Causes and consequences of soil erosion in northeastern Himalaya, India

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The Northeastern Region of India, due to its geographical location in the eastern Himalaya, exhibits unique features of hilly terrain and abundant rainfall with wide spatial variability. Due to inappropriate and unsustainable land-use practices along the steep hill slopes, the region is prone to severe water erosion and soil loss. Only a few discrete, small-scale studies on measured soil loss in the region are available. Inadequate information at the regional level restricts devising site-specific soil and water conservation measures for the vulnerable areas of this region. To illustrate regional scenarios for future use, including projection studies, we have reviewed studies of soil loss in the region over the past three decades. The literature revealed significant variation in annual soil loss measured or estimated (range) across different land-use practices: traces to 229.5 t ha^{-1} yr^{-1} in shifting cultivation (jhum) and traces to 836.0 t ha^{-1} yr^{-1} in other non-jhum major land uses (agriculture, open forest and wasteland). The information generated will help prioritize research activities and in planning conservation measures for various stakeholders.

Keywords: Hilly terrain, land degradation, land-use practices, soil loss, water conservation.

SOIL erosion poses a major challenge for environmental sustainability, particularly in India's tropical hilly regions. The Indian Himalaya occupies an area of 53.7 M ha, representing 16.4% of the geographical area (GA) of the country. The Himalaya consists of two distinct subregions, viz. eastern Himalayan region or the northeastern hills (NEH: 26.2 M ha) and western Himalayan region or the northwestern hills (NWH: 27.5 M ha). The NEH region receives higher annual rainfall (1,500–11,500 mm) than the NWH region (350–3,000 mm). Hence a higher percentage of the area (GA: 22.3) in the NEH region is vulnerable to soil erosion than the NWH region (GA: 12.6)[1]. About 77% of the NEH region is in hilly terrain[2], which encourages the loss of significant annual rainfall in the form of run-off. This results in loss of topsoil of the hill slopes and sloping highlands, depletion of soil fertility, siltation of downstream water bodies, frequent flooding in the large low-lying central plains and ecological imbalances in the region[3]. The severity of soil erosion has further intensified due to unsustainable land-use practices along the hills and other anthropogenic activities such as deforestation, vegetation burning, urban development, mining and quarrying, etc. Agricultural practices in the region are largely of two types: shifting cultivation (SC), locally known as jhum, and sedentary or plain agriculture. SC is practised largely by tribal farmers in Arunachal Pradesh, Meghalaya, Mizoram, Nagaland, Manipur, hilly region of South Assam and Tripura[4]. Plain or sedentary agriculture is usually practised on the fertile alluvial plains of Assam, Brahmaputra plain in southern Arunachal Pradesh, intermontane valleys of Barak, the plains of southeastern Nagaland, Tripura and the Imphal Valley of Manipur.

Jhum is the main crop husbandry practice and support for the livelihoods of tribal populations in the hilly regions of North East India[5]. The culture cycle in jhum is crucial and varies widely throughout the region. However, over the past few decades, due to population pressure and increased food demand from limited land resources and the inaccessibility of pristine forests in difficult hilly terrain, the fallow periods/cycles have changed from the previous practice of 10–15 years to the current practice of 2–3 years. The short fallow cycle causes frequent disturbance and is now the primary concern as it completely diminishes the ability of jhum to regenerate the ecosystem[6], causing a considerable loss of fertile soils carrying nutrient loads through run-off/leaching and making the land unsuitable for agriculture[7]. Shorter fallow periods and continued cultivation of tuber or root crops along steep slopes promote severe water erosion and soil loss (32–79 Mg ha^{-1} yr^{-1})[8]. Bun or terrace cultivation is another form of modified jhum cultivation practised mainly in the hills of Meghalaya and some areas of the Northeastern Region of India (NER)[9]. It is essentially a type of ridge and furrow method of cultivation with varying length (2.0–7.0 m), width (1.0–1.25 m), and height (0.20–0.25 m). Buns are prepared along the hill slopes, and tuber crops (turmeric, ginger and sweet potato) are grown in the ridges during the first year, followed by upland rice in the second year. Tribal farmers choose a virgin forest area, clean it to remove all vegetation, including trees, shrubs, etc. and

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grow vegetables, cereals and spices for 2–3 consecutive years. Once the land loses its productivity in 2–3 years, they move to a new forested area for cultivation. The potential for soil erosion and soil loss per unit area is significantly higher in bun cultivation than in jhum cultivation[9].

These traditional framing practices (short fallow jhum, bun, terrace agriculture along steep slopes, etc.) have led to the burning of huge amounts of forest phytomass every year. This ultimately leaves the land barren, vulnerable to soil erosion and degradation, particularly during the rainy season. It also causes loss of genetic diversity of flora and fauna in jhum practices. Water erosion and soil loss are the major threats to sustainable agriculture and ecosystem functioning in the region. Site-specific approaches for reclamation of degraded lands, including future management strategies using projection studies and regional soil erosion scenario are important and currently lacking in the region. Therefore, we have reviewed studies from the past three decades on soil loss in NER and have put in place a regional scenario to address the above needs.

Land use–land cover in NER

The land use–land cover (LULC) map of the region at 1 : 50,000 scale revealed that 58.1% of 26.2 M ha GA is under different types of forest cover (e.g. evergreen/semi-evergreen/deciduous/forest plantation) (Figure 1)[10]. Almost half (30.7% of GA) of the total forest cover is evergreen to semi-evergreen, while the remaining is found in deciduous forests. Evergreen/semi-evergreen forests are native forests dominated by subtropical pine (e.g. *Pinus* spp.), broadleaved forests (*Castanopsis indica* Roxb., *Quercus serrata* Murray., *Michelia oblonga* Wall, etc.), and tropical wet semi-evergreen forests (e.g. *Shorea robusta* Gaertn. f., *Mesua ferrea* Linn, etc.). Deforestation from shifting cultivation, bun agriculture, coal mining, etc. has transformed significant areas (>11.5% of GA) of forests to wastelands (including scrub forests). The area under agriculture, including uplands, lowlands and current fallow, accounts for only 14.9% of GA (Figure 2). The agricultural crops in the uplands are mostly dry-seeded rice, maize, pulses, vegetables, etc. which occupy 2.81% of GA, while in the lowlands, puddled transplanted rice–fallow system is practised in 12.18% of GA. Grassland occupy 3.3% of GA and are spread across alpine to tropical regions, dominated by wild grass species like *Setaria sphacelata* Moss., *Panicum maximum* Jacq., and *Thysanolaena maxima* Roxb., with scattered trees/shrubs like *Eupatorium odoratum* Linn., *Ageratum conyzoides* L. and *Quercus serrata* Murray (Figures 1 and 2)[2]. Plantations and horticulture occupy 2.04% of GA with predominance of tea, rubber, coconut, areca nut, pineapple, citrus fruits and other unmanaged orchards. Shifting cultivation of multiple crops (rice, maize, tapioca, yam, turmeric, ginger, root crops, etc.) is practised in 1.20% of GA (excluding abandoned jhum area) along the steep slopes. The remaining 8.97% of GA is under water bodies, settlements, snow and glaciers, and wastelands[10].

Land degradation status in NER

Land degradation in the form of water erosion is a severe threat to ecosystem sustainability in NER. The unsustainable land-use practices (including deforestation) in the undulating terrain, particularly in the land capability classes VI and VII under high rainfall occurrences, encourage severity of soil erosion vis-à-vis land degradation, hill-slope instability, and collapse of the mountain ecosystem[11]. The total degraded land area in the region is nearly 4.60 M ha (18.2% of 26.2 M ha GA), of which water erosion alone caused nearly 30% (1.42 M ha) of it, while the remaining 70% degraded area (3.35 M ha) can be attributed to multiple other forms of degradation (soil

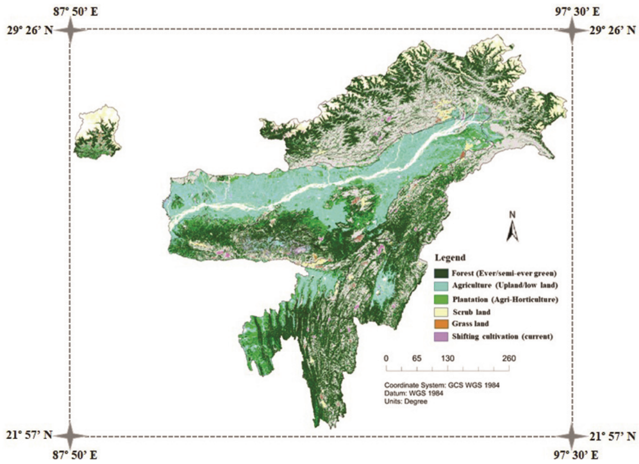

Figure 1. Land use–land cover (LULC) map of the Northeastern Region of India (NER) derived from multi-date Resourcesat-2 orthorectified LISS-III satellite data of 2015–16 (modified and adopted from NRSC[10]).

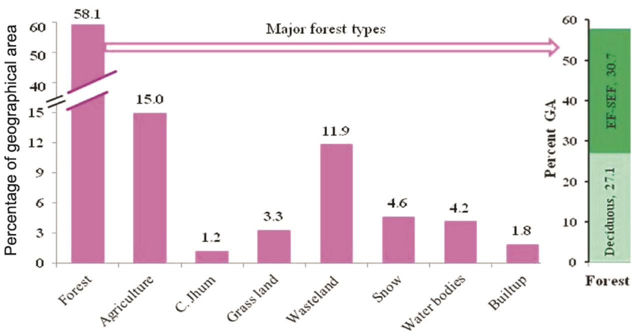

Figure 2. Percentage of geographical area under major land use types of NER (modified and adopted from NRSC[10]). EF-SEF, Evergreen to semi-evergreen forests.

Table 1. Percentage of geographical area under water erosion and other forms of land degradation in the Northeastern Region of India (NER)

		% of TGA				
		Degradation by water erosion				
North East states	TGA (km^2)	Slight (*A*)	Moderate to severe (*B*)	Total (*A* + *B*)	Others (*C*)	Total land degraded (*A* + *B* + *C*)
Arunachal Pradesh	83,743	4.84	0.45	5.29	6.45	11.74
Assam	78,438	0.99	3.57	4.58	4.87	9.45
Manipur	22,327	3.05	6.89	9.94	23.27	33.21
Meghalaya	22,429	1.25	2.62	3.87	24.51	28.38
Mizoram	21,081	7.86	4.78	12.65	22.28	34.92
Nagaland	16,579	1.71	0.46	2.16	44.89	47.05
Sikkim	7,096	0.01	0.74	0.76	10.00	10.75
Tripura	10,486	0.12	0.46	0.58	6.70	7.28
NER	262,179	2.95	2.48	5.43	12.76	18.20

TGA, Total geographical area; Slight, Soil loss of 10–20 t ha^{-1} yr^{-1}; Moderate to severe, soil loss of >20 to >40 t ha^{-1} yr^{-1}; *A*, Sheet erosion; *B*, Rill to gully erosions, *C*, Soil acidification, waterlogging, mining, barren rocky, riverine sands, industrial effluents, etc. (source: modified from NRSC[10]).

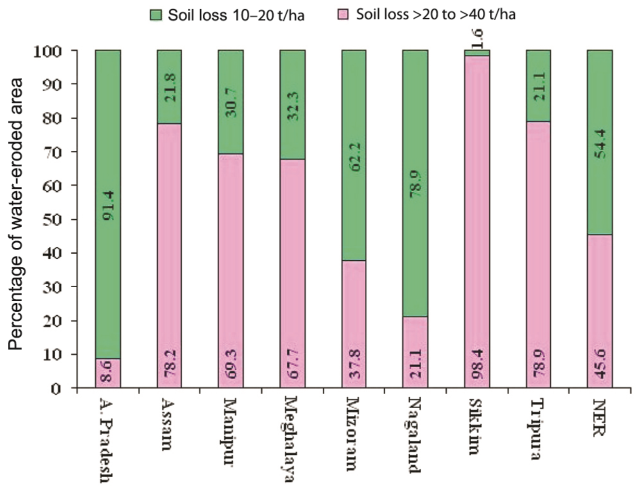

Figure 3. Percentage of total water erosion degraded land (14,245 km^2) under different severity classes of soil loss (slight: 10–20 t ha^{-1}; moderate to severe: >20 to >40 t ha^{-1}) (modified from NRSC[10]).

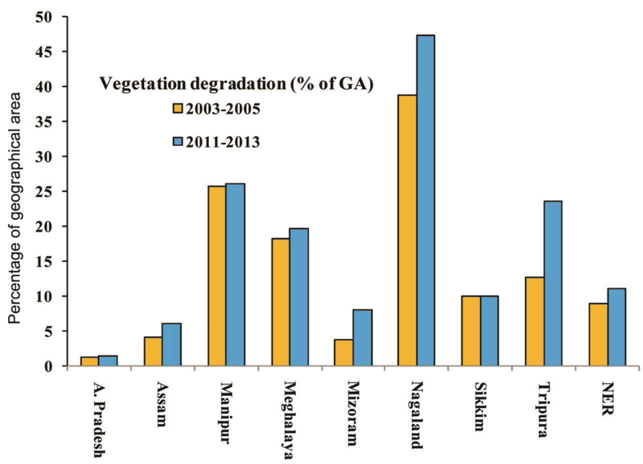

Figure 4. Percentage of geographical area under vegetation degradation in NER (modified from ref. 68).

acidification, waterlogging, barren rocks, mining, quarrying, riverine sands, industrial effluents, etc.) (Table 1)[10].

Among the eight NE states, Nagaland has nearly half of its total land area (47.1% of 1.66 M ha GA) degraded, followed by Mizoram (34.92% GA), Manipur (33.21% GA) and Meghalaya (28.38% GA). Similarly, the extent of land degradation by water erosion is more severe in Mizoram (12.6% GA), followed by Manipur (9.9% GA) and Arunachal Pradesh (5.3% GA). The sheet, rill and in some places gully erosion are the forms of water erosion dominant in the region. In the other NE states (Arunachal Pradesh and Assam), a significant area is also degraded (>0.74 to >0.98 M ha) by both water erosion and other forms of land degradation. The severity of high annual soil loss (moderate to severe: >20 to >40 t ha^{-1} yr^{-1}) is the largest in Manipur (6.89% GA), followed by Mizoram (4.78% GA) and Assam (3.57% GA) (Table 1)[10]. Mizoram has the highest proportion of water-eroded GA (7.86%) with annual loss ranging from 10 to 20 t ha^{-1} yr^{-1}. In six out of the eight NE states (except Arunachal Pradesh and Nagaland), the annual soil loss (>20 to >40 t ha^{-1} yr^{-1}) is severe in one-third to almost 99% water-eroded degraded areas (Figure 3). This is several-fold above the critical tolerance limit (12.5 t ha^{-1} yr^{-1}) of the region[12]. The severity of soil erosion is mainly attributed to large-scale deforestation and exposure of topsoil to high-intensity rainfall in the sloping uplands. This is evident from the degradation of 2.33 M ha vegetation cover in 2003–2005 and an additional 2% increase over a short eight-year period (from 2003–2005 to 2011–2013) (Figure 4). Each year, 50–80 tonnes of plant biomass is burned by jhumming alone, resulting in an annual loss of 88.3 million tonnes of soil in the region[13]. In Arunachal Pradesh, soil loss due to jhum cultivation is estimated at about 669.4 million tonnes, with a yearly average loss of 90.9 t ha^{-1} (refs 11, 12, 14).

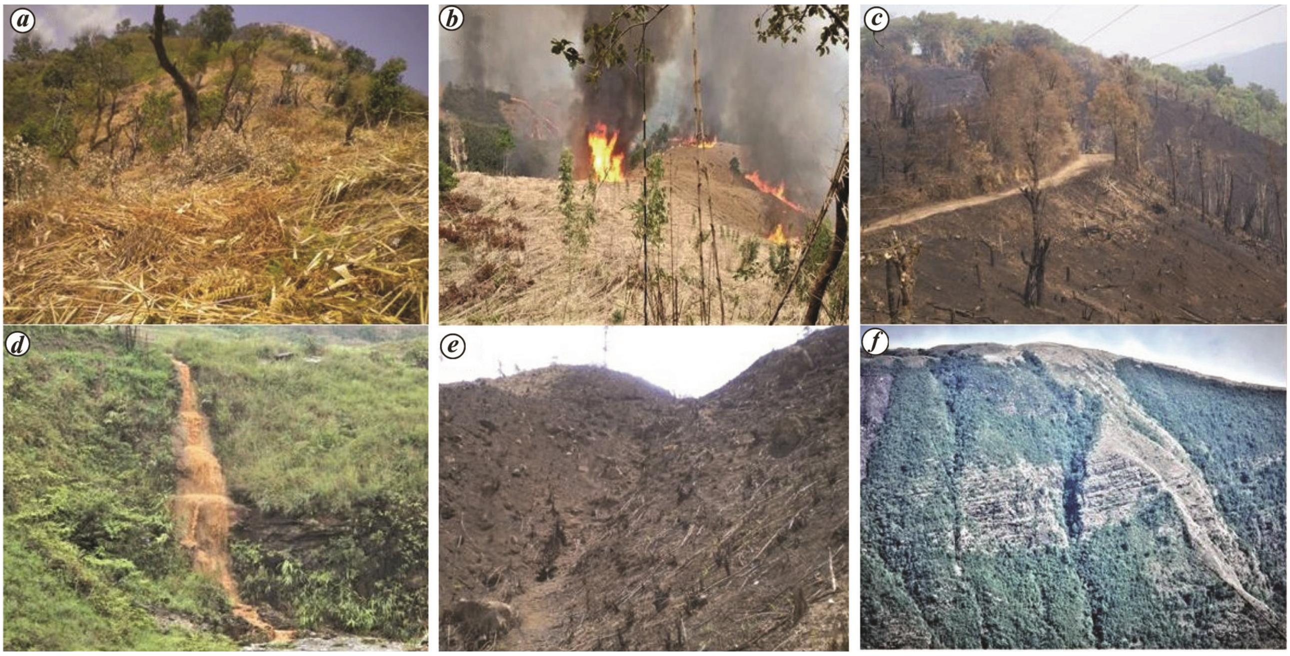

Figure 5. Soil erosion processes in shifting cultivated land uses associated with (***a***) deforestation, (***b***) burning of slashed vegetation[47], (***c***) post-burn field, (***d***) runoff and soil loss, and (***e***, ***f***) post-jhum eroded hills.

Research initiatives on soil erosion in NER

Over the past decades, many researchers have provided information on run-off and soil loss in flood-prone valleys and hilly mountain ecosystems in NE India. Unfortunately, the conclusions of most of these studies have remained reclusive and obscure to policy-makers and implementers alike. This restricted exploration in the development of site-specific conservation measures for the restoration of degraded land. With these in view, we compiled and analysed separate research findings from the past three decades on soil erosion in NER for the benefit of various stakeholders. Regardless of the extent of the study (plot to river basin) and whether it was measured at the plot level or simulated at the watershed level using hydrological models, previous work on soil erosion is primarily based on jhum-based land use (with different fallow periods) and compared with non-jhum forest and sedentary agricultural land use in the region. Few large-scale (watershed to river basin) studies using hydrological models were used to estimate or predict soil loss with special interest in deforestation and conversion of forests to cropland. Most of these studies reported only soil loss, while run-off loss was ignored. Therefore, based on the available literature, we have divided previous research work on soil loss into two broad categories: (i) land use under shifting cultivation (SC/jhum), and (ii) land use under non-jhum practices. We have also geo-referenced and generated a spatial map to represent all previously reported soil losses from water erosion in the region on a common platform. We have also suggested potential soil and water conservation (SWC) measures to reduce the alarming rate of soil erosion. This review will help in prioritizing research activities, identifying vulnerable areas and devising conservation measures to minimize soil loss, while sustaining land productivity of this fragile region of India.

Soil erosion studies under shifting cultivation in NER

SC in its traditional form was ecologically viable since the fallow cycles were long enough (>15 years) for post-jhum restoration of soil health and vegetative surface cover. However, due to population pressure and the demand for more food grains from declining land availability (virgin forests), the fallow cycles have reduced to 1–2 years. The threat of the present form of the short fallow cycle to land and ecosystem degradation was first realized during the early 1980s. SC is a year-round agricultural practice starting from January onwards till crop harvest in December. The process of soil erosion is initiated as soon as the cutting, burning and clearing process of forest cover starts in the hill slopes (Figures 5 and 6). Rapid soil erosion continues till 1–2 years post-jhum fallow period. Another typical type of jhum cycle, where seed sowing generally starts in the pre-monsoon month of May and weeding of crop continues till June, also highly encourages soil loss along the slopes. This practice causes loss of topsoil up to 60 t ha^{-1} yr^{-1} from heavy pre-monsoonal downpour (Figures 5 and 6)[5]. Studies on soil erodibility characteristics under various land-use systems in the region revealed that SC had the highest erosion ratio (12.5) and soil loss (30.2–170.2 t ha^{-1} yr^{-1}), followed by the conventional agriculture system (5.1–68.2 t ha^{-1} yr^{-1})[15]. The potential erosion and soil loss per unit area in the modified form of SC, i.e. bun agriculture is much higher than jhum cultivation (40.0 to 153.1 t ha^{-1} yr^{-1}) (Figure 7 and Table 2)[16]. Other land-use practices that significantly contribute to soil loss in the region are bare fallow (83.8 t ha^{-1} yr^{-1}), followed by medium plot cropping system (51.0–83.8 t ha^{-1} yr^{-1}), tuber crops on raised beds (40.0–50.0 t ha^{-1} yr^{-1}), rice crop on hillside slopes (32.9–45.0 t ha^{-1} yr^{-1}), pineapple cultivation on slopes (24.0–62.0 t ha^{-1} yr^{-1}), mixed crop of maize and rice (19.7–21.0 t ha^{-1} yr^{-1}) and natural bamboo forest (0.04–0.52 t ha^{-1} yr^{-1}) (Table 2)[5].

Soil erosion under SC is highly unpredictable due to yearly variation of rainfall characteristics. A previous study on soil loss under SC in steep slopes (44–53%) of Meghalaya reported an annual estimated soil loss of 40.9 t ha^{-1} (ref. 17), while another study in the relatively steeper slopes (60–79%) of Meghalaya (Shillong Plateau) reported wide interannual variability in soil loss with jhum cultivation[18]. The estimated annual soil loss in Shillong Plateau was 147 t ha^{-1} in the first year, which increased to 170 t ha^{-1} in the second year and then reduced drastically to 30 t ha^{-1} on abandoning SC in the third year. In a hilly macro-watershed at the Dikrong river basin in Arunachal Pradesh, the conversion of significant forest area (1089 ha) into jhum increased annual run-off and estimated soil loss (Figure 8)[19]. Nearly 27–39% of the annual rainfall (1519–4169 mm) was lost in the form of run-off (Table 3). Estimation of long-period (1988–2005) soil loss in the jhum area in Dikrong river basin, using the Universal Soil Loss Equation (USLE) at a 200 m × 200 m resolution grid size, revealed wide interannual variations ranging from 19.16 to 155.5 t ha^{-1} yr^{-1}, with average soil loss of 51.0 (SD: ±32.0) t ha^{-1} yr^{-1} (ref. 11). On doubling the resolution of grids to 100 m, interannual variability in the USLE-estimated soil loss increased further (21.1–172.8 t ha^{-1} yr^{-1}), with 12% increase in average soil loss (57.1 ± 36.5 t ha^{-1} yr^{-1}) (Table 3 and Figure 7)[20]. Due to variability in the watershed features, particularly elevation (84–1426 m amsl) and annual rainfall (1519–4169 mm), the amount of run-off loss also varied widely. On shifting from USLE to another hydrological model, i.e. MMF (Morgan–Morgan–Finney), the estimated interannual average soil loss for the same area (jhum) with similar grid size (100 m) further increased by 33% (75.7 ± 14.9 t ha^{-1} yr^{-1}) over the USLE-predicted soil loss (57.1 t ha^{-1} yr^{-1}) (Table 3)[20]. Such wide variation in inter-model (USLE versus MMF) estimation of soil loss in the same geo-environmental set-up, including land use, has been attributed to differences in the model configurations, model-specific techniques of parameter estimation, spatial resolution of the datasets used, etc. MMF ignores ground slope conditions and considers the least values of soil loss between splash detachment and overland flow. This results in more sensitivity to the least values of detachment rate in the model[20]. The coarseness in soil texture of the watershed (sand to sandy loam) in Dikrong river basin has reduced the water-holding capacity of the soil and restricted rooting to shallow depths. This has been further aggravated by poor land and crop management practices in the jhum areas, thus yielding higher overland flow. Zonunsanga[21] reported a considerable increase in USLE-estimated annual soil loss when dense forests were (canopy density >40%) transformed into jhum than into open forests (canopy density <40%) and plantations in a hilly macro-watershed at Teirei (Mizoram) (Table 3 and Figure 8). The estimated annual soil loss increased from 10–20 t ha^{-1} yr^{-1} in the forests (at steep slopes) to >40–80 t ha^{-1} yr^{-1} in jhum than in the open forests (20–40 t ha^{-1} yr^{-1}). The loss of top fertile soil, organic matter and soil structural degeneration under high rainfall

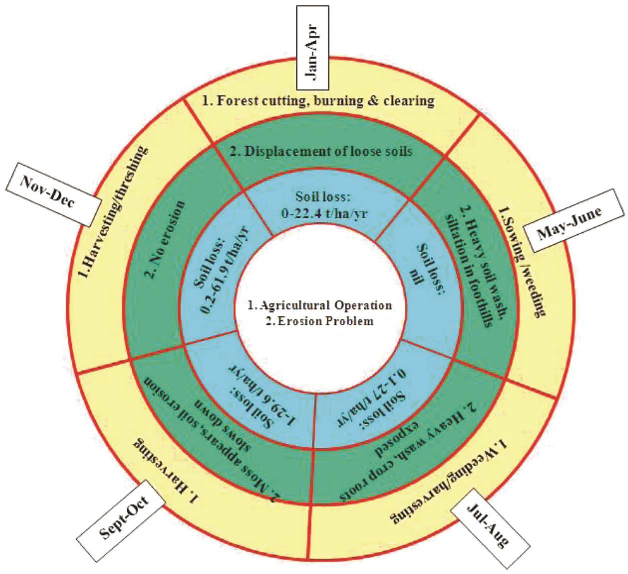

Figure 6. Year round agricultural operations and associated soil erosion calendar in jhum cultivation practised across NER (adopted and modified from Satapathy and Sarma[5]).

Table 2. Rate of soil erosion under different land-use practices in NER

Land use	Soil loss (t ha^{-1} yr^{-1})
Natural bamboo system	0.04–8.2
Grass cover (planted)	10.83
Mixed crop of maize and rice	19.7–21
Homestead area	16.8
Abandoned jhum fallow	30.2
Bun cultivation	40–50.0
Tuber crop on raised bed	40–50
Road construction	67.2
Slope cultivation with contour bund	68
Pineapple along the slope (first two years)	6.3–62.6
Cropping system	51–83.8
Bare fallow land	83.8
Shifting cultivation	10.37–153.1

Source: Refs 5, 25, 46, 64.

Table 3. Overview of run-off, soil erosion/sediment yield under shifting cultivation (jhum) in NER

Study site	Area	Average rainfall (mm)	Elevation (m amsl)	Slope (%)	Description	Run-off (mm)	Soil loss (t ha^{-1} yr^{-1})	Reference
Dikrong river basin, Arunachal Pradesh	152,800 ha	1,519.4–4,169.4	84–1,426	<15 to >45	Humid climate with average temperature (T_{avg}) ranging from 10°–32°C	410.8–1611 (571.6 ± 233.3)	–	19
						–	19.2–155.5 (51 ± 32)	11
						–	21.1–172.8 (57.1 ± 36.5)*	20
							48.9–101.64 (75.7 ± 14.9)#	20
Teirei watershed, Mizoram	68,800 ha	2,796	718	0 to >25	Annual temperature (T) of 21.7°C	–	Trace to >40	21
Assam	23,550 ha	1,300–3,200	45–1,960	–	Subtropical climate		38.98	23
Karbi Anglong, Assam	1,048 ha	1,200	75–900	0 to 17	T_{avg} ranging from 18°–30°C	0.3–147.7 (34.5 ± 37.9)	Trace to 52.5 (10.37 ± 16.62)	25
North Cachar Hills, Assam	1,036.5 ha	1,200–1,800	600–1,866	–	Relative humidity (RH) of 73–84% along with T_{avg} ranging from 10°–30°C	1.3–214.8 (35.8 ± 55.5)	Trace to 76.8 (24.28 ± 27.82)	25
Umroi watershed, Meghalaya	239.4 ha	2,508.8–2,842.5	900–1,240	>0 to 100	Temperature ranging from 3.9°–32.5°C, RH of 51–96% with average evaporation of 4.1–6.6 mm/day		21.91 to 76.5 (21.92 ± 0.02)	16
Shillong, Meghalaya	–	–	–	60 to 79	Undulating topography with high-intensity rainfall	–	30–170	18
Khasi Hills, Meghalaya	40 m^2	1,800–1,900	1,500	40	Humidity of 84% with T_{avg} of 16°–24°C	542–845	49.7–56.3 (53 ± 3.3)	29
Cherrapunji, Meghalaya	2.58 ha	11,000–12,000	1,820–1,850	20–40	T_{avg} ranging from 10°–21°C with a subtropical climate		6.3–72.3 (53 ± 19)	31
Wokha, Nagaland	15,410 ha	1,940	1,313	–	Warm temperature ranging from 2°C to 32°C with T_{avg} of 17.8°C	–	91.8–229.5 (153.1 ± 68.99)	46
Changki, Nagaland	–	–	–	>15	T_{max} ranging from 24°C to 33°C, T_{min} from 12°C to 25°C with a subtropical climate	–	29.75–38.1	63
Umiam, Meghalaya	–	–	–	–	Temperature ranging from 3.9°C to 32.5°C, RH of 51–96% with average evaporation of 4.1– 6.6 mm/day	–	1.5–42.0	64

*USLE estimation; #MMF estimation.

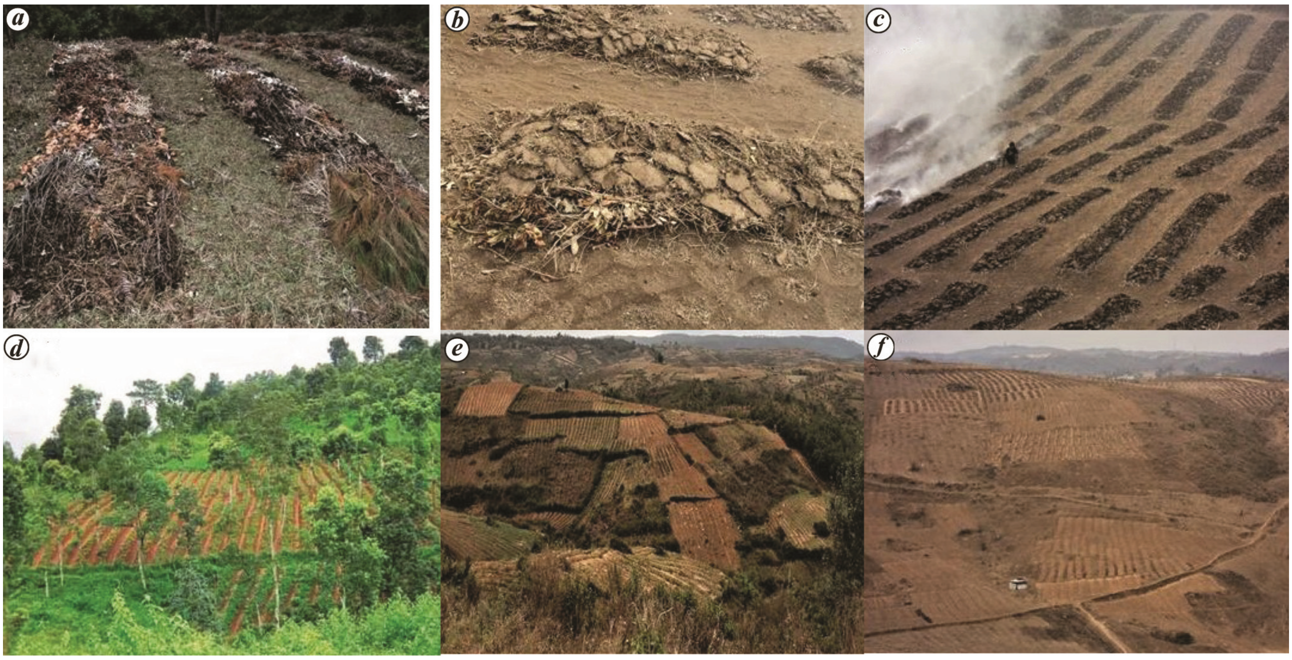

Figure 7. Soil erosion processes in traditional agriculture (bun cultivation)-based land uses associated with (***a***) deforestation and placing biomass over raised beds, (***b***) covering phytomass with soil layer, (***c***) cooling of soils in post-burned beds, (***d***) cultivation of vegetables in beds under bun system, (***e***) vegetable post-harvest buns, prone to erosion and (***f***) eroded forested hills after 2–3 years of bun cultivation[9].

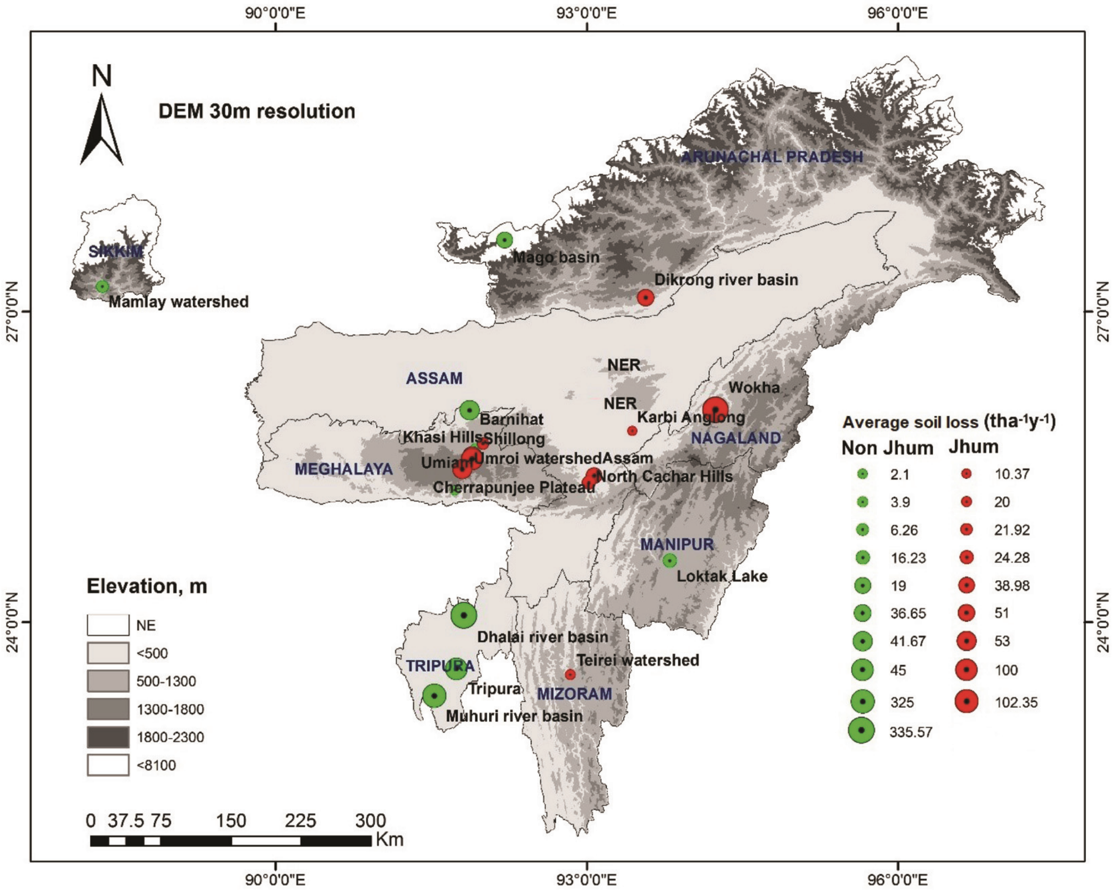

Figure 8. Average soil loss reported under jhum and non-jhum land use practices across NER (prepared based on all previous studies on erosion loss in NE India). The values of soil loss reported in the map are the average values from Tables 3 and 4.

(2796 mm annually) in the sparsely covered jhum areas caused high overland flow and a higher rate of soil loss along the steep slopes.

In Assam, considering the permissible limit of annual soil loss at 4.5–11.2 t ha^{-1} (ref. 22), almost 65% area of the state (7.8 M ha)[12] remained over the permissible range[23]. Using the USLE model, Sen *et al.*[23] estimated an annual soil loss of 306 Mt (38.8 t ha^{-1}) over Assam (Table 3), and demarcated that the flood-prone Brahmaputra valley was the most vulnerable part of the state. Area under SC in Assam reduced from 839,148 ha in the 2000s to 6000 ha, in 2015 (refs 10, 24). It is now mostly confined in two hilly districts (Karbi Anglong and North Cachar (NC) Hills) of the state. The long-period (1986–2000) measured annual run-off loss was 8–12% (in Karbi Anglong) and 12–17% (in NC Hills) of the total annual rainfall (1200–1800 mm) respectively, in the jhum areas of the districts (Table 3 and Figure 9)[25]. The measured long-period (15 years) interannual average soil loss was almost double (24.28 t ha^{-1}) than the permissible limit in the NC Hills, while it was 10.37 t ha^{-1} in Karbi Anglong. The highest loss in a single year exceeded 52 t ha^{-1} in Karbi Anglong and 76 t ha^{-1} in NC Hills[25]. The measured soil loss was proportional to run-off and due to higher rainfall (>1200 mm annually), they were nonlinearly related (coefficient of determination, $R^2 = 0.794$) (Figure 9). In low-rainfall areas, the relationship among rainfall, run-off, soil loss and sediment yield was linear, but became nonlinear with high-intensity rainfall[26,27].

Singh *et al.*[28] estimated sediment yield using the water erosion prediction project (WEPP) model in the high-rainfall (>2400 mm annually), hilly, mini watersheds (>0.50 to <4.0 ha) at Umiam, Meghalaya. They also reported four times greater sediment yield under jhum (36.6 kg ha^{-1} mm^{-1} rainfall) than terraced cultivation (8.6 kg ha^{-1} mm^{-1} of rainfall) of maize based on agricultural land use. From a plot-level study (40 m^2) under jhum cultivation in the hilly ecosystem of Meghalaya (Khasi Hills, Shillong), Mishra and Ramakrishnan[29] measured several-fold higher annual soil loss (49.0–56.3 t ha^{-1}) than the critical limit (12.5 t ha^{-1} yr^{-1}). Shortening of the fallow cycles (from 10 to 5 years) increased soil loss by another 13% (Table 3). The higher soil loss was attributed to 55% higher surface run-off in plots with a five-year fallow cycle than those with a ten-year fallow cycle (542 mm). Short fallow cycle encourages degradation of vegetative surface and corrosion of soil aggregation, thereby enhancing the susceptibility of rainfall erosivity and soil erodibility, especially in steep slope areas[6,23,30].

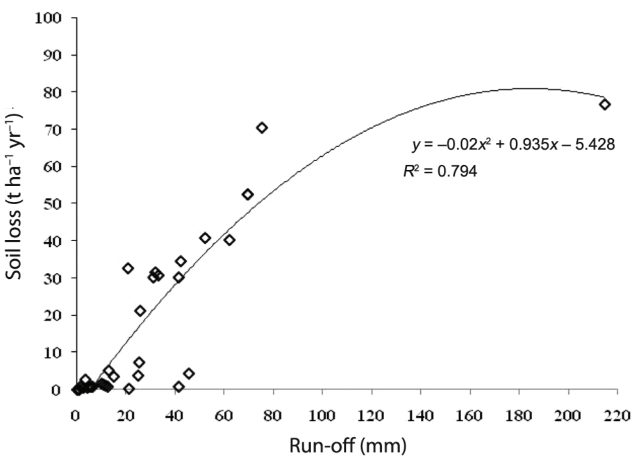

Figure 9. Relationship between long-term (1986–2000) observed soil loss and run-off under jhum cultivation from two hill districts of Assam (Karbi Anglong and North Cachar Hills) (modified from Baruah *et al.*[25]).

Singh *et al.*[16] reported twofold higher measured average soil loss (48.7 t ha^{-1} yr^{-1}) in a one-year-old bun (nearly 22 ha) in a hilly micro-watershed (239.4 ha) at Umroi, Meghalaya, than that from the entire watershed (WEPP simulated: 21.9 t ha^{-1} yr^{-1} against measured: 23.0 t ha^{-1} yr^{-1}) (Figure 8). The soil loss further increased to 76.5 t ha^{-1} yr^{-1} when one-year-old bun was brought under paddy cultivation (Table 3). However, soil loss reduced substantially (29.1 t ha^{-1} yr^{-1}) when cultivation was abandoned (left fallow). Bun cultivation along the steep slopes in high-rainfall hilly areas encourages scouring action of run-off flow (37% of total rainfall) to form rill and inter-rill erosion channels. Abandoned buns take many years to stabilize the structurally degenerated soil and reduction in soil erosion rate[16]. Using radio-tracer cesium (^{137}Cs) technique, Poreba and Prokop[31] estimated soil loss in a small catchment (2.58 ha) of the world's highest annual rainfall (>11,500 mm) receiving zone in Meghalaya (Cherrapunji plateau). In the foothills, soil loss varied from 6.3 to 21.3 t ha^{-1} yr^{-1}, while in intermittently cultivated buns in the hilly eroded slopes with short fallow cycles (2–3 years), the loss was several-fold higher (34.3–72.3 t ha^{-1} yr^{-1}). Long-period intermittent bun cultivation with a decline in fallow periods from 5–10 to 2–3 years encouraged a progressive decline in vegetative cover (Figure 7) and frequent destabilization of the soil. In post-jhum and post-bun cultivation, the soil surface in the steep slopes becomes barren. High-intensity rainfall during monsoon months on the barren soil surfaces degenerates soil aggregation and causes blocking of soil pores. This reduces infiltration and percolation (downward movement), and increases run-off and soil loss. Extremely high rainfall along the steep slopes further accelerates the downwash of topsoil and thus, soil loss increases several-folds higher than the tolerance limits.

Soil erosion studies under non-shifting cultivation in NER

Two major rivers of the region, namely Brahmaputra and Barak, transport an annual run-off of 597 km^3 water

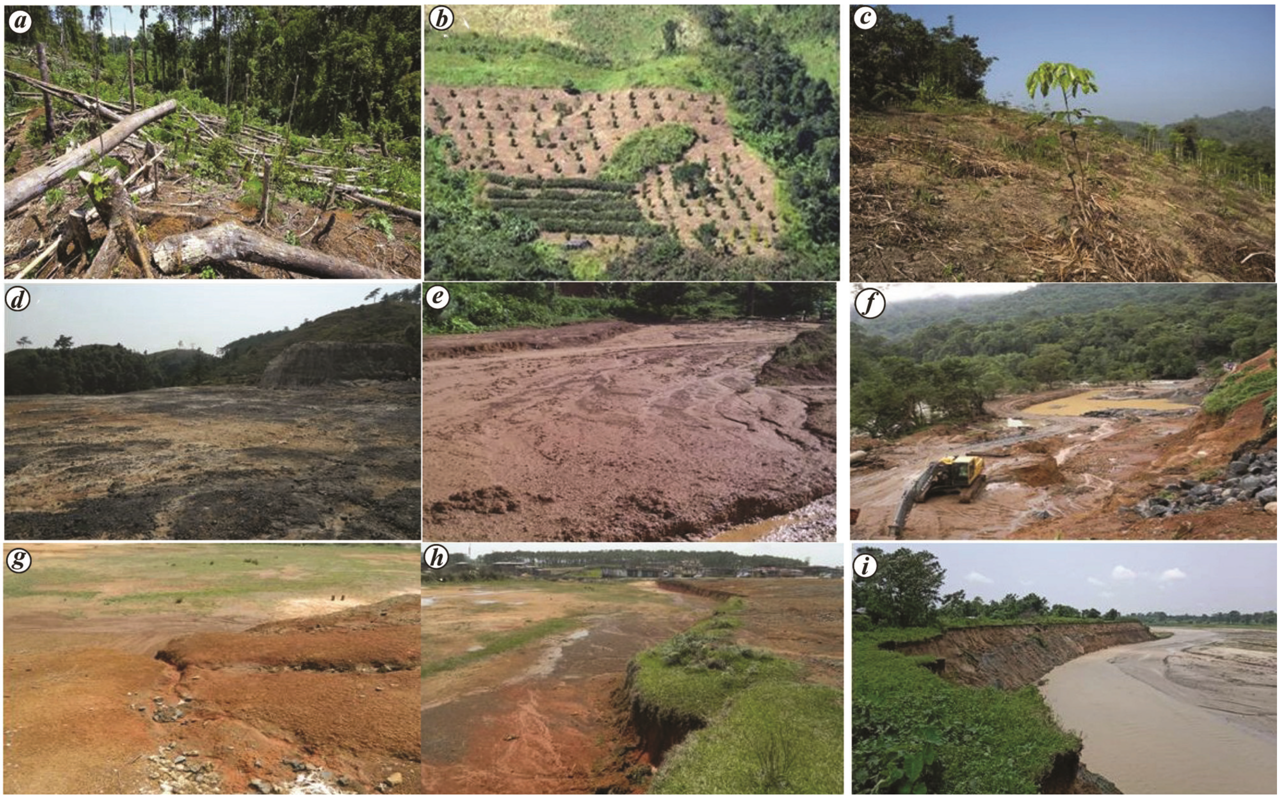

Figure 10. Soil erosion processes in non-jhum land uses associated with (***a***) deforestation, (***b***) cultivation of oranges, (***c***) rubber plantation, (***d–h***) sheet and rill erosion and (***i***) a river bank erosion in non-jhum land uses. Photo courtesy: (***a***) Northeast now; (***b***) Indian Council of Forestry Research and Education, Mizoram; (***c***) T R Shankar Raman; (***e***) TWIN; (***f***) *Deccan Herald* and (***i***) Sentinel Digital Desk.

loaded with nutrient (NPK: 17,040 t)-rich sediments (88.3×10^6 t soil)[32]. Flooding followed by massive erosion of the banks of these mighty rivers and their tributaries, causing permanent loss of agricultural and non-agricultural land, is a common phenomenon (Figure 10). The sediment load in run-off water varies from 1500 to 3000 mg l^{-1}, with a mean of 2250 mg l^{-1}. Deforestation followed by cultivation of plantation and fruit crops (e.g. rubber, oil palm, oranges, etc.) and mining (coal/sand) activities along the slope in hilly upstream areas result in transportation followed by deposition and siltation of huge sediment loads in the downstream water bodies, which is a common feature in the region (Figure 10)[32]. This practice silted nearly 10% area in one of the largest (1046 km^2) freshwater lakes of the region (Loktak in Manipur). Using the radio-tracer technique (lead-210), Singh *et al.*[33] estimated an annual soil loss of 13.5–18.6 t ha^{-1} in the upper hilly catchments of the lake under various land uses (cultivated fallow, paddy and mixed forests). The average soil loss from the entire catchment area of Loktak was 16.23 t ha^{-1} yr^{-1} and nearly 0.34 metric tonnes of silt load is being deposited in the lake annually (Table 4). This causes the occurrence of frequent floods, thus leading to severe soil erosion, soil and nutrient loss.

Climate (particularly rainfall intensity), land-use practices, vegetative cover, elevation, slope and other characteristics, including soil properties and configuration of watersheds play a significant role in influencing soil erosion. Using $^{210}Pb_{ex}$ and ^{137}Cs activity in the soil, Froehlich[34] observed an erosion rate of 2 t ha^{-1} yr^{-1} from grasslands on the hill slopes of Maw-Ki-Syiem drainage basin, Meghalaya. From an assessment on erosion vulnerability using the E_{30} model in a hilly, mega-watershed (71,500 ha) at Kynshi in Meghalaya, Sinha *et al.*[35] reported wide variation in predicted annual soil erosion rate from traces to 583 mm yr^{-1}, and attributed this to the varied slope (30–50%), elevation (25–1400 m), and vegetative cover (dense forest to shrub) in the watershed. Effective SWC measures (such as contour bunds, bench terracing, trenches, etc.) and sustainable land-use practices, however, help in reducing soil erosion. In two hilly (slope 32–52%) micro-watersheds at Byrnihat and Umiam in Meghalaya, Singh *et al.*[36] measured an annual soil loss of <0.5 to 7.8 t ha^{-1} yr^{-1} under forests (pine and bamboo). However, with the cultivation of agricultural crops without any SWC measures, soil loss increased to 83.3 t ha^{-1} yr^{-1}. On the adoption of SWC measures in agricultural land uses, the measured soil loss decreased by several folds (5.0–10.0 t ha^{-1} yr^{-1}). The soil loss further decreased to ≤2.0 t ha^{-1} yr^{-1} when cultivation practices were done in integrated farming system (IFS) mode with adequate SWC measures. Rai and Sharma[37] reported long-period

Table 4. Overview of run-off, soil erosion/sediment yield under different non-jhum land uses in NER

Study site	Area (ha)	Average rainfall (mm)	Elevation (m amsl)	Slope (%)	Soil loss (t ha^{-1} yr^{-1})	Description	Land use–land cover (LULC)	Reference
Loktak lake, Manipur	104,600	1,183	780–2,068	>35	13.5–18.6 (16.23 ± 2.13)	Temperature ranging from 0°C to 35°C	Lake	33
Maw-Ki-Syiem drainage basin and	21.0	8,000–24,000	1,308–1,390	–	2.10	Soils range from Alfisols, Inceptisols to Ultisols	Agriculture	34
Kynshi basin, Meghalaya	564,500	Maximum up to 10,000	25–1,400	30–50	0–583 (mm/yr)	A mild tropical climate with temperature ranging from sub-zero to 28°C	Vegetation shrub, moderate forest cover	35
Byrnihat, Meghalaya	–	1,600	100	40–45	0.04–83.30	–	Experimental plots on different farming systems with and without engineering measures	36
Umiam, Meghalaya	–	2,554	1,000	32–52	Trace to 7.8	–		36
Mamlay watershed, Sikkim and	3,014	1,494–2,100	300–2,650	30–40	4.18–8.82 (6.26 ± 2.27)	T_{avg} ranging from 14°C to 27°C	Agriculture	37
Tripura	1.02 × 10^6	2,000–3,000	15–780	–	>10–>80	Humid subtropical climate with RH ranging from 100% to 42%	Mixed LULC	38
Dhalai river basin, Tripura	67,813.6	2,150	11–836	–	43.15–628 (165.48 ± 138)	T_{avg} ranging from 10.5°–35°C	Degraded forests, agricultural land	39
Muhuri River basin, Tripura	62,440	2,072–2,496	50	–	0–650	Maximum RH during June	Agriculture	40
Mago basin, Arunachal Pradesh	83,900	1,139	2,355–6,436	–	5.0 to 33.0	The region is characterized by narrow undulating features	A mix of various LULC	41

(10 years) average annual soil loss of 4.18–8.82 t ha^{-1} yr^{-1} when dense forests were transformed to large cardamom-based agroforestry systems in a hilly (slope 30–40%) milli-watershed (3014 ha) at Mamlay in southeastern Sikkim.

In Tripura, nearly 10% area under mixed forests was degraded to wasteland and some areas were converted into agricultural land uses. Bhattacharyya *et al.*[38] estimated the effect of this land-use change on high rainfall-induced soil loss using USLE at coarser grid resolution (500 km × 500 km) for the state. They reported that nearly 30% of state area (10,492 km^2) experienced average soil loss of >10–80 t ha^{-1} yr^{-1}, while in the wastelands soil loss was extremely severe (>80 t ha^{-1} yr^{-1}) (Table 4). Other studies also affirmed that land-use change along steep slopes is one of the major factors of soil loss in Tripura[38,39]. Using modified USLE in the Dhalai river basin, Tripura, Ghosh *et al.*[39] estimated wide variation in annual soil loss ranging from 11 to 836 t ha^{-1} yr^{-1}. In the dense forest, estimated soil loss was <50 t ha^{-1} yr^{-1}, while in the degraded forests and forests converted to agricultural lands (one-third of total 678 km^2 basin area), soil loss exceeded 200 t ha^{-1} yr^{-1} and recorded over 800 t ha^{-1} yr^{-1} (Table 4). Nearly 70% area of the basin had an estimated soil loss of >50 t ha^{-1} yr^{-1} and it was more severe (>200 t ha^{-1} yr^{-1}) in the middle portion of the basin under degraded forest or used for cultivation with high soil erodibility factor (K) value. Similarly, another basin in Tripura (Muhuri basin, 624.4 km^2) experienced rapid degradation of forests from 45% basin area in 1972 to <10% area by 2016. Another 11.4% and 24% forest areas in the basin were transformed to agriculture and rubber plantations respectively. Using the USLE model, Bera[40] estimated marginal to 650 t ha^{-1} yr^{-1} soil loss in the Muhuri river basin of Tripura (Table 4 and Figure 10 *e*). Forest and rubber plantation areas had annual soil loss below tolerance limit (<12.5 t ha^{-1}), while agricultural areas had 10–25 t ha^{-1} annual soil loss. In the high-rainfall (>3353 mm annually) receiving downstream catchments and valleys, soil loss exceeded 70 t ha^{-1} yr^{-1} and reached up to 650 t ha^{-1} yr^{-1}. Due to faulty land-use practices (jhum, agriculture and deforestation) in the upper catchments, nearly 20% downstream area experienced several folds higher soil loss than the critical tolerance limit. Despite having 57% area under mixed forests with deep soils (>150 cm depth) under humid climate, the state lost topsoil at 15.17 Mt yr^{-1} across 1.02 M ha area, mostly attributed to the land-use change from forests to agriculture and degraded scrub forests or wastelands.

Using revised USLE (RUSLE), Bhadra *et al.*[41] estimated long-period (10 years) soil erosion in a milli-watershed (Mago basin: 839 km^2) in Tawang district of hilly Arunachal Pradesh. The basin is characterized by narrow, undulating features with elevation ranging from 2355 to 6436 m amsl and average annual rainfall of 1139 mm. In terms of severity of soil loss, the variation of annual soil loss showed a reduction under slight soil erosion class (<5 t ha^{-1} yr^{-1}), while it increased under moderate (5–10 t ha^{-1} yr^{-1}) to very severe soil erosion classes (>80 t ha^{-1} yr^{-1}) in the areas where forests were transformed to cultivated lands or scrubs. Thus, across NER, land-use change along with hilly topography under high rainfall is one of the primary factors of severity of soil erosion and loss of topsoil.

Conservation measures to check soil erosion in the hilly North East India

The area under agriculture in the region is only 3.77 M ha (14.4% of TGA) and 76% of this is under lowland paddy cultivation mostly in the alluvial plains (valleys of Brahmaputra, Barak, Imphal, Tripura and Meghalaya)[42]. The remaining 0.82 M ha area (<3.5% of TGA) is under settled cultivation (0.50 M ha) and SC (0.32 M ha) in the hilly uplands[10]. The frequent occurrence of floods in the valleys has restricted the farmers to cultivate only paddy crops in the lowlands, since paddy survives excess moisture and standing-water regimes. This compels the farmers to grow other food crops (upland rice, maize, pulses, oilseeds, fruits, etc.) in the hilly uplands by unsustainable soil erosion encouraging methods (jhum, bun and cultivation along the slopes). Therefore, adoption of effective and possible SWC measures in hill agriculture is the only option to reduce severity of soil erosion.

Traditional SWC measures

Farmers of the region have developed many indigenous, traditional SWC measures over the years, but they have remained location-specific and discrete. The popularization of these effective methods across NER is needed. Some of these well-established and well-documented methods are described below[3].

Zabo or ruza system: This is an integrated community-based farming system for effective rainwater management and prevention of soil erosion (Figure 11 *a*). Slope gradient is a key factor in determining the allocation of specific land-use practices. The summit of the hill is guarded under the protected forest (silviculture), while siltation tanks followed by ponds to store run-off water are constructed in the middle of the hill. Run-off water is stored in the siltation tanks for 2–3 days and then the filtered water (silt-free) is channelled through the inlet channels into the main ponds. De-silting of tanks is carried out annually or depending on the amount of silt deposited. On the banks of the pond, horticulture (vegetables and fruits like squash, colocasia, cucurbits, banana, papaya and citrus) is practised. Livestock such as cattle, buffalo, goat, pig and poultry are reared in the mid-hill stretches. This facilitates fertilization of paddy fields in the foothills from animal manure, urine and other washes.

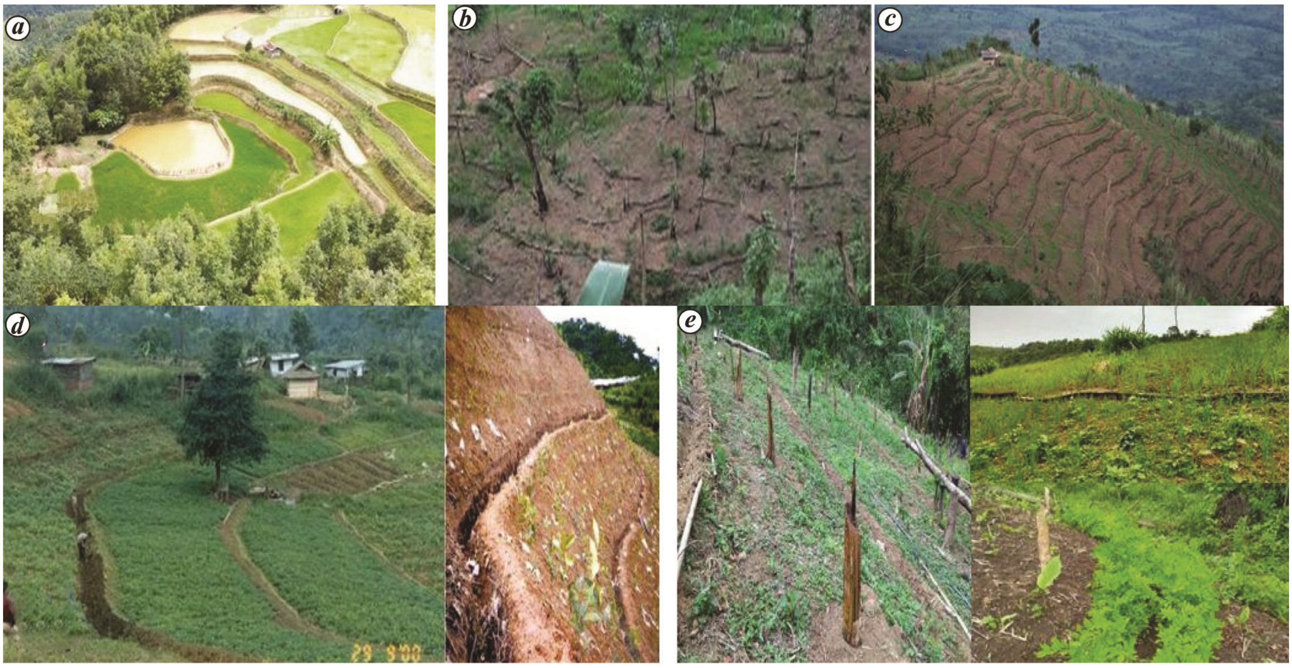

Figure 11. Soil and water conservation measures in traditional farming such as (***a***) Zabo, (***b***) Echo[43], (***c***) Modified echo[46], (***d***) Contour trench and (***e***) SALT[47]. Photo courtesy: (***a***) Directorate of Information and Public Relations, Nagaland; (***d***) Tamil Nadu Agricultural University, Agritech portal.

Terracing is followed in the middle hill and paddy growing on terraces is practised all along the slope. The paddy fields are irrigated using water stored in the ponds at the middle of the hills, either by open channels or using bamboo pipes[43]. On many occasions, paddy-cum-fish farming is practised in low-reach terraces (in the foothills), recharged from the base flow and seepage losses from the top of the hill. In some areas, if the topography is not conducive to terracing, run-off from the watershed is diverted directly to the rice fields for irrigation[44]. The basic structure of the system allows maximum interception of rainfall at the top of the hills through forest vegetation while increasing infiltration, reducing the kinetic energy of the falling raindrop to initiate the erosion process. The retention ponds in the middle of the hills and terraces with the adoption of specific land-use systems, including rice paddies, further reduce the flow velocity and volume of run-off. The resulting effect makes the zabo farming system capable of preventing soil erosion while ensuring food and nutritional security.

Echo system: This is an indigenous method to conserve soil and water in hilly watersheds under SC-based land-use practices. In its traditional form, locally available bamboo and wooden logs are randomly placed at a vertical interval of 3.0–4.0 m along the hill slopes depending on the degree of the slope (Figure 11 *b*). Steeper the slope, shorter is the vertical interval, thus requiring more logs. The logs are placed in a zigzag pattern at the base of the cut and burned trees so that overland flows cannot carry them away. By controlling run-off flows, echo reduces sediment yield and soil loss from the watershed. This translates into increased infiltration, increased water recharge in the soil profile and increased availability of nutrients to maintain crop productivity[45]. Echo is economical because local bamboo and wood logs are easily available and can last at least 3–5 years. Singh *et al.*[46] modified this traditional approach by introducing mechanical soil and water conservation measures. In the modified system, shallow contour bunds are prepared across slopes and wood/bamboo logs are placed in the contours only (Figure 11 *c*). This allows the formation of a permanent contour-bunding system over time and is more effective than the traditional echo in reducing run-off and soil loss. In addition, the echoes along the contour lines cannot be easily swept away by flashfloods. It rather captures scoured particles and stabilizes and converts them to a permanent contour, thus avoiding periodic placement of logs/bamboo every 3–5 years. This was validated in the jhum-cultivated hilly watershed (size 15,410 ha) in Wokha, Nagaland. Modified echo could retain 229.5, 153 and 91.8 t ha^{-1} yr^{-1} of soil in the first, second and third years of adoption respectively (Table 3)[46].

Contour trench farming system: In this method, hills with slopes of more than 15% are converted into cultivation by constructing contour trenches across the slopes to prevent soil erosion and are used as a way to conserve more rainwater (Figure 11 *d*). Contour trenches are ditches excavated along a hill in such a manner that they follow the same elevation and run perpendicularly to the flow of water. The soil dug serves as a berm on the downside of the ditch[43]. The trench interval varies (1.4–3.1 m) with slope gradient; steeper slopes have a narrow trench interval, whereas milder slopes are farther apart. The size of the trench depends on local climatic and soil conditions; it should be large enough to retain all water and no water should flow over the bottom edge. Contour trenches slow down the overland flow of water and thus, reduce run-off velocity down the slope. They also increase deep percolation, reduce evaporation loss and help the crop overcome moisture stress in later stages of growth. Trenches trap eroded soils that are generally highly fertile and their use on the lower slopes improves soil fertility. The trenches are silted by soil erosion, requiring physical removal, which is carried out each year before the onset of monsoon. The run-off collected in the trenches allows enough time to seep into the soil, replenishes the moisture in the soil profile and thus provides enough water to support agricultural production[44].

Sloping agricultural land technology approach: To address the challenges of soil erosion faced by the Jhumias (shifting cultivated farmers) in the hilly regions, the sloping agricultural land technology (SALT) project was launched and led by Gandhi[47]. It involves planting nitrogen-fixing plants to create a vegetative barrier (hedgerows) along the contours in order to control surface run-off and soil loss (Figure 11 *e*), while enhancing soil fertility by nitrogen fixation. The hedges are pruned regularly and the clippings are applied to the inter-row strips as mulch. The strips between the hedges are planted with field crops, vegetables and trees. Legume forage crops are harvested periodically to feed small animals such as goats, which are part of the system. A SALT pilot project was successfully implemented in Aben village, Manipur, during the monsoon season in 2017 and showed great potential for adaptation in shifting cultivated areas. This can be applied to similar land uses in the northeastern hilly region. It is a less labour-intensive and climate-friendly sedentary agriculture that provides enough food for a family.

Structural/engineering measures

In addition to these native SWC techniques, engineering interventions such as contour strips, graded bunds, bench terraces, half-moon terraces, grassed waterways, water-harvesting ponds and impoundments such as a spillway, rock-filled dam and loose boulder check dam are also required to reduce soil erosion. These conservation techniques on 2–8% sloped plots can reduce run-off from 8% to 40% and soil loss from 6% to 35% (ref. 48).

Contour bunding: This is a SWC measure for retaining surface run-off to control soil erosion. It is particularly suitable for slopes between 4% and 8% (Figure 12 *a*). When bunds are constructed on contour lines, they are considered as contour bunds. They become graded bunds when a grade is provided along the bunds for safe disposal of run-off water. Contour bunds are not suitable for clay soils and on land slopes >8%. Their main function is to reduce the length of the slope and refill the soil with water impounded for crop cultivation. Graded bunds are generally adopted on less permeable soils that are susceptible to water erosion and have waterlogging problems. They are strongly recommended for slopes of 6–10%, which receive high annual rainfall exceeding 750 mm. Small variations in the grades are provided in different sections to keep the run-off velocity within permissible limits and not cause any soil erosion. Mane *et al.*[49] reported that the graded bund with vegetative hedge was highly effective in controlling surface run-off (<72.0 mm) and soil loss (<2.0 t ha^{-1}) on steep slopes in the Konkani–Maharashtra region.

Terracing: A terrace is an earthen embankment constructed across the slope to control run-off and minimize soil erosion (Figure 12 *b*). It acts as an intercept to land slope, thereby shortening slope length, and divides the hill slopes into strips. The run-off and soil eroded by overland flow are blocked by terraces. By reducing the length of the slope, the run-off rate remains below the critical value and, consequently, abrasion-induced soil erosion can be avoided. Terraces can be broadly classified into two major types: broad-base terraces and bench terraces. Broad-base terraces are adopted where water needs to be removed or conserved in sloping land, whereas bench terraces are adopted where the primary objective is to reduce the slope of the land. Bench terraces are conservation structures where steep slopes are slowly converted into a series of level steps and ledges to arrest run-off and reduce soil erosion. These are mostly recommended for hill slopes of 6–30%, which receive high annual rainfall. As bench terraces involve the construction of a series of platforms along contours cut in a step-like formation, they are used in agricultural fields and orchard plantings where climatic conditions are conducive to cultivation. Sharda *et al.*[50] reported that conservation bench terrace systems reduce run-off from 36.3% to 7.4% and soil loss from 10.1 to 1.19 t ha^{-1} compared to the conventional system in the experimental plots of the western Himalaya (Selakui, Dehradun, Uttarakhand). On long periods (1991–2005) of adoption, run-off and soil loss had reduced by 78.9% and 88% respectively, at the same site[51].

Trenching: This is mainly used for slope stabilization and drainage line treatment. It acts as a flow barrier, restricting the flow velocity within safe limits, and facilitating *in situ* water conservation and groundwater recharge through percolation (Figure 12 *c*). Generally, trenches can be divided into four types: continuous contour trench (CCT), graded contour trench (GCT), line trench and staggered contour trench (SCT). CCT is suitable for low

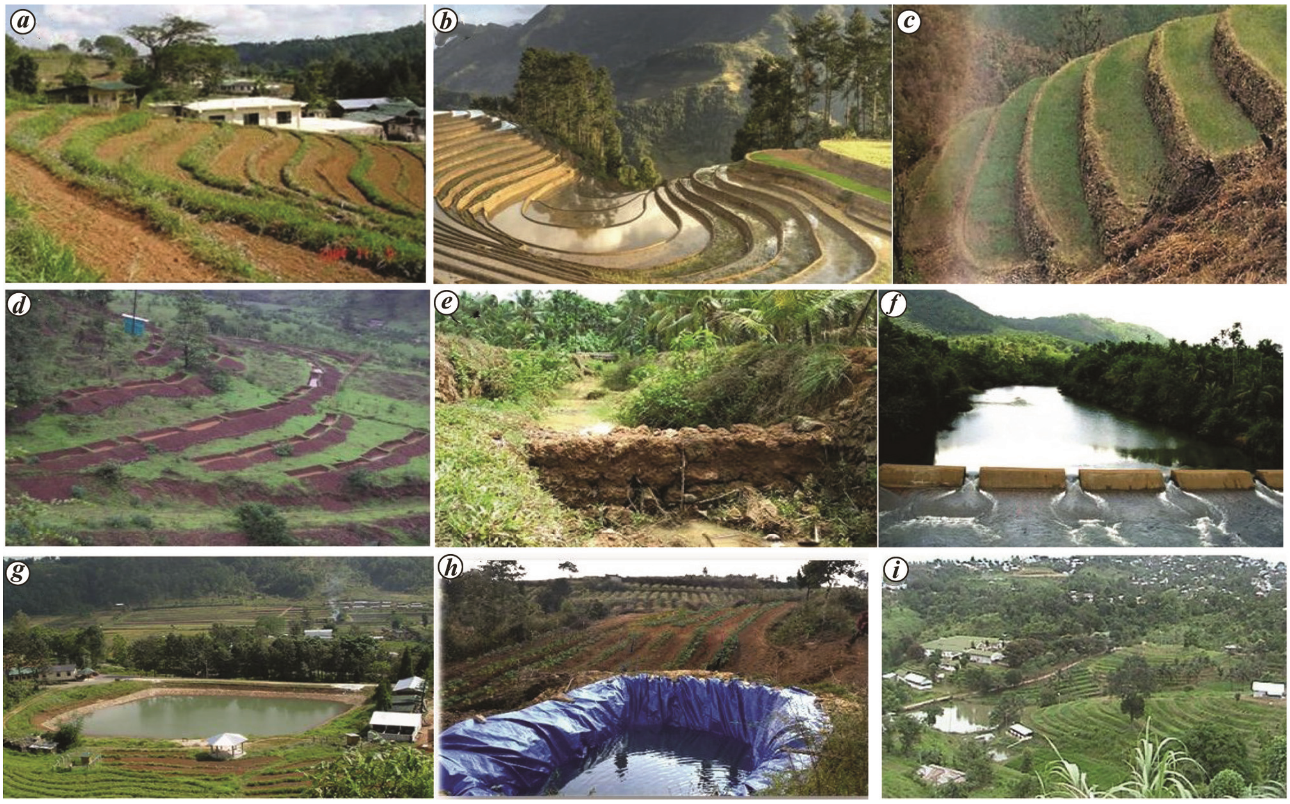

Figure 12. Soil and water conservation measures using structural/engineering methods such as (***a***) contouring, (***b***, ***c***) bench terracing, (***d***) contour trench, (***e***) loose boulder check dam, (***f***) RCC check dam, (***g***) retention pond, (***h***) jalkund and (***i***) IFS. Photo courtesy: (***a***, ***e–i***) ICAR Research Complex for NEH Region; (***b***) farmers of Meghalaya and (***d***) Low External Input Sustainable Agriculture, India.

to medium annual rainfall areas (up to 1000 mm) with land slopes <6%. GCT is recommended in areas with annual rainfall between 1000 and 1200 mm, and a slight slope of 0.1–0.5% is given for the safe removal of retained water. SCT is recommended in high-rainfall areas (>1200 mm annually) and on steep hill slopes (10–50%). These trenches are built to allow part of the run-off to escape. Trench-cum-bund structure in the Eastern Ghats of Odisha reduced run-off loss by 8–10%, while maintaining soil losses below 10 t ha^{-1} (ref. 52).

Semi-permanent structures: These structures like rock-filled check dams, loose boulder check dams, geo-textiles, sand-bag check dams, gravel bags, retaining walls with bamboo mats, concrete stacked blocks, etc. are efficient in controlling gullies and erosion by reducing the rate of flow (Figure 12 *d* and *e*). They may be adopted according to the availability of the raw materials required. For instance, rock-filled dams are preferred in areas where loose rocks are readily available and where vegetation cannot be established to reduce the rate of flow. They are built using stones laid across the width of the ravines that are packed with galvanized wire grills with the provision of spillway for safe disposal of water. A non-erodible apron should be provided at the base to dissipate the energy of water falling through the spillway. From a WEPP simulation study, Singh *et al.*[16] reported that installing porous rockfilled dams and waste barriers in hilly watersheds at NEH (Umroi, Meghalaya) may reduce sediment yield by 54.7%.

Other SWCs: Interventions such as farm ponds, dugout ponds, lined ponds and jalkund (a small water-harvesting structure) can be installed for increasing rainwater storage at the watershed level and extend its availability in rainless periods[53] (Figure 12 *f* and *g*). They are usually constructed in areas with annual rainfall greater than 500 mm. These structures help mitigate the adverse effects of rainfall variability, allow use of water during prolonged dry spells and also help in groundwater recharge. Farm ponds are constructed at the lower section of the farms and can be used for multiple uses such as supplemental irrigation under agriculture-based integrated farming systems (IFSs). For groundwater recharge, highly permeable soil areas are best suited for constructing high-capacity structures, also known as percolation tanks.

Vegetative barriers and grasses

In addition to structural measures, vegetative measures, buffer strip crops, vegetative barriers in contour bunds, mulching (biomass and stone) and cover crops in furrows

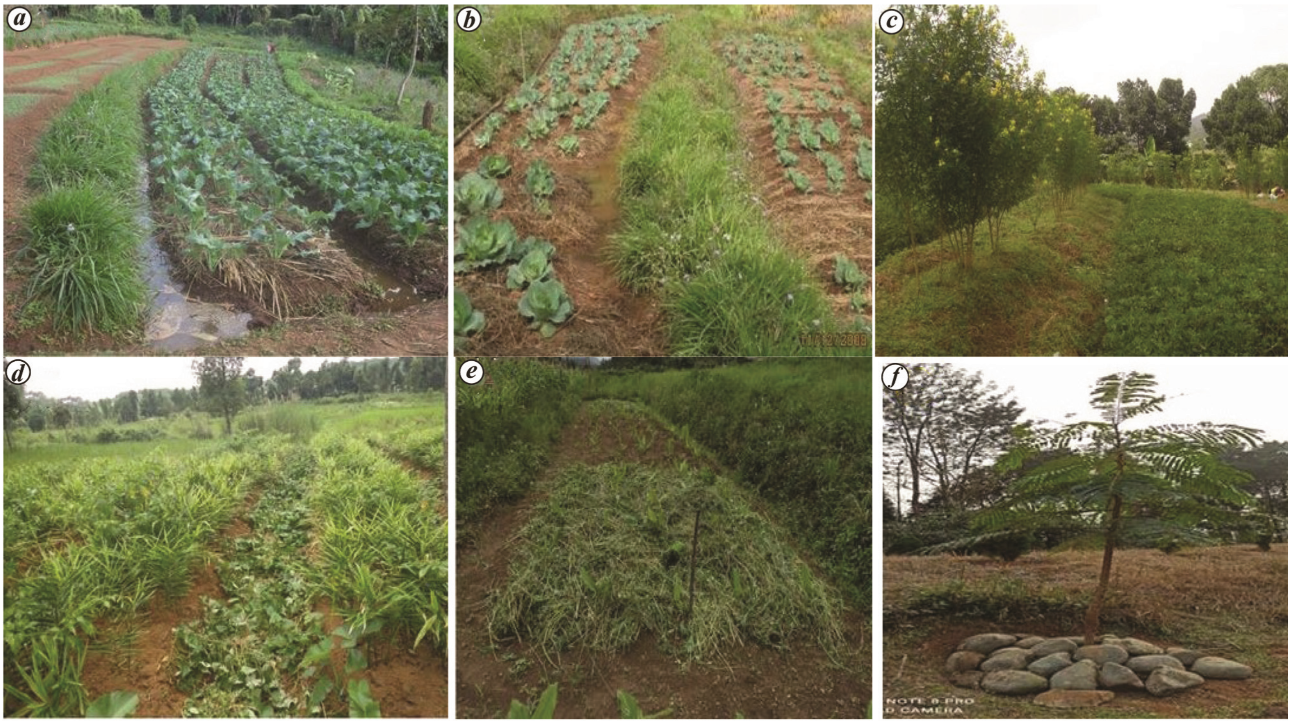

Figure 13. Soil and water conservation measures using biological methods such as (***a***) vegetative barrier in bed and furrow, (***b***) contouring with grasses, (***c***) contouring with hedge grow, (***d***) intercrop as cover crop in furrows, (***e***) weed biomass as mulching and (***f***) stone as mulch.

are necessary to conserve rainfall and in the preservation of moisture *in situ*, while reducing the number of structures to make it more cost-effective (Figure 13). Buffer strips are an inexpensive method of controlling soil erosion. They act as a sponge by absorbing run-off water and reduce the flow velocity so that it will deposit the eroded soils from the cultivated field above. They maintain soil porosity and lead to the formation of a small terrace, which transforms the landscape into gently sloping fields and banks protected by broadleaved vegetation. All leafy plants provide good coverage on erosion control strips, but the presence of deep-rooted perennial grasses improves infiltration. Lal[54] observed that *Panicum maximum* (Guinea grass), *Vetiveria zizanioides* (khuskhus) and *Eulaliop sisbinata* (bhabar) were effective in reducing overland water flow for vegetative strips in the Siwalik hills because of their erect, stiff and uniformly dense hedge formation. Growing vetiver grasses in the inter-row spaces can reduce soil loss from 142 t ha^{-1} in fallow to 1.3 t ha^{-1} in croplands[55]. Planting aromatic herbs such as citronella and lemon grass on degraded soils with slopes of up to 12% can reduce run-off from 28.9% to 34.5% and soil loss from 54.3% to 60.7% (ref. 52). Use of aromatic grass as a vegetation strip with minimum tillage and other organic amendments such as vermicompost, manure, etc. may reduce run-off and soil loss by 30% and 34% respectively[56].

Mulching and planting cover crops are effective in increasing infiltration of rain water, reducing run-off and evaporation, and protecting the soil from erosion. Organic mulches, such as crop residues, bark, dry leaves, etc. reduce the detachment and transport of soil particles through run-off water[57] and also provide essential nutrients for crops[58]. Borst and Woodburn[59] used a thin 0.6-inch layer of mulch to reduce run-off and soil erosion by 43% and 86% respectively, in silt loam of the east central part of Ohio, USA. Megahan[60] reported a 95% decrease in soil erosion when straw mulch was used in barren soil. The major challenge for mulching is adequacy in the availability of biomass production in the fields. Deep-rooted pulses as cover crops in maize crops increase soil-binding organic matter and thus help reduce the risk of erosion and run-off[61]. The expansion in the canopy of growing main crops competes for sunlight and space with pulses as cover crops. This suppresses the growth of pulses and induces deeper penetration of taproots, and gradually forms a carpet of leaves. Once the main crop has been harvested, space and light allow the pulse crops to grow faster during the few weeks when there is still enough water in the soil. The soil is covered by a carpet, promoting meso-fauna activities, including earthworms in humid tropical areas, and termites in semi-arid areas, including sandy soils.

Few researchers have reported the effectiveness of adoption of engineering concepts in living systems, known as bio-engineering measures to reduce soil erosion. Vegetative barriers, cover crops, terraces, trenches and a combination of other mechanical measures with biological conservation may be adopted to control soil erosion.

Conservation techniques such as contour farming, tillage, mulching, vegetative barriers, inter/mixed crops, etc. on 2–8% sloped plots reduced run-off from 8% to 40% and soil loss from 6% to 35% (ref. 48). Jha and Mandal[62] reported that with the adoption of biological engineering measures, soil erosion could be reduced to the specified target of 2.5–7.5 t ha^{-1} yr^{-1} in critical areas of 20–55% in a Uttrakhand watershed. Incorporation of hedgerow species in the jhum fields at Changki, Nagaland, reduced soil loss by 22% compared to traditional jhum practices (38.1 t ha^{-1} yr^{-1})[63]. Based on a simulated WEPP study, Singh *et al.*[16] reported a reduction in sediment yield of 29.6% and 27.7% when the upland paddy was replaced with soybean and groundnut respectively, in a hilly watershed of Meghalaya (Umroi).

Effects of integrated farming systems

The IFS (combining seasonal crops and multipurpose trees, including fruits) (Figure 12 *h*) developed for hilly regions offers a viable option to meet the needs of farmers while reducing soil erosion. Agri-horti-silvi-pastoral land-use system can reduce soil erosion from 42 to 1.5 t ha^{-1} yr^{-1} (ref. 64). Hazra and Singh[65] observed a reduction in soil loss from both barren hillocks (from 41.0 to 9.5 t ha^{-1}) and wastelands (from 20.5 to 5.5 t ha^{-1}) after adoption of silvi-pastoral IFS along with SWC measures. Singh *et al.*[66] established several IFS in combination with various SWC measures in the hilly micro-watershed at Umiam, as an alternative land use to SC. The conversion of forested areas to agriculture under IFS mode (specifically horticulture and agri-horti-silvi-pastoral) even in steep slopes (>40%) reduced soil loss (>10% to 15%) over dense forest. The adoption of bench terraces in hill agriculture in IFS mode could reduce annual soil loss to <8.0 t ha^{-1} yr^{-1}. Combining conservation measures such as contour bunds, terraces (half moon and bench) and grassed waterways was more effective in hill agriculture, and reduced soil erosion (by more than 25%) compared to adopting single conservation measures such as contour bund[67]. Similarly, converting traditional hill farming into a micro-watershed based on agri-horti-silvi-pastoral system in Meghalaya reduced soil loss (by 99.3%) and soil erosion (by 45.9%), while increasing soil moisture retention *in situ* (by 20.6%)[15].

Conclusion

NER has a vast area under various hilly ecosystems and extensive forest cover in almost two-thirds of its GA (26.2 M ha). The conversion of forests to croplands and the adoption of non-scientific land-use practices (e.g. jhum, bun and sedentary farming on steep slopes) are crucial factors affecting loss of topsoil and siltation in downstream areas. The predominant wet climate with high-intensity rainfall further accelerates soil loss and makes the region more prone to water erosion. The exceptionally high inter- and intra-variability in the reported annual soil loss from both the jhum (minimum to maximum: traces to 229.5 t ha^{-1} yr^{-1}) and non-jhum (minimum to maximum: traces to 836 t ha^{-1} yr^{-1}) sedentary agriculture, necessitates precision of capturing actual field variability in such studies, given that many of them are predictive in nature.

Individual initiatives for estimating soil erosion vary considerably with methodological details, watershed characteristics and most importantly, lack comparison of soil loss from pre-transformed lands to transformed land uses. Use of different hydrological models (USLE/MUSLE/MMF/WEPP, etc.) with different model structures and approaches for estimating soil erosion complicate the comparison studies. This is due to the lack of adequate information on the quality of the training and test datasets, parametrization, sensitivity and accuracy assessment techniques used. The non-uniform scale of coverage (from plot to basin level), and finally resolution of the data (coarse to fine grid) make the comparison more difficult. Among the few soil-loss studies considered, the scale of the study was too small (controlled plots as small as 40 m^2), but extrapolated to the entire region[29]. Consequently, there was the possibility of over- or under-estimation for such a diverse region in terrain configuration, landscape dynamics (6 to over 7800 m amsl with varying slopes), climatic heterogeneity (annual rainfall varying from <1500 to over 11,500 mm), land-use practices, site-specific soil quality and other agro-physical parameters. Thus, extrapolation of small and medium plot studies to the regional scale remains questionable where geo-environmental heterogeneity is more common than homogeneity. The large variation in estimated soil loss may be partly attributed to difficulties in reproducing the complex physical process of erosion using fewer parameters in the models for such heterogeneous agro-physical conditions of NER. Though there is a need for retrospection to verify the observed or estimated results, the reality is that the availability of alternative soil loss data measured specifically in this hilly region is a challenging task.

Nonetheless, most studies agree that forest degradation is one of the major causes of soil erosion and soil loss in NER, and is several times greater than the critical tolerance level of the region (12.5 t ha^{-1} yr^{-1}), as suggested by Mandal and Sharda[12]. Erosion can be mitigated through appropriate land-use practices and adoption of appropriate soil and water conservation measures. The vulnerability of the region increases further with changing rainfall patterns, particularly rainfall intensity and increase in extreme rainfall events under changing climate scenarios[67]. We hope this compilation and critical analysis will help the stakeholders in prioritizing vulnerable areas and planning conservation measures. A land use policy that considers long-term sustainability of land productivity and ecosystem functioning is needed for sustainable management of natural resources across NER.

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