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Soil management and production of Alfisols in the semi-arid tropics. IV* Simulation of decline in productivity caused by soil erosion

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Abstract

Maintenance of a productive soil base by minimizing soil erosion is vital to long-term crop production. In this study, a modelling approach is used to estimate the effects of soil erosion on productivity for a sorghum cropping system on an Alfisol in the semi-arid tropics of India. Predictions of erosion, runoff and yield decline due to erosion, for variations in initial soil depth, slope, tillage strategy and amendment treatment, are presented.

On average, soil depth decreased by 0·91 cm/year at Hyderabad for a 10% slope, 80 cm initial soil depth, shallow tillage at planting and no surface amendment. Rates of soil removal and subsequent yield decline were higher for shallower soils, steeper slopes and if management practices provided less surface cover during the crop. The productive life of the soil was less than 91 years for some soil depths, slope and management combinations. For other combinations, significant yield decline was predicted after 91 years of cropping.

The quantification of erosion–productivity relationships allows us to identify regions with a higher risk of degradation from soil erosion and to estimate the impact of various management options on long-term sustainability. Models provide a basis to focus research and a means of assessing alternative management strategies to preserve long-term production.

Keywords: model, erosion, productivity, surface management.

Introduction

Short-term constraints to crop production include a range of environmental factors such as soil attributes, climate characteristics and on-farm management. Maintenance of a productive soil base by minimizing soil erosion is vital for the long-term support of crop production. The effects of soil erosion on productivity are well documented. Soil erosion reduces productivity by decreasing depth of soil and plant available water capacity, removing valuable nutrients, and altering soil physical properties resulting in less infiltration, poorer crop establishment and root penetration.

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Many areas of Alfisols in the semi-arid tropics (SAT) of India are currently degraded or are subject to degradation from agricultural practices (Freebairn and Turner 1991). Increasing pressure from expanding populations will result in the cultivation of marginal lands including shallow soils and steep topography. Lal (1987) observed that a slight degree of erosion may be severe for shallow soils such as Alfisols but the effects of severe erosion may be slight for a deep fertile soil. Therefore, an emphasis on quantifying the effects of cultivation on marginal lands is required so that recommendations on sustainable land uses can be made.

Soil management options to reduce runoff and erosion on an Alfisol in the SAT were described by Smith *et al.* (1992). They showed that surface protection in the form of surface amendments (straw, farmyard manure) resulted in dramatic decreases in runoff and erosion. In comparison, the effects of shallow and deep tillage on runoff were relatively minor. In Part I of this series of papers, Littleboy *et al.* (1996) validated a cropping systems model on the data set described by Smith *et al.* (1992) and showed that computer simulation can accurately predict differences in runoff and erosion resulting from a range of surface amendments and tillage treatments. In Part III of this series, Cogle *et al.* (1996) applied modelling to extrapolate short-term experimental results to long-term probabilistic estimates of runoff, drainage, erosion and sorghum yield for combinations of soil depth, slope, climate and management. Quantification of one aspect of the long-term sustainability of agriculture in more marginal land can be determined by simulating the effects of erosion on productivity.

It is difficult to quantify the relationship between erosion and productivity. Technological advances such as fertilizers, higher yielding crop varieties, herbicides, insecticides and new planting technology have disguised the cumulative effects of erosion on production. Low levels of soil loss are almost imperceptible to the casual observer (Edwards 1988) and major erosion events may be infrequent due to the sporadic nature of erosion as illustrated by Freebairn and Wockner (1986). Erosion rates less than 30 t/ha.year are difficult to recognize (Kimberlin and Moldenhauer 1977) and the National Soil Erosion–Productivity Research Planning Committee (1981) suggested that, in some cases, erosion may not be perceived as a problem on a parcel of land until the land is no longer viable for cropping.

The relationship between erosion and productivity decline can be quantified by a range of computer simulation models that operate at different levels of complexity. An example of a simpler model is the Productivity Index (PI) model developed by Pierce *et al.* (1983). This model requires inputs of annual erosion rate, plant-available water capacity, maximum root depth, bulk density and pH. Erosion is assumed to alter these properties which subsequently affects productivity. The main limitation of the PI model is that climate variability is ignored. Lal (1987) reported that trends between erosion and productivity are cumulative and strongly dependent on seasonal climatic fluctuations. This limitation can be overcome by using a dynamic computer simulation model with long-term climate data. The most reported example of such a model is the Erosion–Productivity–Impact–Calculator (EPIC) model described by Williams *et al.* (1983). This model contains water balance, soil erosion, and crop growth models that operate on a daily time-step with historical weather data. EPIC is applicable for the range of soils, environments and crops encountered in the United States (Williams *et al.* 1983).

The computer simulation model PERFECT (Littleboy *et al.* 1992) was developed and validated for cropping systems in the subtropical region of northern Australia. PERFECT simulates the daily water balance, soil erosion, crop growth and yield in an agricultural system. It contains many algorithms that are conceptually similar to EPIC. The major differences between the two models are the algorithms to estimate plant growth and yield. EPIC contains relatively simple crop growth models that require the user to define parameters that describe plant growth (e.g. rate of development of the plant and leaf area development through time). On the other hand, PERFECT contains more detailed plant growth models that estimate plant growth from weather data by using standardized sets of crop parameters. Therefore, the parameterization of the plant growth component of PERFECT is far simpler than EPIC.

PERFECT was modified and validated against experimental runoff and erosion data for an Alfisol soil in India in Part I of this study (Littleboy *et al.* 1996). It uses long-term climatic data, and model outputs reflect changes in topography, soil properties, fallow management and cropping strategy.

The objective of this study was to apply PERFECT to quantify the relationship between erosion and productivity, and to determine how this relationship varies due to depth of soil, topography, tillage strategy and amendment treatment for Alfisols in the semi-arid tropics of India.

Table 1. Average monthly rainfall, maximum and minimum temperature, evaporation and radiation for Hyderabad for the period 1901–1991

Month	Rain (mm)	Max. temp. (°C)	Min. temp. (°C)	Pan evap. (mm)	Solar rad. (MJ/m^2.day)
January	6·3	28·4	14·4	158·7	17·2
February	8·3	31·9	16·9	195·5	19·4
March	11·6	35·0	19·9	282·5	21·3
April	25·1	37·5	23·5	321·8	22·9
May	30·4	38·8	25·6	386·3	23·0
June	108·1	34·2	23·8	275·7	18·5
July	168·3	30·4	22·5	179·0	16·0
August	154·5	29·4	22·0	141·8	15·6
September	171·8	30·1	21·7	136·3	17·3
October	78·1	30·2	19·7	154·8	18·6
November	25·8	28·7	16·0	140·9	17·1
December	6·1	27·7	13·8	143·1	15·9

Methods

Climate data

All model simulations were performed for sorghum grown on an Alfisol at Hyderabad, Andhra Pradesh, India. Daily climate data for the period from 1901 to 1991 were collated by the meteorological laboratory at ICRISAT. Average monthly rainfall, pan evaporation and temperature for the long-term data at Hyderabad are presented in Table 1. The rainfall pattern at Hyderabad is dominated by monsoonal influences from June to September. Evaporation exceeds rainfall for 10 months of the year which indicates that plant growth at Hyderabad is often limited by the availability of water.

Quantifying effects of erosion

Impacts of erosion on the soil profile were simulated using PERFECT by allowing soil depth and plant-available water capacity to decline as soil was eroded. The National Soil Erosion–Productivity Research Planning Committee (1981) stated that the loss of plant available water capacity is the major consequence of erosion on productivity. There was no attempt to simulate the effects of nutrient removal on productivity and hence the simulations may provide conservative estimates of the effects of soil removal.

Yield reductions due to erosion were calculated by comparing simulations both with and without the effect of erosion. The first simulation assumed no effects of erosion on the soil profile but, in the second simulation, erosion reduced soil depth and plant available water capacity. It was assumed that the soil was completely eroded when the soil depth eroded to less than 10 cm. Differences in predicted yield between the two simulations were attributed to erosion.

Simulation analysis

Initially, a control simulation was performed for continuous sorghum cropping, assuming an initial soil depth of 80 cm, plant available water capacity of 116 mm, slope of 10%, a shallow tillage strategy and no amendments added at planting. Each factor (depth, slope, tillage and amendment) was then varied individually from the control simulation. Three initial soil depths (40, 80 and 120 cm), three slopes (5, 10 and 15%), three tillage strategies (deep tillage, shallow tillage and zero tillage) and three amendment treatments (bare, rice straw at 5 t/ha, and farmyard manure at 15 t/ha) were simulated.

In addition, the sensitivity of applying different levels of rice straw at planting was simulated using 2, 3·5 and 5 t/ha of rice straw.

Percentage reductions in yield due to erosion were plotted against time for each 91 year simulation. A 5-year moving average was used to smooth out large variations caused by annual climatic variability.

Results

Predicted average annual soil erosion for the soil depth, slope, tillage and amendment options considered in this study is presented in Table 2. An increase in slope from 5 to 15% increased erosion by over 5-fold. In contrast, soil depth had a negligible effect on erosion. Under bare conditions, changing the tillage strategy from deep tillage to zero tillage resulted in a small increase in predicted erosion. Largest differences in erosion were found for different amendment treatments. The addition of rice straw at planting resulted in an 8 fold decrease in erosion.

Table 2. Simulated average annual soil erosion (t/ha), runoff (mm) and sorghum yield (t/ha) for three slopes, three soil depths, three tillage strategies and three amendment treatments

	Slope (%)			Soil depth (cm)			Tillage[A]			Amendment[B]		
	5	10	15	40	80	120	D	S	Z	St	B	M
Erosion	26	72	138	71	72	72	67	72	76	9	72	19
Runoff	199	199	199	198	199	200	181	199	210	48	199	104
Yield	4·6	4·6	4·6	3·9	4·6	4·7	4·7	4·6	4·4	4·8	4·6	4·8

[A] D, deep; S, shallow, Z, zero.
[B] St, straw; B, bare; M, manure.

A summary of predicted annual runoff for the soil depth, slope, tillage strategy and amendment options considered in this study is also presented in Table 2. The only major differences in runoff were evident for the amendment treatments with the addition of rice straw, resulting in a 4 fold decrease in runoff.

Average annual sorghum yield under control conditions (10% slope, 80 cm initial soil depth, shallow tillage and no amendment) was 4·6 t/ha. A reduction in soil depth to 40 cm decreased average annual yield by 0·7 t/ha. Deep tillage operations produced a slight increase in yield while zero tillage resulted in a small decrease in yield. The addition of amendments, either straw or manure, resulted in a 0·2 t/ha increase in average annual sorghum yield.

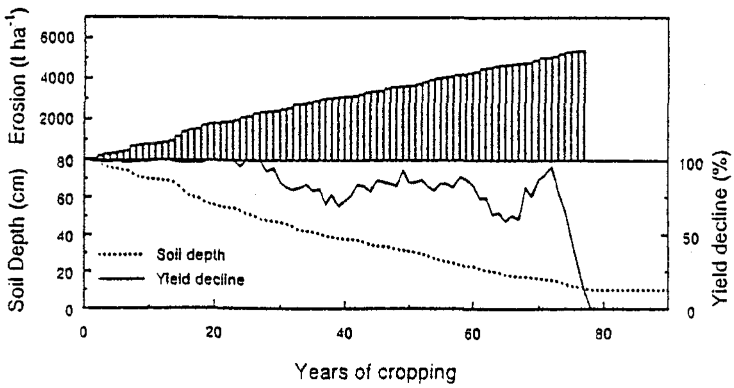

Fig. 1. Simulated soil depth, percentage decline in sorghum yield, and cumulative soil erosion *v.* years of cropping for Hyderabad. An initial soil depth of 80 cm, a slope of 10%, shallow tillage and no amendment at planting were simulated.

The dynamic effects of erosion on soil depth and sorghum yield during the 91 year simulation under control conditions (10% slope, 80 cm initial soil depth, shallow tillage and no amendment) are shown in Fig. 1. Soil depth decreased as cumulative erosion increased, with soil depth decreasing on average by 0·91 cm/year with the soil eroded to approximately 10 cm after 77 years of cropping. The decline in sorghum yield due to erosion was minimal for the first 25 years of the simulation.

Effect of slope

In comparison to the control simulation (10% slope), the decline in sorghum yield due to soil erosion was greater with the 15% slope and less with the 5% slope (Fig. 2). The largest effect of slope was evident with the 15% slope, with the soil totally depleted after only 34 years of cropping compared with 77 years for the control simulation. Yield decline after 91 years of cropping for the 5% slope was approximately 20%.

Effect of soil depth

In comparison with the control simulation (80 cm initial soil depth), decline in sorghum yield due to soil erosion was greater on the 40 cm initial soil depth

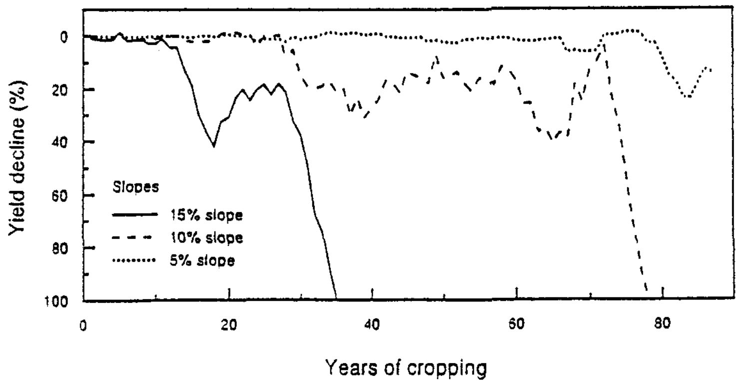

Fig. 2. Simulated percentage decline in sorghum yield *v.* years of cropping with slope of 5, 10 or 15% at Hyderabad. An initial soil depth of 80 cm, shallow tillage and no amendment at planting were simulated.

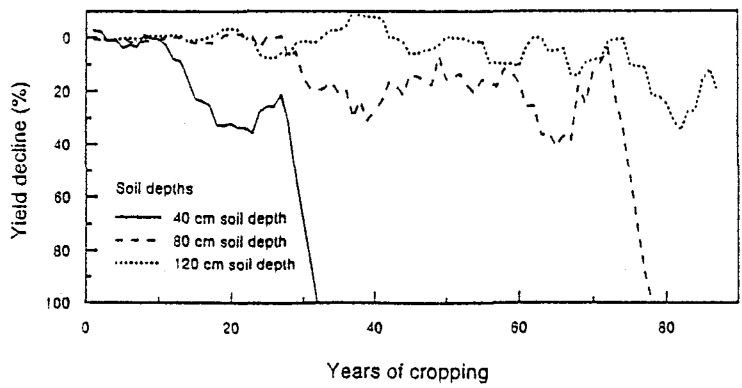

Fig. 3. Simulated percentage decline in sorghum yield *v.* years of cropping for soil with initial depth of 40, 80, or 120 cm for Hyderabad. A slope of 10%, shallow tillage and no amendment at planting were simulated.

and less on the 120 cm initial soil depth (Fig. 3). The shallow 40 cm initial soil depth was totally depleted after 31 years of cropping. Yield decline on the deeper 120 cm soil was 35% after 91 years of cropping.

Effect of tillage strategy

In comparison with the control simulation (shallow tillage), the decline in sorghum yield due to erosion associated with tillage strategy was greater with zero tillage and less with deep tillage (Fig. 4). Zero tillage resulted in total depletion of the soil after 71 years of cropping compared with 77 years for shallow tillage and 84 years for deep tillage.

Effect of amendment

In comparison with the control simulation (no amendment), the decline in sorghum yield due to erosion associated with amendment treatment was less

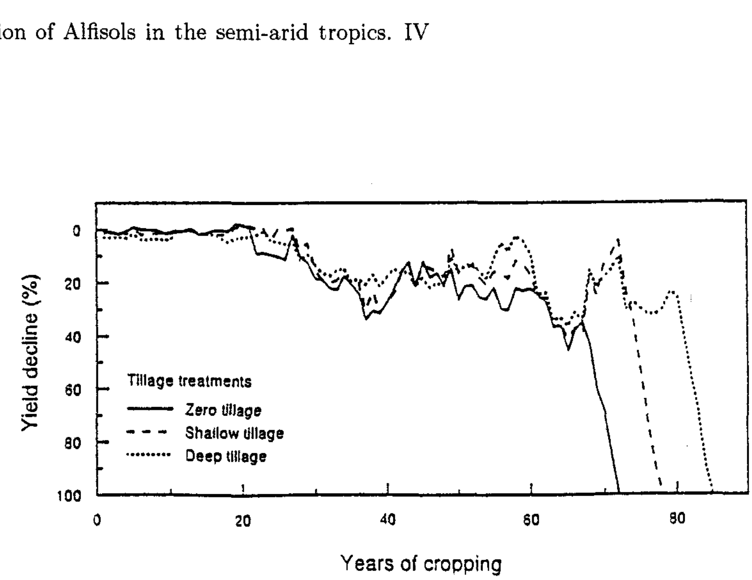

Fig. 4. Simulated percentage decline in sorghum yield *v.* years of cropping associated with a tillage strategy of zero tillage, shallow tillage or deep tillage for Hyderabad. An initial soil depth of 80 cm, a slope of 10%, and no amendment at planting were simulated.

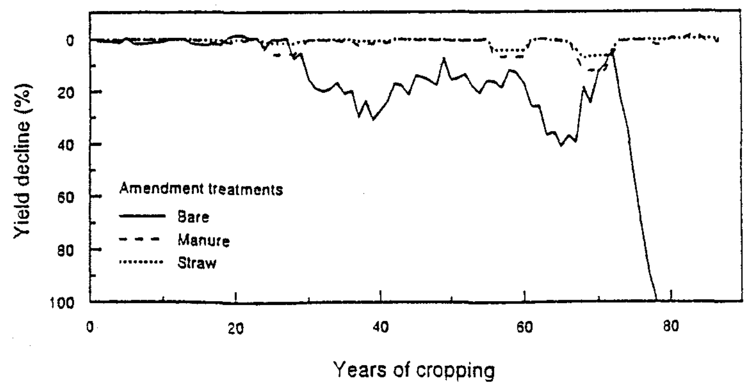

Fig. 5. Simulated percentage decline in sorghum yield *v.* years of cropping associated with an addition of amendment at planting of no amendment, farmyard manure or rice straw for Hyderabad. An initial soil depth of 80 cm, a slope of 10%, and shallow tillage were simulated.

with either rice straw or farmyard manure applications (Fig. 5). The decline in sorghum yield due to erosion after 91 years of cropping was negligible with either farmyard manure or rice straw applications at planting. The rice straw and farmyard manure treatments were the only factors that restricted yield decline to negligible amounts in the 91 year simulations (Figs 2–5).

Rice straw amendments

The effectiveness of rice straw applications on three initial soil depths (40, 80 and 120 cm) is presented in Fig. 6. The decline in sorghum yield due to soil erosion with rice straw amendment was greatest on the 40 cm initial soil depth and least on the 120 cm initial soil depth. The decline in sorghum yield on the 40 cm initial soil depth with rice straw application was approximately 25% after

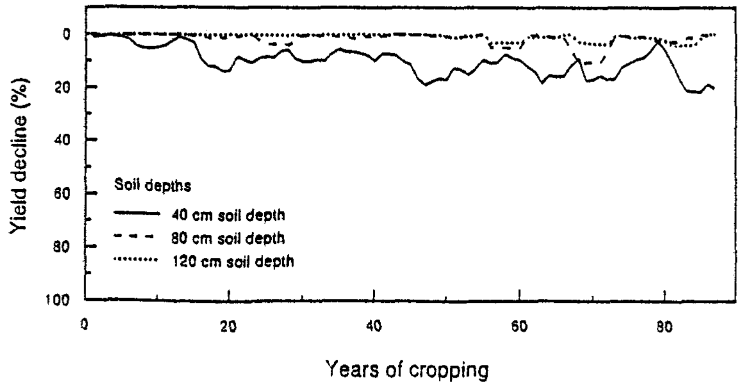

Fig. 6. Simulated percentage decline in sorghum yield *v.* years of cropping associated with an addition of rice straw at planting for soil with initial depth of 40, 80 or 120 cm. A slope of 15% and shallow tillage were simulated.

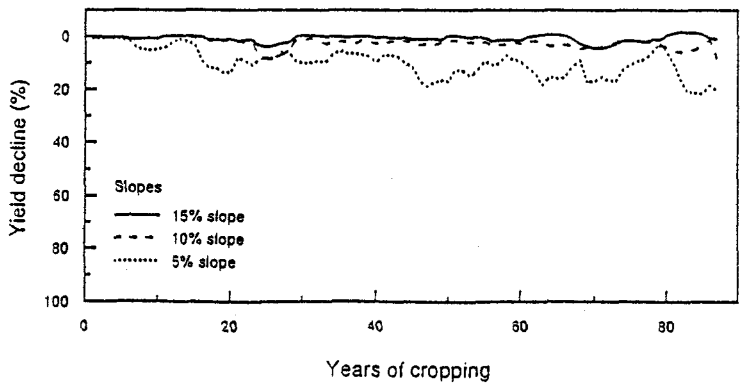

Fig. 7. Simulated percentage decline in sorghum yield *v.* years of cropping associated with an addition of rice straw at planting for a slope of 5, 10 or 15%. An initial soil depth of 40 cm and shallow tillage were simulated.

91 years of cropping compared with a cropping life of only 31 years under bare conditions (Fig. 3).

The effectiveness of rice straw applications with three slopes (5%, 10% and 15%) is presented in Fig. 7. The decline in sorghum yield due to soil erosion with rice straw amendment was greatest with the 15% slope and least with the 5% slope. The decline in sorghum yield with a 15% slope with rice straw application was approximately 25% after 91 years of cropping compared with a cropping life of only 34 years under bare conditions (Fig. 2).

Fig. 8 shows the effects of different levels of rice straw applications (2·0, 3·5 and 5·0 t/ha) on the decline in sorghum yield due to erosion for the worst case scenario of the shallowest soil (40 cm) with the steepest slope (15%). An application of 2 t/ha of rice straw was not effective in reducing erosion and resulted in a productive life of only 32 years. An application of 3·5 t/ha of rice straw increased the productive life of the soil to 89 years.

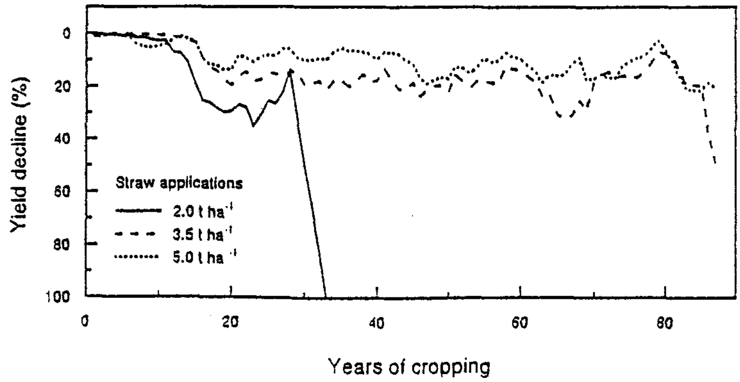

Fig. 8. Simulated percentage decline in sorghum yield *v.* years of cropping associated with an addition of 2, 3·5 or 5 t/ha of rice straw at planting. An initial soil depth of 40 cm, a slope of 15%, and shallow tillage were simulated.

Discussion

Factors affecting erosion rates

This study quantified the factors that affect the relationship between erosion and productivity for a sorghum monoculture system on an Alfisol in the SAT of India. Factors such as soil depth, slope, tillage operation and amount of surface amendment alter the relationship between soil erosion and productivity. For some factors, the productive life of the soil ended within 91 years of cropping while other factors produced minimal decline in yield. The treatments with minimal effects of erosion on yield are those that included the application of a surface amendment at planting. The extra surface cover from the amendment protected the soil surface and reduced both runoff and erosion. Marginal lands with shallower soils and steeper slopes were especially prone to yield decline due to erosion. The model simulations suggested that the application of at least 3·5 t/ha of rice straw at planting is required to protect these soils from erosion. Lower rates of application were not appropriate as much of the rice straw and the protection it offered would decay prior to the end of the wet season. Therefore, a period of erosion risk would exist late in the wet season.

Large variations in average annual erosion were predicted for the slope, soil depth, tillage and amendment options considered. In contrast, variations in average annual runoff were much smaller and this emphasizes the importance of factors other than total runoff on erosion. Soil depth had minimal affect on runoff (Table 2) as surface properties rather than soil depth dominated the relationship between rainfall and runoff. A reduction in the initial soil depth from 120 to 40 cm had little effect on average annual erosion (Table 2) but the different soil depths did produce differences in decline in production due to erosion (Fig. 3). Slope had no effect on runoff as PERFECT does not contain algorithms that account for the effects of slope on runoff. Influences of tillage on runoff were small as discussed in Part I of this study (Littleboy *et al.* 1996). For the amendment options, there was a 800% (8-fold) variation in the amount of soil erosion for the range of amendment strategies, compared with a variation of 400% (4-fold) for runoff. Therefore, for the amendment options, cover is influencing both the runoff volume and the sediment concentration in runoff.

Tillage had little effect on the relationship between erosion and productivity. In India, tillage is considered a traditional practice for Alfisols in many farming systems. It is used to break surface crusts and improve infiltration. The effects of tillage on erosion and runoff were relatively small compared with surface amendments. The simulations presented here assumed a single tillage operation prior to planting. The effects of tillage on the relationship between erosion and production may change if in-crop tillage is considered. In-crop tillage operations are generally less destructive than the deep and shallow tillages considered in this study. However, they can disturb a surface crust resulting in less runoff and erosion.

When studied individually, variations to soil depth, slope, tillage and amendment had a substantial impact on the relationship between erosion and productivity. A combination of a number of factors, for example, steep slope, shallow soil, and no amendment, would invariably produce higher erosion rates and quicker yield declines than presented here. This is supported by the data presented in Fig. 8 where a steeper slope and a shallower soil were simulated.

Productivity half-life

The productivity half-life of a soil ($P_{1/2}$) is a useful index to quantify the impact of soil erosion on productivity. It is the time taken for a soil to lose 50% of its production potential. The $P_{1/2}$ of the shallow 40 cm initial soil depth was 28 years with no surface amendment (Fig. 3). The $P_{1/2}$ of the deepest soil (120 cm) was greater than 91 years. Rate of yield decline was highest for shallower soils. This implies that a higher plant available water capacity can act as a buffer against the effects of erosion on production for an Alfisol soil.

Increasing slope results in higher rates of erosion and yield decline. The $P_{1/2}$ for the highest slope (15%) with no surface amendment was 30 years. The $P_{1/2}$ of the shallowest slope (5%) was greater than 91 years. Therefore, only short-term production can be expected for continual cropping on more marginal areas that have shallow soils or steeper slopes and do not utilize conservative soil management practices such as the application of amendments at planting.

The use of surface amendments applied at planting resulted in less erosion and lower rates of yield decline. The $P_{1/2}$ for the bare treatment was 78 years. In contrast, $P_{1/2}$ values for the straw and farmyard manure treatments were greater than 91 years. These results show the value of surface amendments as soil management options to minimize erosion and subsequent yield losses. An understanding of the effects of amendment for more marginal land can be gained by examining the effects of rice straw application at planting for steeper slopes and shallower soils. The results showed that the $P_{1/2}$ was always greater than 91 years regardless of soil depth (Fig. 6) or slope (Fig. 7).

The control conditions for these simulations assumed that 5 t/ha of rice straw was applied at planting. In practice, these amounts of straw may not be available as straw is often used as fodder. The $P_{1/2}$ for an application of 2 t/ha of rice straw at planting was approximately 30 years for a 40 cm soil on a 15% slope. An increase in straw applications to 3·5 t/ha increased $P_{1/2}$ to 85 years (Fig. 8). Therefore, higher levels of cover using rice straw or other suitable material are required to minimize soil erosion and yield declines due to erosion on the more marginal cropping lands.

The simulations presented are conservative estimates of the impact of erosion on productivity. Only reductions in soil depth and plant available water capacity were simulated. The incorporation of algorithms including nutrients and modification of soil physical properties affecting infiltration characteristics, crop establishment, and root penetration will provide more confidence in model predictions. On the other hand, no attempt has been made to incorporate the effects of technology such as improved genotypes or fertilizer management.

Conclusions

This study illustrated the effects of soil management options on the relationship between erosion and productivity for a range of soil depths and slopes for an Alfisol in the SAT of India. The dominant factors affecting the relationship between erosion and productivity were slope, soil depth and surface amendments. The damaging effects of traditional cropping practices on steeper slopes and shallower soils that are common in more marginal cropping lands were identified. Our study showed that for the steepest slope (15%) and shallowest soil (40 cm) under consideration, an application of at least 3·5 t/ha of rice straw at planting would be required to maintain productivity for at least 90 years.

The types of analyses presented in this paper are useful to identify areas at high risk from erosion, and demonstrate the value of soil management options on long-term productivity.

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