Permissible soil loss limits for different physiographic regions of West Bengal

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Land degradation due to water erosion is a major impediment for optimum land productivity in West Bengal (WB). Sustainable development of the state needs appropriate land-use planning taking into account the heterogeneity in soil and land resources. In this study, the maximum permissible soil loss rates (*T* values) were computed for 115 mapping units of WB by integrating the most sensitive soil indicators such as infiltration rate, bulk density, water stable aggregates, organic carbon and fertility status to assess soil quality governing soil resistibility to erosion. For each mapping unit, indicator soil attribute values were quantitatively expressed in the 0 to 1 scale and an aggregate score was computed from the attribute scores and the corresponding weights. The results suggested a wide difference in the *T* values among the regions and mapping units, with values ranging from 2.5 to 12.5 Mg ha^{-1} yr^{-1}. In the state as a whole, about 88% of the area has '*T*' value of 12.5 Mg ha^{-1} yr^{-1}. The relatively plain lands in the Indo-Gangetic plain, coastal and delta plain and the Bengal basin have a higher soil loss tolerance of about 4.0 Mg ha^{-1} yr^{-1} than the hilly and undulating regions in the Eastern Himalaya and Eastern plateau regions. The information generated will serve as a useful guide for devising differential conservation and resource use plans on the basis of soil resource potential.

Keywords: Biophysical model, physiographic regions, soil erosion, soil conservation planning.

SOIL erosion and consequent land degradation are the major threats to Indian food security. According to a recent estimate of ICAR, more than 120 m ha of land area is under various forms of land degradation in India, out of which 74 m ha is affected by water erosion[1]. It has been estimated that water erosion alone contributes to 5334 million tonnes (mt) of soil loss every year, at a rate of 16.4 t ha^{-1}. The impact of soil erosion is particularly severe in regions with hilly and undulating topography with unsustainable land management practices. In West Bengal (WB), about 2.2 m ha of land is degraded out of the total 8.87 m ha. Water erosion alone contributes to 54% of degraded lands[1]. In the densely populated state, there is heavy pressure on the meagre land resources. About 75% of the population has per capita land holding of around 0.16 ha.

WB is primarily divided into five physiographic zones, viz. Eastern Himalaya (in the north), Chhotanagpur plateau (in the west and southwest), Bengal basin and alluvial and deltaic plains (in the east and south)[2]. The Eastern Himalaya includes mountainous terrain of Darjeeling and northern fringe of Jalpaiguri, comprising foothills of the Bhutan Himalaya. According to the USDA soil taxonomy, soils of the state belong to 3 orders, 10 suborders, 19 great groups and 36 subgroups. Inceptisols are predominant soils, followed by Alfisols and Entisols, occupying 52%, 23% and 22% respectively, of the total geographical area of the state[2].

As soil is a highly heterogeneous entity across space and time, assessing the potential and limitations of the soil forms the basis for developing location-specific sustainable land development plans. However, 11.2 Mg ha^{-1} yr^{-1} is taken as the default value of soil loss tolerance limit worldwide[3] and most of the conservation plans in India are also based on this default value, without taking into account the heterogeneity in soil properties and variations in inherent soil capability. Good quality soils having better soil depth, and soil properties can be put to more intensive use; they can afford to lose more soil without much reduction in productivity. On the other hand, shallow and degraded soils can little afford a similar rate of soil loss and can be put under more intensive use only at a higher risk. A given rate of erosion is not equally serious in all types of soils. For instance, a shallow soil experiencing soil erosion rate at 5 Mg ha^{-1} yr^{-1} compared to soil loss tolerance (*T* value) of 2.5 Mg ha^{-1} yr^{-1} is at higher risk to be used sustainably. On the other hand, the same erosion rate of 5 Mg ha^{-1} yr^{-1} is not important against the *T* value of 12.5 Mg ha^{-1} yr^{-1} for a different soil. Thus, for sustaining long-term productivity of a soil, equilibrium between 'rate of erosion' and 'tolerance to erosion' of a soil has greater relevance than erosion rate alone. Higher rate of erosion than the tolerance limit leads to unsustainability of the production system and results in associated ecological problems.

Soil loss tolerance limit (*T* value) is defined as the maximum rate of soil erosion which will permit a high level of crop productivity, that can be obtained economically and indefinitely[4]. It is also called permissible soil loss which is related to the average soil loss, a given soil type may experience and still maintain its productivity over an extended period of time[5].

Defining the maximum rate of soil erosion that occurs while permitting sustainable and high-level crop productivity has been a challenge for a long time[6] and underlies the concept of tolerable soil loss rate. The generally accepted *T* value[3] is 11.2 Mg ha^{-1} yr^{-1}, despite different

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estimates by others[7]. The USDA-SCS (1973) recommended T values based on favourable rooting depth[8]. However, T value estimated by taking into account the key soil functions which affect soil erosion processes, along with rooting depth can be a better approximation than rooting depth alone. Instead of taking a single parameter, it will be more realistic to include parameters relating to water entry and transport, properties relating to soil resilience, soil quality and plant growth sustaining functions of the soil. In other words, the major soil functions that describe the soil erosion process can be combined to result in an integrated index, which would reflect the tolerance limit of a particular soil to erosion. In this study, all these soil functions have been incorporated through measurable soil properties to determine the T value at the scale of mapping units for WB.

The state of WB located between 21°38′–27°10′N lat. and 85°50′–89°50′E long., has wide variation in soil, climate and agro-ecological situations. With a total geographical area of 8.87 m ha (2.69% of total geographical area of India), the state has a population of 91.34 million according to the 2011 census report (7.55% of the country's population). It receives average annual rainfall of 1750 mm, with considerable variation among the districts, ranging between 1234 mm in Birbhum and 4136 mm in Jalpaiguri. Out of the total annual rainfall, about 70–80% occurs during the monsoon period (June–September). In the summer months, the daily average temperature goes as high as 35°C in the plains and western plateau region, and about 18°C in the hills. The corresponding daily average temperature values in the winter period (December and January) range from about 18°C in the plains and western plateau region to about 7°C in the hills[9]. The state is surrounded by the Bay of Bengal in the south and by the states of Assam and Sikkim in the northeast, Jharkhand in the west, Bihar in the northwest and Odisha in the southwest.

Spread over all the physiographic regions, WB has been delineated into 115 mapping units[2]. The data for major soil parameters such as soil depth, pH, soil organic carbon (SOC) and mechanical composition (% sand, silt and clay) were collected for each mapping unit from the soil map sheets prepared at 1 : 500,000 scale by NBSS&LUP, Nagpur. The soil bulk density and basic infiltration rate were estimated using pedotransfer functions[10] from SOC and soil texture data. Erodibility factor (K-factor) was estimated from the standard nomographs[3].

The soil loss tolerance limit was computed by selecting relevant soil functions and identification of potential indicators to describe the selected function, assigning weights to the soil functions, and then by quantitative expression of the selected indicators in the 0 to 1 scale. The aggregate score in the 0 to 1 scale, after multiplying with the weights assigned to the particular function, was computed and then soil loss tolerance limit values from the aggregate score and soil depth were assigned.

Table 1. Soil functions relevant to soil loss tolerance and potential indicators for each soil function

Function	Indicators	Weights
Accommodate water entry	Final infiltration rate	0.35
Water transport and absorption	Bulk density	0.10
Resist physical degradation	Erodibility factor (K)	0.25
Resist biochemical degradation	Total soil organic carbon	0.15
Sustain plant growth	Available NPK status/soil pH	0.15
Total score		1.00

For this study, five soil functions describing the resistance of soil to water erosion were selected based on the results of sensitivity analysis of the Water Erosion Prediction Project (WEPP) model[11,12]. Specific indicator soil properties were identified for each soil function (Table 1) to derive an integrated index based on weights for each selected indicator. Weights were assigned to each function on the basis of results of sensitivity analysis of WEPP model to express their relative importance[11,12]. Since the primary function of the soil with respect to erosion is to permit water entry[11], the highest weight of 0.35 was assigned to this soil function (Table 1).

The next step was to transform the indicator values into dimensionless scores ranging from 0 to 1 through fuzzy modelling using a scoring algorithm[13]. For each soil function indicator, class limits based on conventionally used definitions[14] were defined (Table 2). The score of each soil attribute value was computed through two variants of an asymmetric model.

1. Asymmetrical left (model-1, more is better)

$$\mathrm{MF}(x_i) = [1/(1 + \{(x_i - b_1 - d_1)/d_1\}^2)], \quad \text{if } x_i < (b_1 + d_1), \tag{1}$$

where $\mathrm{MF}(x_i)$ represents individual membership function for ith soil property x, $b_1 = 3.0$ and $d_1 = 2.0$.

2. Asymmetrical right (model-2, less is better)

$$\mathrm{MF}(x_i) = [1/(1 + \{(x_i - b_2 + d_2)/d_2\}^2)], \quad \text{if } x_i > (b_2 - d_2), \tag{2}$$

where $b_2 = 2.0$ and $d_2 = 1.0$.

The model parameters include lower crossover point, central concept (b), upper crossover point and width of transition zone (d). The lower and upper crossover points represent the situation where a land attribute is at a marginal level for a given purpose, while b is for an ideal level[15,16].

As there are various soil characteristics to be rated, the membership function values of individual soil characteristics under consideration were then combined using a

Table 2. Ranking of soil attributes used to convert soil properties on the 0–1 scale

Ranking soil attribute		1	2	3	4	5	Model
Infiltration rate (cm h^{-1})	Range	0.5–1.0	1.0–2.0	2.0–3.5	3.5–5.0	>5.0	1
	Score	0.2	0.3	0.5	0.8	1.0	
Bulk density (Mg m^{-3})	Range	<1.40	1.40–1.47	1.48–1.55	1.56–1.63	>1.63	2
	Score	1.0	0.8	0.5	0.3	0.2	
Erodibility factor	Range	<0.10	0.10–0.29	0.30–0.49	0.50–0.69	> 0.70	2
	Score	1.0	0.8	0.5	0.3	0.2	
Total organic carbon (%)	Range	<0.50	0.50–0.75	0.75–1.00	1.00–1.50	>1.50	1
	Score	0.2	0.3	0.5	0.8	1.0	
pH	Range	<5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.5	1
		>9.0	8.0–8.5	8.5–9.0	7.5–8.0		2
	Score	0.2	0.3	0.5	0.8	1.0	

Table 3. Assignment of T values to soil mapping units based on soil depth and aggregated score

	Annual soil loss tolerance (Mg ha^{-1})		
Soil depth (cm)	Group I ($Q < 0.33$)	Group II ($Q = 0.33$–0.66)	Group III ($Q > 0.66$)
<25	2.5	2.5	7.5
25–50	2.5	5.0	7.5
50–100	5.0	7.5	10.0
100–150	7.5	10.0	10.0
>150	10.0	12.5	12.5

Table 4. Range of soil attribute values in different physiographic regions of West Bengal

Physiographic region	Basic infiltration rate (cm h^{-1})	Bulk density (Mg m^{-3})	Soil erodibility (K-factor)	Soil organic carbon (%)	Soil pH
Eastern Himalaya	1.85–5.03 (3.12 ± 1.74)	1.43–1.46 (1.45 ± 0.01)	0.25–0.26 (0.25 ± 0.004)	1.0–1.50	4.2–5.8
Indo-Gangetic alluvial plain	0.08–5.03 (2.80 ± 1.67)	1.36–1.46 (1.43 ± 0.03)	0.25–0.46 (0.28 ± 0.05)	0.50–1.0	4.0–6.5
Bengal basin	0.08–5.03 (1.49 ± 2.30)	1.36–1.46 (1.40 ± 0.04)	0.26–0.37 (0.31 ± 0.04)	0.30–0.75	5.0–7.0
Coastal and delta plain	0.08–11.4 (1.63 ± 3.72)	1.36–1.43 (1.38 ± 0.03)	0.16–0.35 (0.30 ± 0.06)	0.30–1.50	6.5–8.5
Eastern plateau	0.08–5.03 (1.84 ± 0.83)	1.36–1.46 (1.43 ± 0.02)	0.27–0.37 (0.28 ± 0.02)	0.30–0.50	4.5–6.5

Values in parenthesis indicate mean ± standard deviation.

convex combination function to produce a joint membership function (JMF) for all attributes, Y as follows

$$\mathrm{JMF}(Y)=\sum_{i=1}^{n}\lambda_i \mathrm{MF}(x_i), \qquad (3)$$

where λ_i is the weighing factor for the ith soil property x_i and $\mathrm{MF}(x_i)$ is the membership function for the ith soil property x.

Ratings obtained for different soil functions when converted to the 0 to 1 scale were multiplied by their respective weights. The aggregate of all the weighted parameters was then used to quantify the state of soil (Q) for each soil mapping unit:

$$Q = q_1w_1 + q_2w_2 + q_3w_3 + q_4w_4 + q_5w_5, \qquad (4)$$

where q is the individual rating for different soil functions such as: q_1 is the rating for infiltration; q_2 the rating for water transport; q_3 the rating for rate of physical degradation; q_4 the rating for resistance to biochemical degradation and q_5 the rating for ability to sustain plant growth and w represents weights assigned to each function.

Soil mapping units were grouped as follows: group I (Q <0.33), group II ($Q = 0.33$–0.66) and group III ($Q > 0.66$) based on the aggregated score (Q) as obtained in eq. (4). Therefore, soils in group III perform all functions at optimal level and thus permissible soil loss may be higher than those under groups I or II. A general guide developed at the Iowa State University Statistical Laboratory[17] was used to arrive at the soil loss tolerance (T) values for each soil mapping unit (Table 3) based on the soil group of the mapping unit and soil depth. The computed T values for each mapping unit were used to develop maps of soil loss tolerance utilizing the Arc GIS software.

The data on the basic soil attributes spread across 115 mapping units in the five physiographic regions indicate wide difference in the attribute values (Table 4). A wide

Table 5. Range of aggregate score and *T* value along with mean values across physiographic regions of West Bengal

Physiographic region	Score	*T* value
Eastern Himalaya	0.60–0.84 (0.70 ± 0.13)	5.0–10.0 (8.5 ± 2.23)
Indo-Gangetic alluvial plain	0.42–0.76 (0.59 ± 0.13)	12.5
Bengal basin	0.38–0.71 (0.48 ± 0.11)	10.0–12.5 (12.36 ± 0.57)
Coastal and delta plain	0.41–0.71 (0.54 ± 0.08)	12.5
Eastern plateau	0.37–0.70 (0.46 ± 0.06)	2.5–12.5 (8.5 ± 4.15)

Values in parenthesis indicate mean ± standard deviation.

Table 6. Percentage distribution of *T* value across physiographic regions of West Bengal

	Percentage area under particular *T* value (Mg ha^{-1} yr^{-1})				
Physiographic region	2.5	5.0	7.5	10.0	12.5
Eastern Himalaya		0.23	0.46	1.64	
Indo-Gangetic alluvial plain					23.19
Bengal basin				0.92	40.04
Coastal and delta plain					15.97
Eastern plateau	0.68	4.67		0.66	8.63
Total	0.68	4.90	0.46	3.22	87.83

range in the basic infiltration rate (0.08–11.40 cm h^{-1}) was observed due to difference in textural composition. It was a highly variable parameter as observed from high standard deviation (SD) values. In general, infiltration rate was higher in the soils of Eastern Himalaya (mean value of 3.12 cm h^{-1}) followed by those in the Indo-Gangetic alluvial plain (mean value of 2.80 cm h^{-1}). Better infiltration properties in the Eastern Himalaya and Indo-Gangetic plain are due to loamy and coarse-textured soils. There was not much variation in the bulk density of soils among the physiographic regions. For the surface soil layers, it varied from 1.36 to 1.46 Mg m^{-3}, with lowest mean value in coastal and delta plain. The soil erodibility factor (*K*-factor) varied from 0.16 to 0.46, with trends of lower eordibility in the Eastern Himalaya and Indo-Gangetic alluvial plain. This might be due to better soil conditions for higher infiltration and higher SOC storage in the alluvial plain. Higher the *K*-value, lower is the soil resistance to erosive processes. The SOC was higher in the Eastern Himalaya due to the effect of high altitude followed by that in the Indo-Gangetic alluvial plain, which might be due to greater abundance of fine fraction in the soil. Though the soil pH of most of the mapping units was in the acidic range varying from 4.5 to 6.5, higher pH values from 6.5 to 8.5 were observed in the coastal and delta plain, which may be due to seawater inundation in the coastal lands and high water table and waterlogging problems in the delta plain.

The soil state (*Q*) is defined according to the aggregate score obtained from the individual attribute score and weights of the corresponding attributes. The soil state (*Q*) and tolerance limit (*T*) values for the physiographic regions are presented in Table 5. The *Q* values varied from 0.37 to 0.84, with higher mean values (0.70) for Eastern Himalaya followed by Indo-Gangetic plain (0.59). The Eastern plateau region had the lowest average *Q* value (0.46). Despite the differences, data range of all the mapping units shows that the soils of WB come under groups II and III.

Compared to *Q*, there was wide variation in the *T* values, which ranged from 2.5 to 12.5 Mg ha^{-1} yr^{-1} (Table 5). This is attributed to variation in the soil depth limitations. The same score of *Q* results in a higher *T* value when the soil depth is more (Table 3). In contrast to a single permissible soil loss value of 11.2 Mg ha^{-1} yr^{-1}, variation in *T* values ranging from 2.5 to 12.5 Mg ha^{-1} yr^{-1} according to soils characteristics has also been reported for two states of Central India[18], Lakshadweep islands[19], Uttarakhand[20] and North West Himalaya[21]. Thus with similar scores of *Q*, the Eastern plateau has a *T* value lower by about 4.0 Mg ha^{-1} yr^{-1} than the Bengal basin due to the undulating topography and soil depth limitations in the former. Also, even though the *Q* value was highest for the Eastern Himalaya, the average *T* value was lower by about 4.0 Mg ha^{-1} yr^{-1} than the Indo-Gangetic plain, coastal and delta plain and soils of Bengal basin. Among the physiographic regions, the highest *T* value of >12.5 Mg ha^{-1} yr^{-1} was observed for all the mapping units in the Indo-Gangetic plain, and coastal and delta plain. On the other hand, a lower soil loss tolerance was observed in the hilly and undulated regions, with mean *T* value of about 8.5 Mg ha^{-1} yr^{-1} for soils of Eastern Himalaya and the Eastern plateau.

The spatial distribution of tolerance limits in WB is presented in Table 6 and Figure 1. For the state as a whole, about 88% of the area has a soil loss tolerance limit of 12 Mg ha^{-1} yr^{-1}, 3% up to 10.0 Mg ha^{-1} yr^{-1} and 6% below 7.5 Mg ha^{-1} yr^{-1}. A major portion of total area of the state having *T* value of 5.0 Mg ha^{-1} yr^{-1} (4.7%) lies in the Eastern plateau, thus indicating the need to prioritize

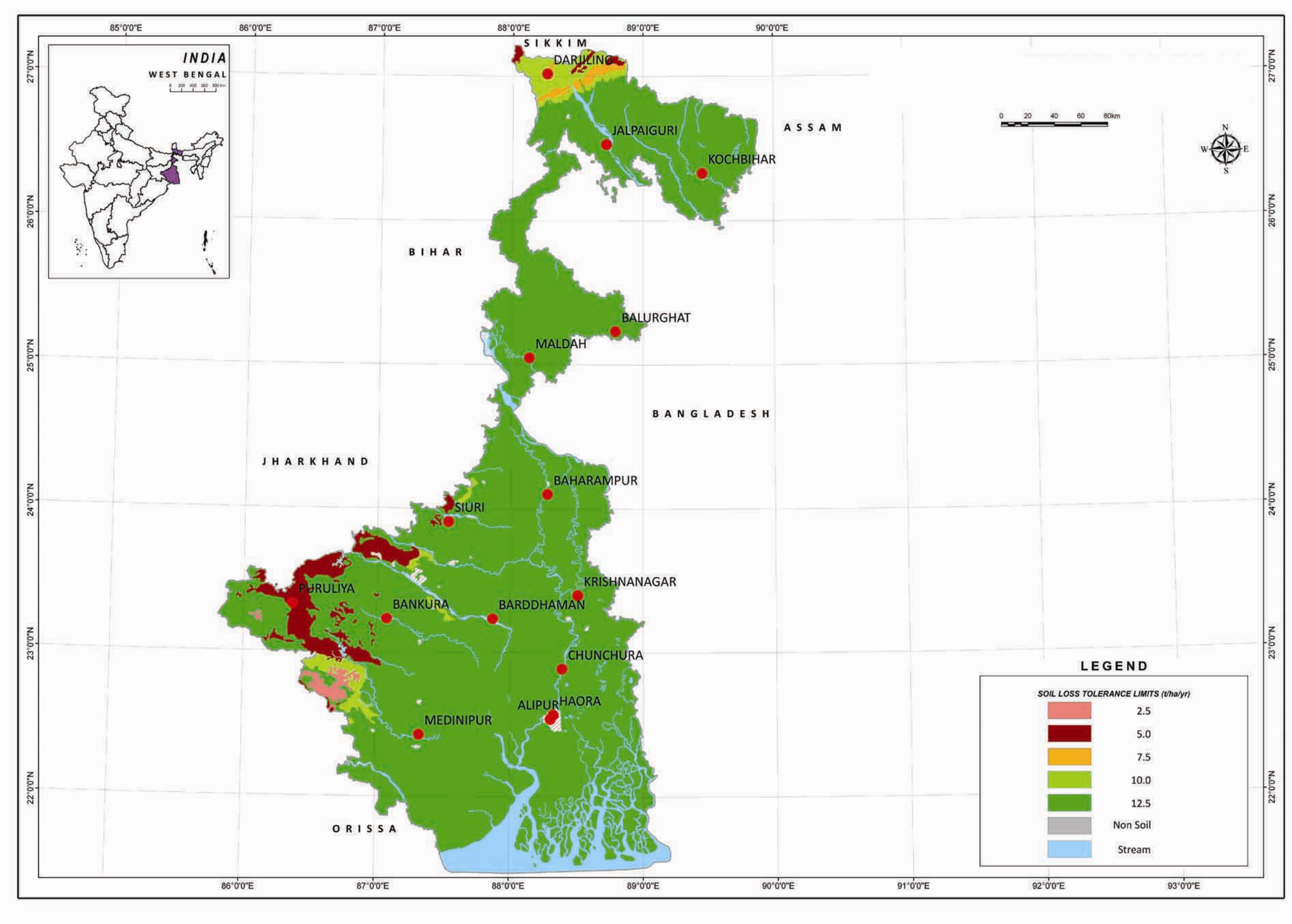

Figure 1. Soil loss tolerance limit for West Bengal.

conservation plans so as to sustain long-term productivity of the particular physiographic region.

The areas under the districts of Purulia, Bankura, Paschim Medinipur, Darjeeling, Birbhum and Bardhaman showed lower T values ranging from 2.5 to 5.0 Mg ha^{-1} yr^{-1}. Therefore, these areas are most sensitive and attract greater attention to minimize further deterioration of land quality. Soils of the Indo-Gangetic plain, coastal and delta plain and Bengal basin have a higher tolerance limit (10.0–12.5 Mg ha^{-1} yr^{-1}) due to greater soil depth and higher erosion resistance capacity. On the other hand, soils of the Eastern Himalaya had a T value ranging from 5.0 to 10.0 Mg ha^{-1} yr^{-1} and the Eastern plateau from 2.5 to 12.5 Mg ha^{-1} yr^{-1}. The lower tolerance values in the two physiographic regions are primarily due to soil depth limitations and the hilly and undulating terrain.

Thus, the present study indicates a wide difference in the soil loss tolerance limit ranging from 2.5 to 12.5 Mg ha^{-1} yr^{-1}. In WB as a whole, about 88% of the area has T value of 12.5 Mg ha^{-1} yr^{-1}. Relatively plain lands in the Indo-Gangetic plain, coastal and delta plain and the Bengal basin have a higher soil loss tolerance than the hilly and undulating regions in the Eastern Himalaya and the Eastern plateau. The T value of the three physiographic regions with plain lands is higher by up to 4.0 Mg ha^{-1} yr^{-1} than the two hilly and undulated physiographic zones. The study underlines the need for prioritization of conservation needs on the basis of spatial differences in soil loss tolerance values compared to the prevailing erosion rates. Higher the difference between the permissible soil loss limit and the prevailing erosion rate, greater is the risk involved in using the soil without optimum conservation measures. On the other hand, erosion rate lower than the T value allows the soil to be used with the on-going management without much risk involved. A comparison of the soil loss tolerance value as against the prevailing erosion rates, can serve as a useful guide for prioritization of conservation planning.

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Cost estimation of soil erosion and nutrient loss from a watershed of the Chotanagpur Plateau, India

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Soil erosion is a major threat to the sustainability of agriculture in mountain regions of the world. The present study was conducted to assess overland flow, soil and subsequent nutrient loss from different land-use/land-cover in a watershed of Chotanagpur Plateau. It was observed that overland flow was greatest in orchard (30.73%) and lowest in vegetable field (15.84%). Soil loss from the field plots ranged between 9 and 37 tonnes/ha during the monsoon months. Nutrient leaching was highest in paddy fields. A strong positive correlation was observed between organic carbon and soil loss ($P < 0.01$). On an average, 590 kg of macro-nutrients (N, P and K) were lost per hectare during the monsoon season. Approximately INR 8893 ha^{-1} (US$ 137 ha^{-1}) would be required to replace this loss through inorganic fertilizers. Agricultural practices in mountain areas should be strengthened with more agroforestry components to promote conservation of soil, water and nutrients.

Keywords: Agroforestry, land-use/land-cover, macronutrients, watershed.

SOIL erosion is a major threat to the sustainability of agriculture all around the world and more specifically in developing countries. It adversely affects the productivity of agricultural, forest and rangeland ecosystems[1–4]. Soil erosion rates are highest in Asia, Africa and South America, with an average rate of 30–40 tonnes ha^{-1} annually[5,6]. In the last 40 years, about 30% of the world's arable land has become unproductive and much of it has been abandoned for agricultural use[7]. Farming systems are managed traditionally and are dependent on surrounding natural resources. The soil without tree cover on hilly slope associated with more intensive agricultural practices is vulnerable to erosion and reduced fertility. Various studies[3,8,9] suggest that removal of organic matter and essential nutrients takes place during the process of soil erosion. However, nutrient erosion is not given the needed attention, as it is a slow process and does not lead to major catastrophes. Often, to offset the nutrient loss caused by erosion, large quantities of fertilizers are applied. This shadows the debilitating effect that soil erosion has on the productive capacity of agricultural lands. Topsoil depletion not only results in depleted nutrients, but also

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