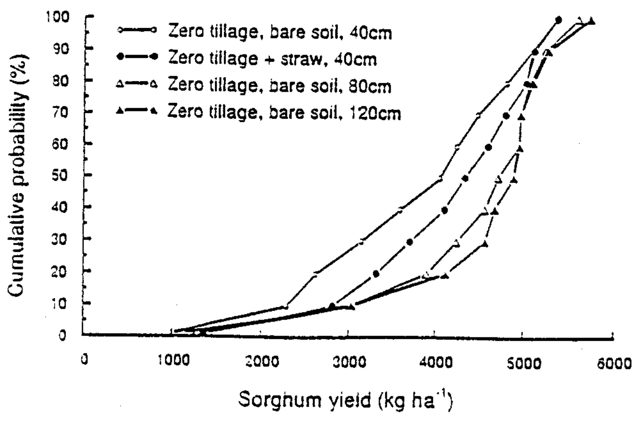


**Fig. 5.** Cumulative probability for sorghum yield for zero tillage bare at three soil depths (40, 80, 120 cm) and zero tillage straw at 40 cm on a 2% slope and 50 m slope length.

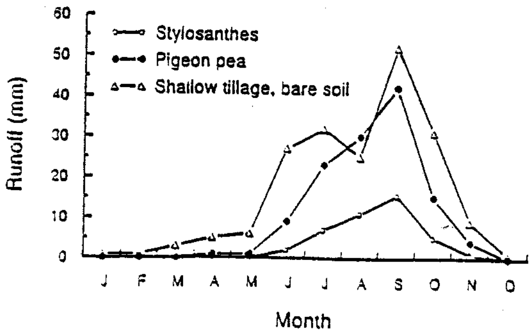


**Fig. 6.** Average monthly runoff from Stylosanthes, pigeon pea and shallow tillage bare on a 2% slope, 50 m slope length and 80 cm soil depth.

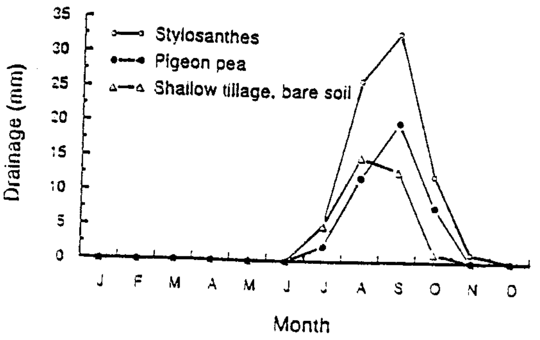


**Fig. 7.** Average monthly drainage from Stylosanthes, pigeon pea and shallow tillage bare on a 2% slope, 50 m slope length and 80 cm soil depth.

*Effects of soil depth on runoff, drainage and crop yield*

Soil depth had no or little effect on runoff for all soil managements (tillage, amendment or perennials). However, drainage under tillage (zero, 10 cm and 20 cm) was determined, to a large extent, by soil depth. Drainage in 80 cm deep soils was slightly higher than in 120 cm soils, while drainage in 40 cm deep soils was generally more than twice that in 120 cm soils (data not shown). Conversely, there was no soil depth effect on drainage when soils were amended with FYM or straw.

Yields in 80 and 120 cm deep soils were generally similar, but yields from 40 cm deep soils were substantially lower than the 80 and 120 cm deep soils.

## Discussion

*Water conservation*

The water conservation benefit of organic- and tillage based soil management options varies both within and between seasons. Organic amendments were shown to control runoff throughout the season at both Hyderabad and Anantapur, however, tillage was of short-term value (1–3 months) at both locations. Tillage was more beneficial at Anantapur with its lower monthly rainfall. It is clear that, in annually cropped soils, amendments are more useful than tillage, at the start of the growing season, in substantially reducing runoff volumes.

Perennial systems, for example Stylosanthes, resulted in the largest reductions of runoff due to a dense cover close to the ground (Yule *et al.* 1995). This benefit would occur throughout the season if grazing is well managed. Furthermore, Stylosanthes germination is normally speedy from hard seed carried over from the previous year, and cover develops quickly during the wet season. Pigeon pea, a major food legume in India, provides cover at a 1–3 m height, hence runoff protection is less than for Stylosanthes. Indeed, that runoff is greater than for FYM-amended soils suggests the importance of contact cover.

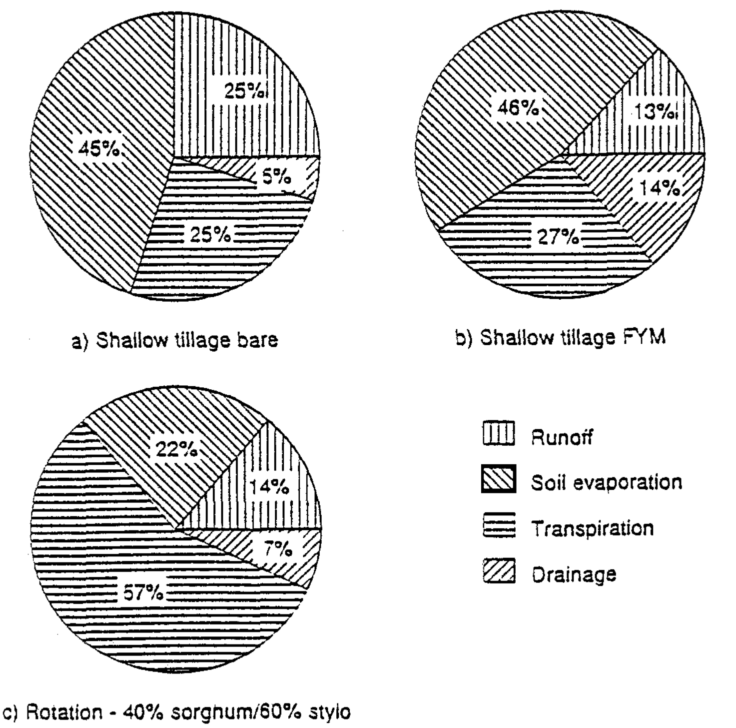


**Fig. 8.** Water balance under three soil managements (shallow tillage bare, shallow tillage plus manure and a rotation of 40% Stylosanthes and 60% shallow tillage sorghum) at a 2% slope, 50 m slope length and 80 cm soil depth.

In agricultural systems with livestock, there is enormous potential to control runoff by having well managed pastures, such as Stylosanthes. This could be as an intercrop with pigeon pea or annual cereal crops. Rotations of varying crop/pasture percentages are another option for reducing runoff and will be discussed later.

Water conserved by controlling runoff can be partitioned in the water balance to either drainage or evapotranspiration. Our results show that the increase in infiltration was generally partitioned into drainage for annual cropped systems. There are a number of potential benefits and possible deficiencies of increasing drainage. Water lost as drainage can recharge the ground-water aquifer and be utilized for both human as well as agricultural uses. This is a major potential benefit of management practices that reduce runoff. However, drainage can remove valuable nutrients from the topsoil, that could reduce crop yields and cause detrimental off-site effects. Consequently, fertilizer practices will need to be modified if soil management options that reduce runoff are implemented. There is a need for good nutrient movement models to explain these possibilities.

Reduction in runoff from pasture and crop/pasture rotation systems was not all partitioned to drainage; a proportion became transpiration. This finding is important as it reveals that replenishment of ground water will not be as great in pasture-based systems as may initially be assumed. It further suggests that, where groundwater is important, model output may be required by land managers to choose appropriate land management practices.

In our simulations with PERFECT, tillage takes place only once, prior to planting. It is assumed that weed control occurs without soil disturbance and benefits in runoff control due to inter-row tillage do not occur. In farming systems in India, inter-row tillage would be expected to reduce runoff more than shown in our results. This suggests that the impact of tillage may be greater than shown in our paper. However, the effects of amendment on runoff should be greater than tillage effects, even in a multiple tillage system.

It is well known that there are competing uses for both FYM and straw in Indian agriculture (Cogle and Rao 1993). As crop cover develops, the need for plant residue cover diminishes. There is potential for removal of some residues as the season progresses. This option would obviously be season dependent and also rely on the availability of farm labour and prevailing prices for residues.

Reduced runoff lessens crop production risks by improving yields at lower levels of probability (Fig. 5); this is reflected in the improved average sorghum yield for both increased tillage depth (6% improvement) and FYM and straw amendment (8% improvement). Straw amendments also reduced the level of yield loss in shallow soils, improving yields in 40 cm deep soils by over 40% of the yield difference between 80 and 40 cm deep soils (Fig. 5). Percentage gains for amending shallow soils are slightly higher than for amending deep soils and this suggests that a management option, when organic materials are in short supply, could be to apply residues to the shallow soils.

*Resource protection*

One objective of good soil management is to reduce soil erosion. Slope and slope length were shown to be major factors for the estimation of erosion in our simulations, as was the effect of management practice. Our results suggest that it is not feasible to commence or continue non-terraced annual cropping on slopes of greater than 5% in the SAT, regardless of the management practice, given the enormous soil loss that was predicted. Pasture systems need to be established on these areas and perhaps cut and carry pasture management or strip grazing would be the appropriate management of such pastures. Furthermore, the simulations presented in Tables 2 and 3 are for 80 cm deep soil; the productivity impact of soil erosion on shallower soils would be greater and more immediate.

Off-site effects of soil erosion are difficult to quantify. On the Vertisols in India, sediment is often trapped and crops are then grown in the trapped soil, for example gully plugs (Kerr and Sanghi 1992). The result is basically a transfer of arable soil from one part of the landscape to another. This may cause ownership problems of the transported soil and hence the crop produce; however, Kerr and Sanghi (1992) found it is often an intentional farmer practice to concentrate soil at an appropriate location. The initial aim of preventing soil erosion discussed above, therefore, becomes more complicated.

Increasing population pressure will lead to attempts to cultivate marginal lands, which include shallower soils and steeper land. The results of our analysis clearly show that every effort should be made to restrict cropping to land classes that are able to cope with annual cultivation, that certain practices are more favourable to soil conservation than others and that pastoral activities are preferable on steep slopes. Equally, if a catchment plan exists to selectively erode parts of the catchment for the benefit of concentrating soil in other parts, then soil management to cause soil erosion for this purpose has been identified. One important question that arises from this later form of management is 'what finally happens to the eroded areas?'

*Soil management options*

A balance between water conservation for crop production, ground-water replenishment and protection of the land resource is difficult for poor farmers who depend on infertile soils. We have outlined how soil management can achieve both improved yields and resource protection, particularly if ground water is a major resource. However, these options may not necessarily fit with current practices used by Indian farmers. Prior to widescale extension of scientifically valid land management practices, surveys of farmer practices, such as those discussed by Kerr and Sanghi (1992), must be conducted to ensure that new practices are amenable to farmer uptake.

In addition, the availability and cost of inputs for new land management practices needs to be balanced against the short- and long-term benefits to production and resource protection. Cogle and Rao (1993) discussed a modelling approach incorporating costs and returns for straw from fodder or improved crop production. They showed that retention of 3 t/ha of straw was possible given measured yield improvements and historical pricing. A more in depth analysis of the potential costs and returns of FYM-, straw- and rotation-based systems is, however, warranted, before clear guidelines on appropriate soil management options can be given.

## Conclusions

Long-term biophysical responses of various soil managements at two differing SAT environments have been described. Organic based practices such as FYM- and straw-amendment and perennial pastures are shown to be optimum for *in situ* water and soil conservation. Furthermore, the detrimental effects of cropping on high slopes and long slope lengths were shown. Our study did not incorporate farmer preferences for soil management, but our modelling techniques and results can be used as an integral part of decision making for optimum soil management. These outputs can then be linked to an economic costs and benefits analysis.

Further work on erosion/productivity relationships needs to be conducted and some of this work is presented in Part IV of this series.

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