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RESEARCH ARTICLE

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Long-term effect of integrated farming systems on soil erosion in hilly micro-watersheds (Indian Eastern Himalayas)

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Abstract

Soil erosion from traditional hill agriculture is a major concern for agronomic development in the Eastern Himalayas (India). An integrated farming system (IFS: is the combination of multipurpose trees-MPT interspersed with seasonal agricultural crops) may reduce the severity of erosion while ensuring food and nutritional security. The aim of our study was to identify an IFS, resistant to soil erosion in the hill ecosystem of Eastern Himalaya. For this, eight micro-watershed (MW)-based IFSs namely livestock with fodder crops (MW_1), forestry (MW_2), agroforestry (MW_3), agriculture (MW_4), agri-horti-silvi-pastoral (MW_5), horticulture (MW_6), cultivated fallow (MW_7), and abandoned shifting cultivation (MW_8, as traditional land use) were established and soil erosion was measured for 24 years in the sloping land (32.0%–53.0%) of the Eastern Himalayas (Meghalaya, Northeast India). In the forests (MW_2), annual average (IA: 1983–2006) runoff and soil losses were 405.5 (±113) mm and 11.0 (±2.4) Mg ha^{-1} yr^{-1}, respectively. The conversion of forests to cultivation caused a decline in the parameters of hydro-physical quality and fertility, more severely in the traditional farming ($MW_{7\&8}$) than in the IFS mode of cultivation ($MW_{3,5,\&6}$). Soil water conservation measures (SWCMs: contour bunding, terracing, and grassed waterways) were more effective at reducing erosion when used together compared to individually. Adoption of these SWCMs in cultivated MWs in IFS mode ($MW_{3,5,\&6}$), reduced the runoff by 13.0%–17.1% and soil loss by 12.6%–15.1% over forests (MW_2). However, in traditional agriculture ($MW_{7\&8}$), runoff increased by 50.6%–87.6% while soil loss was 50.3%–59.8% higher over the forest. The study demonstrated that the adoption of agroforestry, agri-silvi-horti-pastoral or horticulture-based IFSs with appropriate SWCMs may be promoted to reduce soil erosion while sustaining soil quality attributes and food security in the hill ecosystem of the Indian Eastern Himalayas.

KEYWORDS
hilly micro-watershed, integrated farming system, land degradation, soil erosion, sustainable hill agriculture

1 | INTRODUCTION

Soil erosion in the tropical region is a serious environmental concern affecting the environment and ecosystem functions (Lobo & Bonilla, 2019; Pijl et al., 2020). Converting natural forests into cropland reduces surface cover and increases soil compaction. This accelerates surface runoff, leads to loss of fertile soils carrying loads of organic matter, other cementing agents including bases, and nutrients in the Himalayan ecosystem (Pijl et al., 2020). Nearly, two-fifths of the Indian Himalayas (Eastern and Western) are prone to soil erosion which has recently increased by more than four-fold, often to levels higher than the critical tolerance limit of the region (12.5 million g ha^{-1} yr^{-1}) (Mandal & Sharda, 2011). The total degraded land area in the Eastern Himalayas of India is nearly 4.60 million ha (18.2% of the total 26.2 million ha area), of which water erosion alone caused nearly 30% (1.42 million ha) of it (NRSC, 2019). The lack or absence of soil and water conservation measures (SWCMs) further promotes sediment transport through runoff into rivers and streams (Lobo & Bonilla, 2019). Soil erosions pose a severe threat to the mountain ecosystem of the region, mostly due to widespread deforestation from traditional agriculture (shifting and settled cultivation) in sloping uplands. Soil loss in shifting cultivation (deforestation and vegetation burning) in the region varies from 40.0 to 153.1 million g ha^{-1} yr^{-1}(Singh et al., 2011).

Vegetation clearance for cultivation increases the sediment load in the runoff water by 45.5-times compared to cultivation with surface residue retention (Keesstra et al., 2016). Recognizing the severity of degradation due to erosion and restoring eroded land is part of the Indian national policy for the Himalayan region and is aimed to support agricultural productivity in the region (Dabral et al., 2008; Singh et al., 2011). The adoption of SWCMs such as terracing, contouring, grassed waterways, and vegetative barriers in cultivated uplands alters the slope gradient and thereby reduces overland flow. However, mechanical measures (terracing and contouring) are costly, labour intensive and, in some cases, ineffective if not well constructed (Pijl et al., 2020). Biological measures such as grass waterways and vegetative barriers are economically feasible, easy to adopt on steep slopes (Hu et al., 2016) but initially take longer to impart the stabilization effect. Cover crops such as oats, clover, and triticale are also highly effective in reducing soil erosion and runoff by 60%–95% compared to crop land without them (Eshel et al., 2015). Inter-cropping or mixed cropping also substantially reduces (77%–81%) soil erosion while enhancing soil fertility and productivity in tree-based systems on hill slopes in the Zemaiciai upland (Jankauskas, 2001) and Western Himalayas, India (Sharma et al., 2017).

The region of northeast India, situated in the Eastern Himalayas landscape, receives high annual rainfall (>2000 mm), but with wide spatial variability (1500–11,500 mm yr^{-1}) (Prokop & Walanus, 2015). Hilly topography with steep slopes covers more than 3/4th of the region's geographical area (26.2 million ha) (Choudhury et al., 2013, 2016). The demand for more food to feed the growing population with limited cultivable area (<15% of 26.2 million ha has led to intensified deforestation, and expansion of unsustainable traditional land uses (shifting cultivation and cultivation in raised beds along the slopes known as *bun* agriculture) on the steep slopes (land capability classes of VI and VII) (Satapathy, 1996a). As a result, the region over many decades has experienced large-scale deforestation and associated land degradation including hill slope instability, and the collapse of the mountain ecosystem (Singh et al., 2009; Choudhury et al., 2021).

There is a growing interest in the region in the promotion of suitable integrated farming system (IFS) models which can efficiently reduce soil erosion by hill agriculture while ensuring food and nutritional security. IFSs are a diversified agricultural production system, involving multiple complementary farming enterprises (e.g., seasonal crops, timber, fruit trees, livestock, fish, etc.) to reduce dependency on a single enterprise and the risk of failure, while minimizing the use of external inputs by maximizing the use of in-situ farm wastes through bio-resource flow (byproducts of one enterprise become the input of others), to achieve food, nutritional and household livelihood security in a sustainable manner, both economically and environmentally. With these needs as a goal, complementary land use practices at micro-watershed (MW) scale (as a replacement for traditional hill farming - shifting cultivation and *bun* agriculture) were introduced to the region during the 1980s. Presently, IFS-based land-use practices are gaining prominence and their use is expanding, primarily to provide year-round food and nutrition security to the small landholders. However, due to the enormous cost, manpower, and technical skills needed to measure soil erosion on steep slopes, none of the existing IFSs are equipped with a stage-level recorder or any other device to measure runoff and soil loss. At our eight selected MWs, runoff volume and soil losses were measured using hydrological gauging stations (water stage level recorder and H-flume) which funtioneed from MWs establishment (1983) until 2006 (24 years).

Our study, therefore, is one of the very few in the region with such long periods of measured runoff and soil loss as well as robust support data (e.g., daily weather data, soil properties, hillside slopes stiffness, crop/plant, and conservation management factors). The predominant rainfed agriculture in the region is vulnerable to climate change, particularly change in rainfall intensity (Choudhury et al., 2012). For identifying more resilient IFSs and devising adaptation strategies in the context of soil erosion susceptibility to future climate change scenarios, evaluation of these established IFSs hold great significance. We hypothesized that the conversion of undisturbed forests to cultivation in an IFS mode in the hilly micro-watersheds (MWs) would increase the runoff and soil loss. To test the hypothesis, primary mixed dense forests were converted into hilly MWs (slope: 32%–53%) with five different land use practices in an IFS mode (multipurpose trees interspersed with seasonal agricultural crops/cover crops and/or livestock). A set of SWCMs (e.g., bench and half-moon terracing, contour bunding and grassed waterways) was also adopted either jointly or separately. To compare the effect of these five improved IFSs on soil erosion, forests were converted to two additional MWs under traditional agricultural land uses (shifting cultivation and cultivated fallow). Similarly, an additional MW was established by conserving primary dense mixed forests in the vicinity. We compared long-term (24 consecutive years) annual runoff and soil loss for these five IFS-based land uses with two traditional agricultural land uses, retaining mixed dense forests as a reference. Finally, the MW-based IFS model(s) were identified as more resistant to soil erosion on steep slopes (>45%) in the Eastern Himalayas.

2 | MATERIALS AND METHODS

2.1 | Study area and experimental set-up

The study area is located in one of the mountainous states of the Eastern Himalayas (Meghalaya, Umiam, Figure 1), at an elevation of 984–1020 metres above mean sea level (msl). More than two-thirds of the 26.2 million ha landscape is rolling topography with mountains in Sikkim Himalaya reaches beyond 7800 m while cliffs and plateaus stretch to intermontane valleys in a major portion of the region. Forests of deciduous and evergreen species dominate the landscape, but have been in decline over the years (from >80% of the area in 1980 to <63% of the area in 2019) (NRSC, 2019). This decline is mainly attributed to deforestation caused by shifting cultivation (2-year short fallow cycle), expansion of *bun* agriculture, intensive coal mining, and sand quarrying.

To replace traditional, unsustainable agriculture (shifting cultivation locally known as *Jhum* and modified shifting cultivation known as *bun*) with complementary land-use practices, the Indian Council of Agricultural Research (ICAR) Research Complex (RC) for Northeastern Hill Region (NEH) has developed eight MW-based integrated farming systems (IFSs). A set of mechanical and biological soil and water conservation measures (SWCM) was also adopted in MWs (Table 1) since their establishment (1983) at the Institute's research farm (Umiam: 25°41′11″ to 25°41′31" N latitudes and 91°54′44″ E to 91°55′01″ E longitudes, Figure 1). The eight MWs were developed on a forested hillside area (slope: 32.0%–53.18%) of 15.1 ha area, belonging to land capacity class of VIIe with good drainage. Of the total area (15.1 ha), 8.4 ha in the upper portion of the MWs were left under native forest (subtropical pine) while in the 6.7 ha area, planned IFS-based land uses were developed. The total area (including pine forests) of each MW varied from 0.5 to 3.9 ha while the area developed under IFS for each MW varied from 0.5 to 1.0 ha (Table 1, Figures 1 & 2). The eight MW-based IFSs were: livestock-fodder crops (MW_1), mixed forestry (MW_2), agroforestry (MW_3), agriculture (MW_4), agri-horti-silvi-pastoral (MW_5), horticulture (MW_6), cultivated fallow (MW_7), and abandoned shifting cultivation with sparsely planted bamboo and broom grasses (MW_8, traditional land use). The area falls under the mixed subtropical hill agro-climatic zone (AES-III) of India (Jena et al., 2020). The physical boundaries of the MWs were demarcated in such a way that each one of the eight MWs functioned as an independent basin (Figures 1 & 2). All these eight MWs were gauged with an F-type water stage level recorder and H-flume along with a Coshocton wheel runoff sampler installed at the outlet to measure

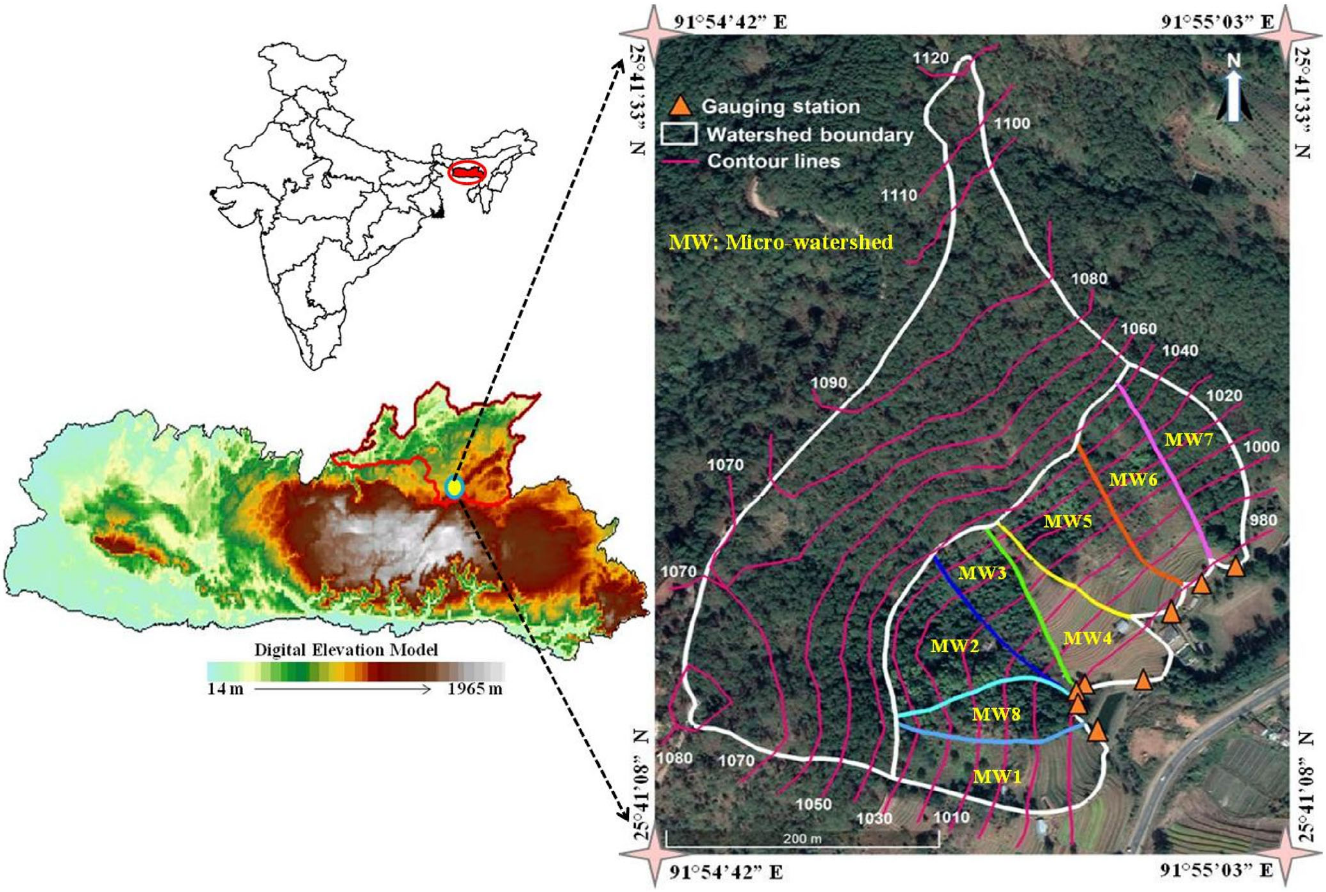

FIGURE 1 Topographical location of the experimental site and the delineation of the boundaries of eight hilly micro-watersheds in the Eastern Himalayas. MW_1: agriculture, MW_2: ixed forest, MW_3: agroforestry; MW_4: agriculture, MW_5: agri-silvi-horti-pastoral, MW_6: horticulture, MW_7: cultivated fallow, MW_8: abandoned *jhum* [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Farming systems (FSs), land use, and soil-water conservation measures under different integrated farming systems (IFSs)-based experimental micro-watersheds (MWs) in the (Indian) Eastern Himalayas region

Micro-watershed	Farming system (FS)	Crops/trees	Soil water conservation (SWC) measures	Land-use
MW_1	Fodder crops	Maize, tapioca, bajra, and perennial fodders (setaria, Guinea, broom grass *Thysanolaena maxima*, etc.)	Contour bund + grassed waterways	Agriculture
MW_2	Timber, fuel, and fodders	*Pinus kesiya*, *Albizia lebbeck*, *Acacia auriculiformis, Alnus nepalensis*, *Symingtonia populnea*, *Robinia pseudoacacia*, etc	None	Forest
MW_3	Timber, fuel, fodder grasses, legume crops	*Acacia mearnsil*, *Alnus nepalensis*, *Symingtonia populnea*, *Ficus hookeri*, *Khasi cherry, pineapple on contour bund. French beans and rice in interspaces*	Contour bund	Agro-forestry
MW_4	Food and fodder crops	Paddy-pea, maize, mustard, linseed, ginger, groundnut, turmeric, and radish. Grasses (Setaria and Guinea) on risers	Contour bund + bench terrace + grassed waterways	Agriculture
MW_5	Food, fodder, and fruits crop	Beans (French /rice), radish, mustard, turnip, pea, turmeric, ginger, guava, hasi mandarin, Assam lemon, pineapple, alder, *Symingtonia populnea*, *Ficus hookeri*. Grasses (Setaria, Guinea and broom) on risers	Contour bund + bench terrace + grassed waterways + half-moon terraces	Agri-horti-silvi-pasture
MW_6	Fruit and vegetable crops	Peach, pear, citrus, guava, radish, turnip, ginger, and beans (cowpea, rice and beans) in interspaces	Contour bund + bench terrace + grassed waterways + half-moon terraces	Horticulture
MW_7	Natural flora	Natural flora in cultivated fallow	None	Cultivated fallow
MW_8	Broom grass and bamboo	Bamboo and broom grasses in abandoned *jhum* land	Contour bund	Shifting cultivation-improvement approach

runoff and soil loss since its establishment (1983) until 2006 (24 years) and readings were compared against the traditional land use (MW_8: abandoned shifting cultivation). Details of the farming systems, soil and water conservation (SWC) practices (contour bund, terracing-half-moon and bench, and grass waterways), and land uses/cropping systems/trees in each MW are provided in Table 1, and details of the watershed characteristics are summarized in Table 2.

2.2 | Climate and soil

The annual rainfall during the study period (1983–2006) varied widely (CV = 15%): from 1829 mm to 3322 mm with a mean of 2394 mm (±373.4). The contribution of monsoon months (June–September) to total annual rainfall varied from 50.3% to 77.4% (mean: 63.4%) while the corresponding contributions during pre-monsoon (March–May) and post-monsoon (October–February) months varied from 13.4% to 34.7% and 9.6% to 26.8%, respectively. The mean annual maximum temperature was 24.8°C while the minimum temperature was 15.8°C with a variation in average relative humidity from 66.9% to 84.0%. Average wind speed varied from 2.6 to 4.4 km hr^{-1} and the evaporation rate ranged between 2.0 to 4.6 mm d^{-1} (Choudhury et al., 2012).

The soils are taxonomically classified at a series level as fine, mixed, thermic, Typic Kandihumults (Jena et al., 2020). Soils are formed from acidic igneous rocks weathered to sandstone and schist parent materials and the soil type is red and lateritic hill soils (Jena et al., 2020). Soil samples down to a depth of 1.8 m (at an interval of 0.15–0.30 m) were collected randomly from each of the MWs at different positions (top, middle, and bottom) annually. Following standard procedures, samples were analyzed for total Kjeldahl nitrogen-TN, cation exchange capacity-CEC, and Walkley and Black organic carbon (Jackson, 1973). From the fresh soil sample, soil microbial biomass carbon (SMBC) was determined using the chloroform fumigation extraction method (Vance et al., 1987). Similarly, air-dried clods larger than 5.0 mm in diameter were used to analyze water-stable aggregates using the wet sieving technique and the mean weight diameter (MWD) of water-stable aggregates was quantified (Majumder et al., 2008). The distribution of soil particle sizes, including finer sand fractions (<0.05 mm), was measured using the international pipette method (Piper, 1966), while saturated hydraulic conductivity (K) was

FIGURE 2 Overview of the hilly watershed (a) comprising six individual micro-watersheds (MW) under different integrated farming systems, namely (b) fodder-based agriculture (MW_1), (c) agroforestry (MW_3), (d) agriculture (MW_5), (e) agri-silvi-horti-pastoral (MW_5), (f) horticulture (MW_7), and (g) cultivated fallow (MW_8) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Characterization and measured soil erosion parameters of different integrated farming system-based experimental micro-watersheds (MWs) in (Indian) Eastern Himalayas region

Watersheds	MW_1	MW_2	MW_3	MW_4	MW_5	MW_6	MW_7	MW_8
Watershed properties								
Total area (ha)	1.39	3.89	2.94	0.64	1.58	3.13	1.03	0.52
(a) Forest area (ha)	0.45	3.05	2.05	0.06	0.55	2.17	0.08	0.02
(b) Planned land-use (ha)	0.94	0.84	0.90	0.58	1.03	0.96	0.95	0.5
Watershed relief (m)	99	100	110	82	89	138	91	65
Average slope (%)	32.0 (17.75°)	38 (20.81°)	32.18 (17.83°)	32.42 (17.96°)	41.77 (22.63°)	53.18 (28.0°)	45.87 (24.6°)	41.35 (22.46°)
Maximum length (m)	301	320	295	240	260	515	250	185
Maximum width (m)	65	230	175	65	85	85	70	48
Drainage/soil texture	Good/clay loam	Good/clay loam	Good/clay loam	Good/clay loam	Good/clay loam	Good/clay loam	Good/clay loam	Good/clay loam
Land capability class	VIIe	VIIe	VIIe	VIIe	VIIe	VIIe	VIIe	VIIe
Treatment imposed in (yr)	1983	1983	1983	1983	1983	1983	1983	1983

Abbreviations: MW_1, agriculture, MW_2, mixed forest, MW_3, agroforestry; MW_4, agriculture, MW_5, agri-silvi-horti-pastoral, MW_6, horticulture, MW_7, cultivated fallow, MW_8, abandoned shifting cultivation.

determined by the constant head aperture method. Soils were texturally classified as clay loam with a variation in clay contents from 26.1% to 41.1%. Soils were strongly acidic in reaction (pH: 4.3–4.9), very high in Walkley and Black soil organic carbon (SOC: 1.9%–4.0%), medium in available nitrogen (275.0–400.0 kg ha^{-1}), but low in Brays 1 available phosphorus (P_2O_5: 13.0–23.0 kg ha^{-1}) and potash (K_2O: 148.0–200.0 kg ha^{-1}) contents (Table 3).

2.3 | Methodology

2.3.1 | Hydrological measurement

The daily runoff data were estimated from the charts of installed F-type stage-level recorders in the eight MWs at the experimental site (Figures 1 & 2). The daily runoff volume from each MW was also measured to cross-check the daily data from the stage-level recorder installed at each channel outlet. The flow from each MW is routed to a monitoring station equipped with an H-flume in conjunction with Coshocton-type runoff samplers which are located at the channel outlets to characterize the runoff outflow. According to the area of the MW, a 0.46 m size H-flume was installed at the outlets of smaller $MW_{1,4,7,\&8}$ while 0.61 m size H-flumes were installed at relatively larger $MW_{2,3,5,\&6}$. The H-Flume converged natural flow through a V-type cross-section. Due to lateral flow restrictions from the flume area, the water level in the throat of the flume rises. To obtain the flow, we simply measured the water depth from the H flume discharge tables corresponding to 0.46 m and 0.61 m H flume sizes. Runoff volume and rate during each storm event were estimated by analyzing the recorded runoff hydrographs of each MW. Daily runoff depths (in mm) were computed by dividing the measured daily runoff volume by the area of each MW. To obtain surface flow, the baseflow was separated using the straight-line method as outlined by Subramanium (1996). In this method, separation of the baseflow is achieved by a straight line joining the beginning of the surface runoff to a point on the recession limb representing the end of the direct runoff. The values between these two points are linearly interpolated to get the complete baseflow hydrograph. Hence, subtracting the baseflow hydrograph from the stream flow produces the surface runoff. Further, to measure the sediment flow after each storm event, water samples with a known volume were drawn from the water collecting drum connected to the Coshocton wheel. Filter paper of pore size 1.2 μm was used to filter the runoff sample. The filtered sediments were kept in an oven at 105° C for 24 hr and the dry weight of sediment was expressed as soil loss (sediment yield) (g L^{-1}). From the known size of each MW and the amount (volume) of runoff, soil loss measured in g L^{-1} was expressed in Mg ha^{-1} yr^{-1} (Choudhury, Nengzouzam, & Islam, 2022; Singh et al., 2012). The sediment concentration was assumed to be uniform throughout the runoff period.

2.3.2 | Statistical analysis

Analysis of variance (ANOVA) was performed to identify significant (statistically) effects of IFSs on long-period average (LPA) measured

TABLE 3 Measured soil properties (mean ± SD) under different integrated farming system-based experimental micro-watersheds (MWs) in the (Indian) Eastern Himalayas

Micro-watershed	Clay	Sand	K	MWD	SOC	CEC	SMBC	TN
	%	%	mm hr^{-1}	mm	%	Cmol$_c$ kg^{-1}	μg gm^{-1}	%
MW$_1$	40.5^{a} (±4.2)	28.3^{d} (±2.2)	4.3^{e} (±1.3)	3.6^{de} (±0.21)	2.0^{de} (±0.1)	20.0^{b} (±1.6)	575.2^{e} (±21.8)	0.39^{d} (±0.09)
MW$_2$	40.5^{a} (±4.0)	36.4^{c} (±3.0)	4.8^{c} (±1.0)	4.3^{a} (±0.21)	4.0^{a} (±0.3)	30.0^{a} (±2.2)	806.9^{a} (±78.6)	0.59^{a} (±0.07)
MW$_3$	39.0^{ab} (±3.6)	42.4^{a} (±4.0)	4.8^{c} (±2.1)	4.0^{b} (±0.17)	2.8^{b} (±0.2)	20.0^{b} (±1.3)	753.2^{b} (±57.9)	0.54^{b} (±0.06)
MW$_4$	40.1^{a} (±4.2)	23.9^{e} (±2.1)	2.0^{f} (±0.8)	3.5^{e} (±0.25)	2.1^{d} (±0.1)	20.0^{b} (±1.4)	519.6^{f} (±48.9)	0.38^{d} (±0.08)
MW$_5$	41.1^{a} (±3.8)	35.9^{c} (±2.9)	4.5^{d} (±1.2)	3.9^{bc} (±0.24)	2.6^{c} (±0.2)	20.0^{b} (±1.2)	723.6^{c} (±54.6)	0.48^{c} (±0.07)
MW$_6$	33.9^{c} (±3.2)	40.4^{ab} (±3.1)	5.6^{a} (±1.4)	3.9^{bc} (±0.25)	2.8^{b} (±0.2)	20.0^{b} (±1.1)	765.9^{b} (±65.1)	0.49^{c} (±0.07)
MW$_7$	37.2^{b} (±4.2)	39.0^{b} (±3.4)	5.0^{b} (±2.1)	3.7^{cd} (±0.20)	2.9^{b} (±0.3)	20.0^{b} (±1.5)	666.3^{d} (±39.6)	0.33^{e} (±0.05)
MW$_8$	26.1^{d} (±3.0)	42.4^{a} (±3.6)	4.5^{d} (±2.3)	2.9^{f} (±0.28)	1.9^{e} (±0.2)	15.0^{c} ± (1.3)	451.5^{g} (±51.2)	0.23^{f} (±0.05)
LSD	2.49	2.04	0.16	0.21	0.19	1.19	23.87	0.017

Abbreviations: K, hydraulic conductivity, MWD, mean weight diameter; SOC, soil organic carbon, CEC, ation exchange capacity; SMBC, soil microbial biomass carbon; TN, total nitrogen. Means in the column followed by different small letters (a-g) are statistically significant ($p < 0.05$). LSD, east significant difference. Figures in parenthesis are standard deviation (SD). MW$_1$, agriculture, MW$_2$, mixed forest, MW$_3$, agroforestry; MW$_4$, agriculture, MW$_5$, agri-silvi-horti-pastoral, MW$_6$, horticulture, MW$_7$, cultivated fallow, MW$_8$, abandoned *jhum*.

runoff and soil loss using PROC GLM procedure in SAS version 9.2 software (SAS Institute, Inc.). The difference among the IFSs in inter-annual average absolute values of runoff and soil loss was statistically significant or not at $p < 0.05$ level, we employed Duncan's multiple ranges test (DMRT), and the significant differences in mean values were indicated by different small letters. We calculated Pearson's correlation coefficient (*r*) to measure the statistical relationship among the factors of heterogeneity.

3 | RESULTS AND DISCUSSION

3.1 | Effect of IFSs and SWC measures on soil properties

Conversion of forest micro-watershed (MW$_2$) into cropland (MW$_2$ to MW$_8$) over long periods (24 years) in the differential IFS mode, with or without SWC measures ($p < 0.05$) had a significant effect on soil quality parameters, although at different magnitudes (Table 3). Forest soils were significantly ($p < 0.05$) superior in the measured quality indicators, represented by important hydro-physical (e.g., clay content, K, aggregation and MWD) and fertility (e.g., SOC, CEC, TN, and SMBC) parameters. Soils under traditional agriculture (MW$_8$ in shifting cultivation and MW$_7$ under cultivated fallow) followed by agriculture-based IFS (MW$_{1\&4}$) degraded more significantly ($p < 0.05$). Among the cultivated IFS, soils exposed to agroforestry (MW$_3$), agri-horti-silvi-pastoral (MW$_5$), and horticulture (MW$_6$) were significantly better ($p < 0.05$) than the traditional agriculture (MW$_{7\&8}$) and less deteriorated relative to forest (Table 3).

Dense forests (MW$_2$) and cultivated IFS (with the exception of MW$_6$) were significantly ($p < 0.05$) clay-rich (>39.0%) compared to MW$_8$ (only 26.1%). Variation in textural composition and level of compaction (soil bulk density: 1.15 in MW$_2$ to 1.28 Mg m^{-3} in MW$_8$) resulted in measured K also varied from 2.0 to 5.6 mm hr^{-1} (Choudhury and Singh, 2013). With a coarser texture (more sand, less clay content), K increased (as in MW$_6$), might be from an increase in macro-pores while less sand and higher clay, K decreased as observed in MW$_4$ (García-Gutiérre et al., 2017). Due to a significant decline ($p < 0.05$) in SOC from 4.0% in MW$_2$ to 1.9% in MW$_8$, other primary fertility parameters like TN, CEC, and more importantly, SMBC also significantly ($p < 0.05$) affected in MW$_8$, followed by MW$_1$, MW$_4$, and MW$_7$. The cumulative effect of deterioration also led to a significant degeneration ($p < 0.05$) of MWD of water-stable aggregates, which declined from 4.3 mm in forests to 2.9 mm in MW$_8$ (Table 3).

The particle size distribution (sand and clay) is a stable and static property, resistant to changes in management practices. However, the decrease in clay content and the increase in sand content in MW$_8$ may be the result of significant soil erosion, as erosion results in coarse soil texture (Wang & Shi, 2015) by detachment and transportation of fine (clay) particles. Similarly, the decline of SOC (even up to 60.0% in shifting cultivation) on converting forests to cropland in the Eastern Himalayas is a common finding (Devi & Choudhury, 2013; Choudhury et al., 2021; Ansari, Choudhury, Layek, et al., 2022). This is mainly due to vegetation clearing and burning (as in MW$_8$), the reduction in leaf litter and root biomass deposits, and the loss of fertile soil through erosion (Lungmuana et al., 2018; Choudhury & Mandal, 2021; Choudhury, Nengzouzam, & Islam, 2022; Ansari, Choudhury, Layek, et al., 2022). The significant decrease of TN and SMBC levels by more than 50% relative to forests may be attributed to SOC reduction, because SOC strongly influences the content of TN and SMBC (Ahirwal et al., 2022). We also observed a strong positive correlation between SOC and TN ($r = +075$) and SMBC ($r = +0.84$). However, the range of TN (0.23%–0.59%) and SMBC (451.0–806.0 μg gm^{-1}) in the studied watershed is comparable to the recently reported ranges from the region under forest to cultivated agro-forestry systems (Ahirwal et al., 2022; Ansari, Choudhury, Layek, et al., 2022).

The stability of soil aggregates is a key factor in soil resistance to surface runoff, and thus water erosion (Canasveras et al., 2010). Significant decline in MWD of water stable aggregates in shifting cultivation and other cultivated IFSs ($MW_{7\&8}$, MW_1, and MW_4) indicated the deterioration in soil aggregation and the susceptibility of the soil to surface runoff and erosion. Reduction of SOC, TN, and particularly SMBC may have limited microbial activity, responsible for the release of soil binding agents (from the decomposition of organic matter), essential for soil aggregation (Ansari, Choudhury, Mandal, et al., 2022; Miltner et al., 2012). Stable land use practices (combination of trees, crops, and legume cover crops) and SWC (contours, terraces, and grassed waterways) measures could have helped restore and offset the relative deterioration of soil quality parameters in agroforestry (MW_3), agri-horti-silvi-pastoral (MW_5), and horticulture (MW_6) than the traditional agriculture (MW_8).

3.2 | Effect of IFSs on annual runoff and baseflow

The eight MWs received an equal amount of annual rainfall (long period annual average of 1983 to 2006, LPAA: 2435 mm) were developed on the same geology, and were all land capability class VIIe (Choudhury, Nengzouzam, & Islam, 2022; Satapathy, 1996a). However, adoption of IFSs with varied land uses and SWC measures significantly ($p < 0.05$) influenced the annual surface runoff loss and baseflow (Figures 3a,b). The percent surface runoff to annual rainfall varied widely across MWs: 13.8 (MW_5) to 31.2% (MW_8), with a mean of 18.2 (±6.4)%. The baseflow also varied from 24.9% (MW_7) to 46.5% (MW_6), with a mean of 36.1 (±7.8)% of the annual rainfall. The abandoned shifting cultivation-based IFS (MW_8) despite improvement in SWC measures (Table 1) recorded the highest LPAA runoff loss (760.8 mm, >30.0% of the annual rainfall) followed by the cultivated fallows (MW_7: 610.7 mm). On the contrary, the baseflow was recorded the lowest in MW_7 (607.0 mm) followed by MW_8 (636.0 mm). In the mixed forests (MW_2), the surface runoff loss was 33.6%–46.7% lower but baseflow was 24.7%–30.5% higher compared to $MW_{7\&8}$ (Figure 3b). In the SWC measures (such as, contour bunding, bench terracing, and grassed waterways) adopted MWs (MW_1 and $MW_{3\text{-}6}$), despite intensive cultivation of agricultural and horticultural crops in combination with trees, grasses, cover crops in IFS mode (Table 1), annual runoff loss was 8.8%–17.1% lesser than the forest (MW_2: 407.2 mm) while it was 51.4%–55.8% lesser than the MW_8 (Figure 3a).

Adoption of SWC measures and cultivation in IFS mode in these MWs even increased the annual baseflow by 9.9%–43.0% over the forest (MW_2) and 37.0%–78.0% increase over shifting cultivation (MW_8). Among these cultivated MWs, the highest average annual baseflow was observed in horticulture (MW_6: 1132.9 mm) followed by agri-horti-silvi-pasture (MW_5: 1043.6 mm), and agroforestry (MW_3: 1019.1 mm) (Figure 3b). In addition to the absence of SWCMs in forests, the presence of pine forests (*Pinus kesiya*) could have promoted soil loss on steep slopes (>38%). Aburto et al. (2020) also measured significant soil loss (18.3–25.9 Mg ha^{-1} yr^{-1}), even in the broad-leaved forests (Patagonian oak - *Nothofagus obliqua*) in the Biobío region of Chile. Soil loss increased further by four-fold (72.7–73.4 Mg ha^{-1} yr^{-1}) in maturing (>20 years old) Pine (*Pinus radiata)* forest. So, regardless of type, soil loss is significant, even in well-established forests, on different scales (Aburto et al., 2020). Similarly, as anticipated, MW_8 also yielded the highest peak runoff rate (86.1 mm hr^{-1}), while forests (MW_2) and the treated MWs yielded peak runoff of only 4.5–5.4 mm hr^{-1} (Satapathy, 1996b). Increased runoff ($p < 0.05$) in MW_8 followed by MW_7 could be caused by deforestation, removal/burning of surface vegetative covers, followed by cultivation along steep slopes. Soil properties, especially organic matter and aggregation structure, also strongly deteriorated ($p < 0.05$) (Table 3) in $MW_{7\ \&\ 8}$ compared to forests (MW_2).

Absence any SWC measures in M_7 also increased the runoff flow and, therefore, reduced the baseflow. From meta-analysis of watershed hydrology of the East African region, Guzha et al. (2018) reported that deforestation increased the surface runoff by 45.0 (±14)%, while the decrease in baseflows could be up to 46.0%. Deforestation and unsustainable land use practices such as in the $MW_{7\&8}$ in the tropics also result in changes in the hydro-physical properties of soils. This results in a reduction in infiltration, groundwater recharge and baseflow while increasing surface runoff (Bruijnzeel, 2004). However, the significant ($p < 0.05$) decline in surface runoff while an increase in baseflow in cultivated IFSs, more particularly in $MW_{3\text{ to }6}$ than the forest could be attributed to two primary reasons: stable land use practices in IFS mode and the adoption of SWC measures. Higher transpiration losses in deep-rooted forest trees from the groundwater reservoir contribute to higher evapotranspiration (ET) losses, resulting in lower baseflow (Huang et al., 2016). The estimated ET losses in our studied MWs in the recent years (2015–2018) also revealed a 14.0%–18.0% higher ET loss in forest compared to the cultivated MWs (Annual report, 2015–2018). Simulation studies also reported an increase in baseflow when forests are converted into cropland, mainly due to a decrease in water use by plants, provided that soil properties, such as infiltration characteristics, are not degraded (Githui et al., 2009). We also observed significantly different baseflows ($p < 0.05$) among cultivated MWs: forage-based MW_1 recorded 7.0%–30.0% less than $MW_{4\text{-}6}$ (Figure 3). This could be due to the interception of surface runoff from terraced fields, allowing' higher infiltration into the soil profile, resulting in an increase in baseflow with SWC measures (Deng et al., 2021).

Inter-annual rainfall variability in the watershed over the study period (1983–2006) highly influenced annual runoff volume. The highest annual rainfall (3323 mm) was received in 1988 and in the same year, the measured runoff loss was also the highest across MWs (701.1 mm in MW_1 to 1425.0 mm in MW_8). A positive correlation ($r = +0.68$ to 0.83) with each other in all MWs confirmed the strong influence of rainfall on runoff loss. In addition, the annual runoff in the MW_8 was extremely high (>1000 to 1425 mm) during the first 4 years of establishment and then slowly decreased (excluding years of heavy rainfall) in the subsequent years. Similar results have been reported by Bruijnzeel (2004) from paired watersheds in Latin American rainforests. The impacts of deforestation on hydrological flows remain

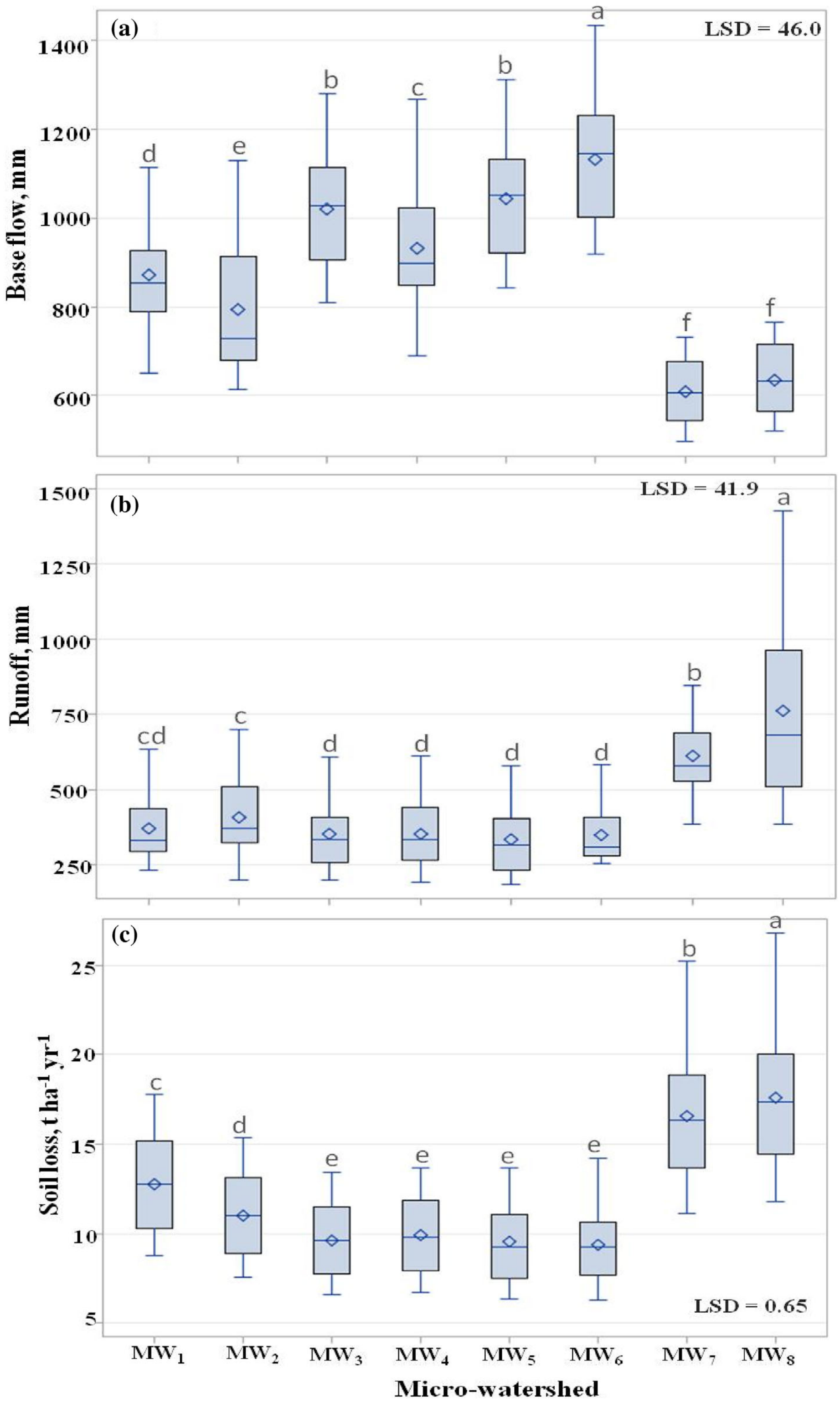

FIGURE 3 Long periods annual average (LPAA: 1983–2006) measured baseflow (a), surface runoff (b), and soil loss (c) in eight IFS-based MWs. The bars represent standard deviations. Different lower-case letters (a–f) in the columns (for each MW) are significantly different at $p \le 0.05$ [Colour figure can be viewed at wileyonlinelibrary.com]

significant in the early years of vegetation clearing and decline in subsequent years (Bruijnzeel, 2004; Ogden et al., 2013). Among the cultivated MWs, MW$_6$ had the highest percent slope (53.2%) (Table 1), but annual runoff was 55.0% lower than MW$_8$ (760.0 mm). This can be attributed to improved agricultural practices with suitable SWCs to control runoff versus traditional agricultural practices in the region (MW$_{7\&8}$).

A significant decrease in runoff was also reported when only agriculture was replaced by plants and grasses (silvi-pastoral) or other SWC mechanical measures in the Eastern Himalayan Region (Meghalaya, Singh et al., 1990). Runoff was reported to be reduced by 18%–21% using vegetative barriers with grasses in the Western Himalayan Region (slopes of 2%–8%) (Sharda et al., 2002, 2013). We also observed the effectiveness of setaria, Guinea, and broom grasses in reducing the runoff losses when planted on the bund risers in seasonal crop grown terraces of MW_{3-6}. These treated MWs had year-round cropping systems involving cereals, pulses, and legume cover crops like cow pea and beans in combination with trees/fruit trees (Table 1). This could have provided sufficient coverage to intercept heavy rainfall, particularly during the peak monsoon months (June–September). Ghosh et al. (2011) also reported a 10.0% decrease in runoff in maize inter-cropped with cow pea against maize alone in the Northwestern Himalaya (Dehradun, 600 to 1500 m asl). Adoption of SWC measures like terracing, contouring, and grassed waterways further played a significant role in reducing runoff (Satapathy, 1996b). Bench terraces collect surface runoff from leveled plots (Durán et al., 2005) and enhance infiltration and thus, reduce the overland flow (Rubaj, 2002). This could be attributed to the significant reduction in runoff loss in terraced MWs (MW_{4-6}) in our study.

3.3 | Effect of IFSs on annual soil loss

The measured LPA annual soil loss also significantly ($p < 0.05$) differed among the IFSs (Figure 3c) and varied annually (CV: 21.7% to 23.6%) ranging from 6.3 to 26.8 Mg ha^{-1} across MWs. The LPA annual soil loss in mixed forest (MW_2) was 11.0 Mg ha^{-1} yr^{-1} with an inter-annual variability ranging from 7.6 to 15.6 Mg ha^{-1} yr^{-1}. In the studied region, the reported soil loss varies widely: traces to 229.0 Mg ha^{-1} yr^{-1} in traditional agriculture while traces to as high as 836.0 Mg ha^{-1} yr^{-1} in deforestation followed by agriculture-/horticulture-/plantation-based land uses (Choudhury, Nengzouzam, Ansari, & Islam, 2022). The critical limit of tolerance for soil loss in the region is 12.5 Mg ha^{-1} yr^{-1} (Mandal & Sharda, 2011) and the soil loss in MW_2 was just at the borderline of it. However, in abandoned shifting cultivation (*jhum*), treated with contouring in MW_8, soil loss increased significantly (+59.8% over MW_2) with wide inter-annual variability (11.8–26.8 Mg ha^{-1} yr^{-1}) as well. Similarly, in cultivated fallow with regenerated natural flora (MW_7), soil loss was more than 50.0% higher than MW_2. Conversely, in treated MWs (MW_{3-6}) with SWC measures under different IFSs, soil loss was significantly ($p < 0.05$) reduced (10.4%–15.1%) over forests (Figure 3c). The horticulture-based IFS (MW_6) reported the lowest inter-annual soil losses throughout the study period despite having the maximum average slope (53%). Relatively higher sand content (43.3%) and hydraulic conductivity (4.9–6.0 mm hr^{-1}), significantly ($p < 0.05$) higher SOC and better soil aggregation (Table 3) in MW_6 might have favored a faster infiltration of rainwater than the overland flow. In addition, higher organic carbon accumulation and water stable aggregates on surface soil reduced the soil susceptibility to erosion (low soil erodibility as estimated following the procedure of Foster [1995], $K = 0.017$ Mg ha h ha^{-1} MJ^{-1} mm^{-1}). Adoption of a range of SWC measures in combination (particularly terracing- bench and half-moon with grassed waterways and contour bund) and inclusion of legume cover crops in the terraces of MW_6 might have increased the effectiveness of SWCM in reducing the erosion (Sharda et al., 2013). At the same time, improved soil hydro-physical (soil aggregation and water transmission) and soil fertility (oxidizable and microbial biomass carbon, total nitrogen, and CEC) parameters (Ghosh et al., 2011; Jankauskas, 2001).

Nguyen and Pham (2018) also reported that terracing was 1.6 times efficient in reducing soil loss under coffee cultivation than contouring. Planting strips of grasses in terraced coffee fields further increased the effectiveness in reducing soil loss by 3.4 times than contouring alone in the Son La Province of Vietnam. Effectiveness of combinations of SWC measures in reducing soil erosion in MW_4 and MW_5 (9.5–9.8 Mg ha^{-1} yr^{-1}), statistically comparable to MW_6 (9.4 Mg ha^{-1} yr^{-1}) was also observed (Figure 3c). The SWC measures along with perennial crop canopy covers might have encouraged infiltration and ET while diverting excessive rainfall toward grassed waterways at a controlled velocity, particularly during monsoon months (June to September) (FAO, 2000; Satapathy, 1996b). Further, year-round crop cultivations (including legumes as cover crops) and tress in combination might have helped in developing strong rooting systems (surface from crops and subsoil from trees) and accumulation of organic matter, total nitrogen, microbial biomass carbon and improvement in soil aggregations and other binding forces against rainfall-induced erosivity (Sharma et al., 2017).

The region's agro-forestry systems are known for improving soil organic matter (SOM), aggregation and soil fertility attributes, primarily through the addition of biomass (surface and underground) and protection against soil erosion (Ansari, Choudhury, Layek, et al., 2022; Dhyani & Tripathi, 2000; Meetei et al., 2020). The addition of leguminous alder (*Alnus nepalensis* D.), albizia (*Paraserianthes falcataria*), and fruit trees like mandarin (*Citrus reticulate*), guava (*Psidium guajava*) in MW_3 and $MW_{5\&6}$ may have contributed to biomass production. These trees produce a large quantity of total root biomass (4.2–8.4 Mg ha^{-1}), including active fine roots at an annual rate of 3.6–6.3 Mg ha^{-1} in the region (Dhyani & Tripathi, 2000). Most of the total root biomasses are fine roots (>77% to 87%) and nearly half are confined to the top 10 cm of soil. Fine roots with a high biomass-necrosis ratio (2.0–3.0) promote faster decomposition and build-up of SOM in surface soils. In the Eastern Himalayas (Manipur, India), Ansari, Choudhury, Layek, et al. (2022) also reported a significant increase in biomass and SOM accumulation by legume agroforestry and woody horticulture (fruits) relative to agricultural crops alone. Furthermore, they enrich the soil by fixing nitrogen (117.0–235.0 kg ha^{-1}) and solubilizing phosphorus by root exudation. This solubilizes native phosphorus and improved cohesiveness and soil aggregation against erosion and soil loss by their deep root systems (Dhyani & Tripathi, 2000; Meetei et al., 2020).

Terraces are more effective than contouring in preventing erosion (Nguyen & Pham, 2018) by reducing slope steepness and divided the slope into series of shorter, more level steps. This allowed heavy rains to infiltrate into the soil rather than runoff and cause erosion. This might have reduced the surface runoff and the soil loss significantly ($p < 0.05$) in MW_{4-6} than the contouring in MW_1 and MW_8. We observed that soil loss increased with the runoff volumes across MWs, also confirmed from a strong positive correlation ($r = +0.58$ to $+0.91$) between them. In MW_8, though annual average soil loss was significantly ($p < 0.05$) higher (17.6 Mg ha^{-1}) than all other MWs, yet many-fold lower than the reported soil losses under the traditional shifting cultivation system in the region (Dabral et al., 2008; Pandey et al., 2008; Singh et al., 2011). Despite soil structural degeneration (Meetei et al., 2020), contouring with sparse plantation of bamboo and broom grasses might have reduced soil loss in MW_8 compared to traditional practices. Sharda et al. (2002) reported that the adoption of conservation bench terraces in the cultivated (agricultural crops) hill slopes reduced the runoff by 4-fold and soil loss by 9-fold compared to the without SWCMs (soil loss of 10.1 Mg ha^{-1} yr^{-1}) in the Western Himalayan Region (Selakui, Dehradun, and Uttrakhand) of India. On long periods (1991–2005) of adoption, the runoff was reduced by 78.9% and soil losses by 88.0% at the same experimental site (Sharda et al., 2013). Similar beneficial effects of crop canopy coverage and a combination of SWCMs like contouring, terracing, and vegetative barriers in reducing soil erosion in hilly watersheds were reported from other regions (FAO, 2000; Garcı'a-Ruiz, 2010; Singh et al., 2011).

4 | CONCLUSIONS

It is generally accepted that deforestation and conversion of forests to agriculture on steep slopes lead to severe soil erosion. We also anticipated an increase in soil erosion when the hilly (slope > 32.0%–53.0%) micro-watersheds under the forests were converted to cultivation in integrated farming system (IFS) mode. However, the results of the study suggest that cultivation in IFS mode (especially agroforestry -MW_3, agri-horti-silvi-pastoral-MW_5 or horticulture-based-MW_6) has reduced annual runoff and soil loss by more than 10.0%–15.0% relative to dense forests. This decrease is partly attributed to stable land use practices (perennials/fruits interspersed with seasonal crops and legume cover crops). In addition, adoption of SWCMs, specifically the combination of terracing (half moon and bench), contour bunding, and grass waterways together were more effective in reducing soil erosion (by >25.0%) in $MW_{5\&6}$ than the only contour bund in the IFS based on forage and livestock (MW_1). Similarly, the key soil quality parameters measured (hydro-physical and fertility) were more resistant to deterioration in these cultivated IFS (MW_3 and $MW_{5\&6}$) than shifting cultivation (MW_8) and agriculture ($MW_{1\&4}$). Thus, it is consistent with earlier findings that terracing in combination with contour bunding is more effective in reducing soil erosion while improving soil properties than contour bunding only on the hill slopes.

However, conversion of forests to traditional agriculture of the region (shifting cultivation, MW_8), even with improved SWCM (e.g., contour bunding), soil erosion increased by 1.5–1.6-times. Similarly, converting forests to cultivated fallow (MW_7) while allowing secondary vegetation to regenerate for 23 years in the absence of SWCM has increased soil erosion from 1.4–1.6-times more. Although soil loss in shifting cultivation exceeded the critical thresholds (12.5 Mg ha^{-1} yr^{-1}) for the region, yet, contour bunding and sparse planting of bamboo and broom grass could reduce the soil loss of many folds compared to a reported soil loss (>50.0 Mg ha^{-1} yr^{-1}) in farmers' fields. Thus, among the IFS models, we recommend the promotion of agroforestry, agri-horti-silvi-pastoral, and horticulture to reduce soil erosion below critical thresholds in the Indian Himalayan region (IHR). The results of the study will help develop adaptation strategies for a climate-resilient farming system in the mountainous Indian Himalayan ecosystem.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on reasonable request from the corresponding author, without commercial use or direct use in publishing the same. The data are not publicly available due to privacy or ethical restrictions.

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