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RESEARCH ARTICLE

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Combined effects of climate change and agricultural intensification on soil erosion in uphill shifting cultivation in Northeast India

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Abstract

Shifting cultivation will face increasing pressure from erosion-related land degradation caused by rising cultivation intensities and climate change. However, empirical knowledge about future trends of soil erosion and thus land degradation in shifting cultivation systems is limited. We use the Environmental Policy Integrated Climate (EPIC) model to first explore the combined effects of climate change and agricultural intensification on soil erosion of uphill shifting cultivation systems, using six surveyed soil profiles. We assess interactions between climate change, the length of the fallow period, and slope inclinations for a near (2021–2050) and far (2071–2100) future period, considering three climate scenarios, five climate models, fallow periods between one and 20 years, and slopes between five and 70% steepness. Our results show a significant nonlinear relationship between global warming and erosion. Until the end of the century, erosion is estimated to increase by a factor of 1.2, 2.2, and 3.1 under the SSP126, SSP370, and SSP585 scenarios, respectively, compared with the historical baseline (1985–2014). Combined effects from climate change, fallow length, and slope inclination indicate that steep slopes require longer fallow periods, with an increase of slope from 5% to 10% multiplying the required fallow length by a mean factor of 2.5, and that fallow periods will need to be extended under higher global warming if erosion rates are to remain at current levels. These findings are novel as they link climate change effects on shifting cultivation systems to different slopes and fallow regimes, making an important contribution to understanding future erosion dynamics of traditional smallholder production systems in mountainous terrain, with relevant implications for policies on agricultural intensification.

KEYWORDS
agricultural intensification, climate change, Northeast India, shifting cultivation, soil erosion modeling, South Asia

1 | INTRODUCTION

Population growth and political agendas on agricultural development have led to an intensification of shifting cultivation and thus rising land degradation due to soil erosion in uphill regions of South and Southeast Asia. In addition, future increases in precipitation intensities due to climate change can be expected to accelerate soil erosion, thus putting additional pressure on uphill shifting cultivation systems. In this study, we seek to address the interplay between climate change and the intensification of shifting cultivation cycles on future soil erosion.

Shifting cultivation is a smallholder rotation farming system where short periods of crop cultivation alternate with typically longer fallow periods. The system is highly vulnerable to climate change because it depends on the natural regeneration of soil fertility during the fallow period. Increasing erosion rates under climate change have the potential to undermine soil recovery of shifting cultivation systems because they result in losses of the organic-carbon-rich top soil, thus reducing soil stability and productivity.

Besides climate change, reductions in the length of fallow periods are increasingly challenging soil productivity. Population growth and political agendas aiming for agricultural intensification through the propagation of settled agriculture have recently increased the pressure on productive land in South and Southeast Asia (Bose, 2019; Bruun et al., 2017; Castella et al., 2013; Fox et al., 2014; Rasul & Thapa, 2003; Ziegler et al., 2012). As a consequence of increasing land competition, shifting cultivation has migrated toward higher altitudes (Adhikary et al., 2019; Feng et al., 2021; Nongkynrih et al., 2018) and fallow cycles have been reduced (Choudhury & Sundriyal, 2003; Lestrelin et al., 2012; Prokop & Poreba, 2012; van Vliet et al., 2012), thus increasing the risk for soil erosion and challenging the sustainability of shifting cultivation systems.

Previous studies from South and Southeast Asia already observed serious increases in soil erosion and linked these to a reduction in fallow periods (Grogan et al., 2012; Jayahari & Sen, 2015; Ziegler et al., 2009). Mishra and Ramakrishnan (1983) measured sediment loss to be higher under a 5-year compared with a 10-year shifting cultivation cycle. However, the exact relationship between the length of the fallow period and soil erosion remains unclear.

Previous studies have also shown that increases in erosion, in particular, take place on the cultivated steeper slopes (Gafur et al., 2003; Sati, 2020). The significant effect of slope steepness on soil erosion has been widely proven (El Kateb et al., 2013; Shen et al., 2019). However, research on the combined impact of slope steepness and cultivation intensity is scarce. While both variables tend to increase soil erosion, their combined effects on erosion have not yet been studied. Filling this research gap is important because increasing demand for agricultural production has led to a simultaneous shortening of fallow periods and cultivation of steeper slopes.

Several studies have pointed to an increasing risk of soil erosion under climate change in the Himalayas, mainly northern India, where erosion was estimated to increase by 15%–235% until the end of the century, compared with the late 20th and early 21st century (Choudhury et al., 2022; Gupta & Kumar, 2017; Khare et al., 2017; Kumar et al., 2022; Sooryamol et al., 2022). However, most of these studies exclusively consider the effect of changing precipitation patterns on the rainfall-runoff erosivity factor, hence missing other climate-related effects on soil erosion, such as indirect effects from temperature, precipitation, and rising CO_2 concentrations on biomass growth and soil moisture (Li & Fang, 2016). Likewise, previous studies do not focus specifically on shifting cultivation systems. Choudhury et al. (2022) analyzed erosion for integrated farming systems, including abandoned shifting cultivation fields, but did not consider areas under active shifting cultivation. Closing this research gap is urgently required since shifting cultivation plays an essential role in securing food supply for the tribal population of uphill regions (Pandey et al., 2020).

We address existing research gaps by analyzing the combined effects of climate change, fallow period length, and slope inclination on future soil erosion of shifting cultivation systems. In particular, we ask: (1) How will climate change affect future soil erosion in shifting cultivation, and what is the relationship between erosion and global warming? (2) How will the seasonal distribution and daily intensity of erosion change? (3) How do fallow periods and slope inclinations influence soil erosion under shifting cultivation? (4) How do combined effects from climate change scenarios and fallow period lengths affect soil erosion on different slopes?

We selected Nagaland state of Northeast India as a study region where shifting cultivation is still widely practiced (Government of Nagaland, 2012). Due to the steep topography and recent reductions in fallow periods, the region has become a potential hotspot for soil erosion and degradation (Krug et al., 2013; Sharda et al., 2010).

We assess interactions of climate change, fallow periods, and slope inclination using a modeling approach based on six surveyed soil profiles from Nagaland. Therefore, we analyze soil erosion rates for the near (2021–2050) and far (2071–2100) future under three climate scenarios, link erosion to global warming levels, and assess changes in the seasonal distribution and daily intensity of erosion. Further, we examine the individual and combined effects of fallow period length and average field slope on future erosion and relate our results to a soil loss tolerance. Finally, we discuss implications for soil degradation and place our findings in the context of increasing agricultural intensification. Our results improve the understanding of future erosion dynamics of uphill shifting cultivation systems and provide recommendations for decision-makers on the field and policy level.

2 | MATERIALS AND METHODS

2.1 | Study area

For this research, we selected Mokokchung district of Nagaland state as a study area. Though shifting cultivation, locally called *jhum*, is practiced in all states of Northeast India, the practice is most dominant in Nagaland state (Jayahari & Sen, 2015). Rice is the most important crop in the system, although, in many places, rice is grown along with other cereals, vegetables, fruits, and root crops (Chatterjee et al., 2021;

FIGURE 1 Shifting cultivation landscape. Photos were taken during the burning operation (left, © Lea S. Schröder), field preparation (center, © Amol Bhalerao), and cultivation (right, © Sesenlo Kath). [Colour figure can be viewed at wileyonlinelibrary.com]

Choudhury & Sundriyal, 2003). The *jhum* cycle typically consists of a 2-year cropping phase following slashing and burning (Figure 1), and a fallow period after cultivation with an average length of currently 8 years (Government of India, 2015).

Nagaland is traversed by mountain ranges, with approx. 98% of the state being mountainous (Jayahari & Sen, 2015). Altitudes range from 194 to 3840 m above sea level (Government of Nagaland, 2019). Accordingly, steep slopes dominate the region, with 63% of the area having slopes steeper than 30% and even 26% steeper than 50% (SRTM, 2013).

The climate ranges from sub-tropical to sub-montane temperate. It is characterized by the Indian Summer Monsoon between mid-May to the end of September, making up over 85% of the total annual precipitation, which amounts to 1200–2500 mm (Government of Nagaland, 2019; Jayahari & Sen, 2015).

Soils in Nagaland comprise Inceptisols, Entisols, Alfisols, and Ultisols, with Inceptisols making up the highest share (66%) (Government of Nagaland, 2012), according to the USDA classification (Soil Survey Staff, 2014). Due to rainfall-related fast weathering processes and steep terrain, soils are relatively acidic (Bandyopadhyay et al., 2018). Soil loss tolerance has been reported as 10 t ha^{-1} year^{-1} for most parts of the study area (Mandal & Sharda, 2011).

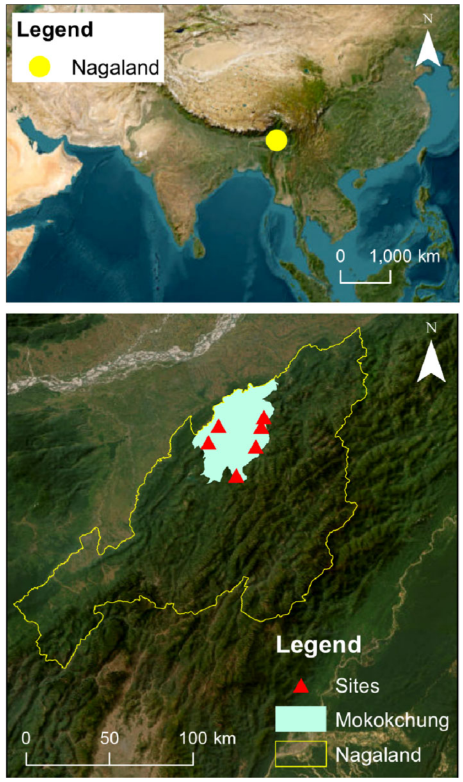

FIGURE 2 Study area with sites of collected soil profiles. Source of satellite image: ESRI, Maxar, Earthstar Geographics, and the GIS User Community. [Colour figure can be viewed at wileyonlinelibrary.com]

2.2 | Data

2.2.1 | Soil and site data

A pedological survey was conducted in 2014 on six soil profiles in Mokokchung district of Nagaland (Figure 2). Five soil profiles belong to the soil order Inceptisols, one to Entisols. All sites were under current *jhum* cultivation or fallow land use during data collection. Soil samples from the different pedological horizons were manually collected with a spade, air-dried (at room temperature to constant weight), ground, and passed through a 2-mm sieve to exclude litter, roots, and coarse particles. For all horizons, depth-wise soil analysis was conducted using standard procedures. The percentage of silt, sand, and clay was determined using the pipette method as described by Piper (1966). Bulk density (BD) was estimated by the core method as described by Blake and Hartge (1986). Wet-oxidation method described by Walkley and Black (1934) was used to determine the soil organic carbon (SOC) content. Hydrological soil groups were derived based on soil textures according to the USDA-NRCS Hydrologic Soil Group Classification (NRCS, 2007). Besides soil data, altitude information and geo-coordinates were collected for model input. Physical soil properties and site information used as model input are provided in Table 1.

2.2.2 | Climate data

We used daily climate data on precipitation, maximum and minimum temperatures, relative humidity, solar radiation, and wind speed for a historical baseline (1985–2014), a near future (2021–2050), and a far

TABLE 1 Site and physical soil properties of collected samples.

		P01	P04	P06	P08	P12	P14
Longitude		94.537	94.319	94.408	94.4	94.262	94.228
Latitude		26.216	26.148	26.337	26.305	26.308	26.254
Elevation (m)		490	774	614	889	445	504
Slope (%)		5	30	10	30	5	33
Soil order		I	I	I	I	E	I
Soil hydrologic group		C	D	C	C	B	B
Number of horizons		4	5	5	4	5	5
Per horizon	Depth to bottom of horizon (cm)	20	25	20	24	7	9
		40	44	50	37	41	45
		60	97	90	67	68	55
		90	135	117	130	101	72
			144	150		125	104
	Bulk density (g cm^{-3})	0.81	0.9	0.88	0.86	1.06	1.13
		0.84	0.91	1.04	0.92	1.06	1.21
		0.96	0.93	1.09	0.9	1.06	1.11
		0.99	1.13	1.16	0.98	1.23	1.16
			1.03	1.18		1.09	1.08
	Sand (%)	44.8	12.85	53.5	36.7	70.3	68.9
		42.55	16.65	44.85	34.25	69.85	71.85
		35.35	23.05	35.8	44.55	71.85	70.15
		32.52	41.4	42	43.1	92.45	57.95
			25.25	42.7		71.0	46.7
	Silt (%)	28.65	30	15.8	28.5	11.4	13.95
		26.15	28	20.7	28.45	12.55	11.2
		29.1	24.95	27.05	16.05	12.35	10.95
		26.05	24.55	26.8	20.35	6	5.1
			43.95	31.65		21.3	18.6
	Organic carbon (%)	1.96	2.67	1.85	1.86	0.89	1.29
		1.66	1.72	1.46	1.42	0.61	0.89
		1.24	0.89	0.54	1.04	0.41	0.95
		0.95	0.57	0.41	0.78	0.4	1.15
			0.53	0.38		0.32	0.01

Abbreviations: E, Entisol; I, Inceptisol.

future (2071–2100) period. The future climate projections include three scenarios from phase 6 of the Coupled Model Intercomparison Project (CMIP6), which combine Representative Concentration Pathways (RCPs) used for CMIP5 climate projections and Shared Socioeconomic Pathways (SSPs) derived from integrated assessment models (IAMs) (O'Neill et al., 2016). The scenarios used in our study include low-end (SSP126), medium-high (SSP370), and high-end (SSP585) scenarios of future forcing pathways. For all scenarios, we used bias-corrected and statistically downscaled climate data from phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) (Lange, 2019; Lange & Büchner, 2021). Those climate data were available for five CMIP6 models: GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL, and IPSL-CM6A-LR. These models are structurally independent regarding their ocean and atmosphere components and are considered good representatives for the CMIP6 ensemble, as they contain models with low and high climate sensitivity (Lange, 2021). We downloaded the ISIMIP3b climate data in February 2022 from the ISIMIP repository (https://data.isimip.org/search/). The five climate models differ in their precipitation projections, mainly during the beginning and peak of the monsoon season. Particularly in the far future under the SSP370 and SSP585 scenarios, precipitation projections diverge, with UKESM1-0-LL projecting the highest increases and GFDL-ESM4 a slight decrease in precipitation during the peak of the monsoon season. At the beginning of the monsoon season, most models predict, to varying degrees, increases in precipitation, whereas precipitation projections of MPI-ESM1-2-HR fall below historic precipitation (see Figure A3 in Supplementary Material). To account for differences among climate models, we applied climate data from all five models in our study.

2.3 | Model

2.3.1 | Environmental Policy Integrated Climate model

We used the Environmental Policy Integrated Climate (EPIC) model, originally called Erosion Productivity Impact Calculator, and developed to simulate interactions between soil erosion and soil productivity in the United States (Williams et al., 1984). While EPIC is not the only erosion model recommended for use in Asia (Guo et al., 2019), it was selected because expertise for this model was already available among the authors. Consisting of different physically based components, including hydrology, erosion, nutrient cycling, and plant growth, the model is capable of simulating various environmental processes resulting from interactions between climate, topography, soils, crops, and management. For details on model parameters and equations regarding the above processes, the reader is referred to Sharpley and Williams (1990) and Williams (1995). Since 1981, the model has been under continuous development, improved and tested for diverse regional and management conditions (Izaurralde et al., 2006), and applied in numerous studies on soil erosion (Benson et al., 1989; Bhuyan et al., 2002; Carr et al., 2021; Favismortlock et al., 1991; Izaurralde et al., 1997; Lee et al., 1996, 1999; Richardson & King, 1995; van Zelm et al., 2018). Besides, the model has been proven suitable for crop–fallow rotation systems, as applied in Gaiser et al. (2010) and Srivastava et al. (2012). In this study, we used the EPIC model version 0810.

The EPIC model captures soil erosion by water using the basic equation (1)

$$Y = R \times K \times LS \times C \times P \tag{1}$$

where Y is soil erosion (t ha^{-1} year^{-1}), R the erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}), K the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS the slope length and steepness factor (dimensionless), C the soil cover and management factor (dimensionless), and P the conservation practice factor (dimensionless). The calculation of the erosivity factor R depends on the specific erosion equation selected by the user, who can choose from seven equations. While the R-factor in the erosion equation USLE and its revisions (RUSLE, RUSLE2) is mainly driven by precipitation intensity, in MUSLE, MUST, and MUSS, it is driven by runoff variables, whereas the Onstad-Foster equation applies a combination (Carr et al., 2020; Williams, 1995). The K-factor is computed based on sand, silt, clay, and organic carbon contents of the top soil horizon at the beginning of each simulation year, using the equation provided in Williams (1995). The LS-factor is calculated from slope steepness and slope length using the equation from Wischmeier and Smith (1978). The C-factor is computed for all runoff-occurring days and is based on simulated above ground biomass and residues, as further explained in Williams (1995). EPIC calculates biomass growth based on Monteith's approach (Monteith & Moss, 1977) from photosynthetic active radiation, a crop parameter for converting energy to biomass, and day length. Photosynthetic active radiation is determined by solar radiation and leaf area index (LAI). LAI is a function of heat units, crop development stages, and crop stress based on stress factors for water, temperature, nutrients, and aeration. Heat units refer to daily average temperatures exceeding the base temperature, which is a crop-specific minimum temperature required for growth. Accumulated daily heat units that are needed to reach crop maturity are defined as potential heat units. They can be entered by the user or computed by the model from daily temperatures between planting and harvesting dates. Further information on biomass growth is given in Sharpley and Williams (1990). The P-factor of the erosion equation refers to the ratio between soil loss under the applied management and soil loss without this management (Morgan, 2005) and has to be supplied to the model by the user.

2.3.2 | Model setup

To set up the model for the topographic conditions of the study region, we tested all of the above erosion equations and found that RUSLE provided the lowest and most realistic soil loss, which is consistent with the findings by Carr et al. (2020). We also tested several combinations of exponential coefficients in the RUSLE C-factor equation and applied the best-performing combination as given in Supplementary Material (A4). As P-factor, we chose the mean value (0.38) for contour bunds, which are mostly applied on *jhum* fields in the study region (unpublished survey carried out in April 2022), from Morgan (2005). We opted against a slope-specific P-factor value because these were unavailable for the entire slope range analyzed in this study. Using a mean P-factor value, we also attenuate the effect that EPIC typically overestimates soil erosion on steep slopes (Carr et al., 2020).

To represent shifting cultivation in the model, we implemented a rotation consisting of a 2-year cropping phase and a fallow period of one to 20 years length (see Section 2.3.4 for details). Due to its importance in local shifting cultivation systems, we chose rice as the crop for the cultivation phase. Rise is planted at the beginning of March by manual broadcasting at a plant density of 250 plants m^{-2}. For field preparation, traditional contouring practices using rocks and wood are applied; no tilling occurs. During the growing period, neither fertilization nor irrigation takes place. Manual weeding, typically carried out between April and July, was not considered in our simulations, as field observations showed only marginal effects on erosion (Ziegler et al., 2007). Rice harvesting starts at the beginning of September and is done by manual cutting (at 50 mm above ground). Crop residues, including rice stalks, remain on the field. After 2 years of rice cultivation, herbaceous fallow vegetation starts growing. As fallow vegetation, we selected Johnson Grass, a weed that is widely distributed over India on cultivated and abandoned fields and well adapted to subtropical climates with warm and wet summers. Albeit fallow areas typically have scrub vegetation and trees growing up after a certain period of time, we limited fallow vegetation in our simulations to grass vegetation for simplicity. This approach is appropriate for erosion studies, as previous research has shown that grass vegetation has the most important effect on erosion; hence the additional effect from secondary vegetation types can be considered marginal (Chen et al., 2018). We did not implement any fallow management except the burning of vegetation at the end of the fallow period, which is in line with the common shifting cultivation practice.

We used two spin-up simulations to compute potential heat units (PHU) required for the maturation of the rice crop and to approximate soil parameters not included in the measurements, which are mostly chemical soil properties relevant for yield predictions but less decisive for erosion. This is in line with the common procedure as outlined in Sharpley and Williams (1990). For further information on model setup, including scenario-specific CO_2 concentrations (Meinshausen et al., 2020) applied per simulation period, we provide a detailed documentation in the Supplementary Material (A1–A4).

2.3.3 | Model evaluation

To evaluate the model performance, we compared soil loss of the historical baseline simulations (1985–2014) to the measured soil loss range of a reference study. As a reference study, we selected Saha et al. (2011), to our knowledge, the only study that measured soil erosion under shifting cultivation in Northeast India over an extended period of time. The study was carried out in Meghalaya, a neighboring state of our study area with comparable climate and topographic conditions. To increase the comparability of our simulations with the reference study, we selected two points (P01, P08) with similar top soil horizon characteristics, and slope inclination and management closest to the described conditions (Table 2). Figure 3 shows that the simulated soil erosion for P01 and P08 corresponds to the range of the reference study. The marginally higher soil loss can be explained by the slightly higher slope inclination and annual precipitation in our simulations. For completeness, simulated erosion for the other sites is also given in Figure 3.

We further compared soil loss in our simulations to the land use and seasonal pattern reported in previous studies. Our simulations showed that mean soil erosion during rice cultivation was between four and six times higher than during fallow when the average of all stages within a 3-year fallow period is considered (Figure A1 in Supplementary Material). This is consistent with previous findings from Gafur et al. (2003). Also, our model simulations reproduced the bimodal seasonal pattern of soil erosion during cultivation reported in Mishra and Ramakrishnan (1983), with the first erosion peak in spring between April and May and the second in September (Figure A2 in Supplementary Material). These are associated with a reduced soil cover before and after sowing, as well as after harvesting.

As the historic annual soil erosion of our simulations matches the measured soil loss range of the reference study and is consistent with land use and seasonal patterns found in previous studies, we presume that our simulations provide an adequate picture of soil erosion dynamics in the region.

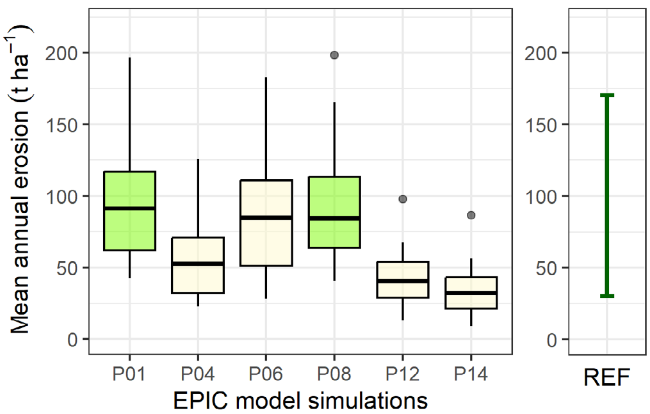

FIGURE 3 Simulated historic soil erosion compared with reference study. Mean annual erosion (y-axis) for six different sites (x-axis) is shown. REF, measured erosion range in reference study (Saha et al., 2011). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Characteristics of simulated sites and reference study site used for model evaluation.

	P01	P08	REF
Time period	1985–2014	1985–2014	1983–2011
Land use	SC	SC	SC
Fallow length	3 Years	3 Years	3 Years
Mean field slope	40%	40%	38.2%
Mean annual rainfall	2793 mm	2518 mm	2439 mm
Texture[a]	Sandy clay loam	Clay loam	Clay loam
Annual soil loss[b]	42.40–196.56	40.39–198.36	30.20–170.20
Method	EPIC model	EPIC model	Multi-slot divisor

Note: Detailed information on soil properties, including particle size distribution, soil organic carbon, and bulk density, is given in Table 1 (P01, P08) and Saha et al. (2011) (REF).
Abbreviation: REF, reference study site; SC, shifting cultivation.
[a]Refers to top soil horizon.
[b]In t ha^{-1} year^{-1}.

2.3.4 | Model simulations

We simulated future soil erosion for three different climate scenarios, namely SSP126, SSP370, and SSP585, and two 30-year time horizons, from 2021 to 2050 (near future) and from 2071 to 2100 (far future). To examine the effect of slope inclination and fallow length on erosion dynamics, we simulated erosion for various slopes and fallow lengths, considering field slopes between 5% and 70% steepness (in 5% steps) and fallow lengths between 1 and 20 years. Previous studies and our model evaluation have shown that soil erosion behaves differently between the first and second years of cultivation and the fallow period. To avoid distorting this pattern due to interannual weather variations, we simulated each year of a simulation period with all three land uses (first year of rice cultivation, second year of rice cultivation, fallow). To achieve this, we started each simulation at a different point in the rotation and repeated this process until all points in the rotation had occupied the starting position. For example, for the shortest rotation we considered, rice–rice–fallow (fallow length 1 year), we started the simulation three times, once in the order of rice–rice–fallow, once in the order of rice-fallow-rice and once in the order of fallow–rice–rice. For each sequence, we prepared one operation file (see Figure 4 for the resulting number of operation files). To analyze the results, we computed average values from all sequences.

3 | RESULTS

3.1 | Annual soil erosion rates under climate change

Our simulations indicate increases in mean annual soil erosion for the far future under all climate scenarios. This increase is particularly strong under the SSP370 and SSP585 scenarios, for which our simulations indicate a mean increase by a factor of 2.2 and 3.1 compared to the reference period, resulting in an average annual soil erosion of 85 and 120 t ha^{-1}, respectively (Figure 5). Under the SSP126 scenario, we estimate mean erosion to increase by a factor of 1.2, corresponding to an annual soil erosion of 45 t ha^{-1}. Our simulations also indicate changes in mean annual soil erosion for the near future; however, these are less pronounced and inconsistent between climate scenarios (Figure 5). On average, our results indicate annual soil erosion rates of 44, 40, and 42 t ha^{-1} for the near future of SSP126, SSP370, and SSP585, respectively, compared to 38 t ha^{-1} estimated for the historical baseline.

Although all applied climate models agree on a sharp increase in annual soil erosion during the far future under the SSP370 and SSP585 scenarios, erosion estimates vary depending on the underlying climate model used in the simulations (Figure 5). For the far future, the highest soil erosion rates were simulated for UKESM1-0-LL (all scenarios) and the lowest for GFDL-ESM4 (SSP126, SSP585) and MPI-ESM1-2-HR (SSP370), while results for IPSL-CM6A-LR and MRI-ESM2-0 rank intermediate (all scenarios). Under SSP585 and SSP370, the difference between the highest and lowest soil erosion estimated for the far future is quite large, with 82 and 58 t ha^{-1}, respectively. Differences in erosion projections for the different climate models can be explained by differing precipitation projections during the beginning and mid of the monsoon season (see Figure A3 in Supplementary Material).

Differences between projected precipitation and hence erosion are the result of diverging global warming levels projected by the different climate models (Figure 6). As climate sensitivity and hence global warming levels are much higher for UKESM1-0-LL than for the remaining climate models of this study, erosion estimates for UKESM1-0-LL turn out to be higher as well. We derive a significant nonlinear relationship between erosion rates and global warming levels ($p < 0.001$, $R^2 = 0.88$), indicating an increase in erosion by more than 60% when global warming levels increase from 1.5 to 3.0°C. We conclude that increases in soil erosion in Northeast India will depend significantly on future global warming levels.

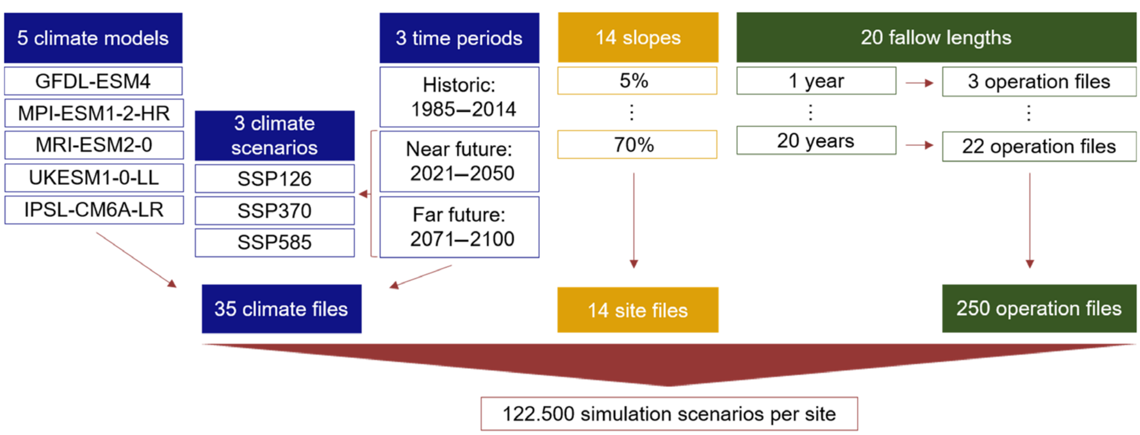

FIGURE 4 Setup of simulation scenarios. SSP, Shared Socioeconomic Pathways, describing low-end (SSP126), medium-high (SSP370), and high-end (SSP585) scenarios of future greenhouse gas emissions. [Colour figure can be viewed at wileyonlinelibrary.com]

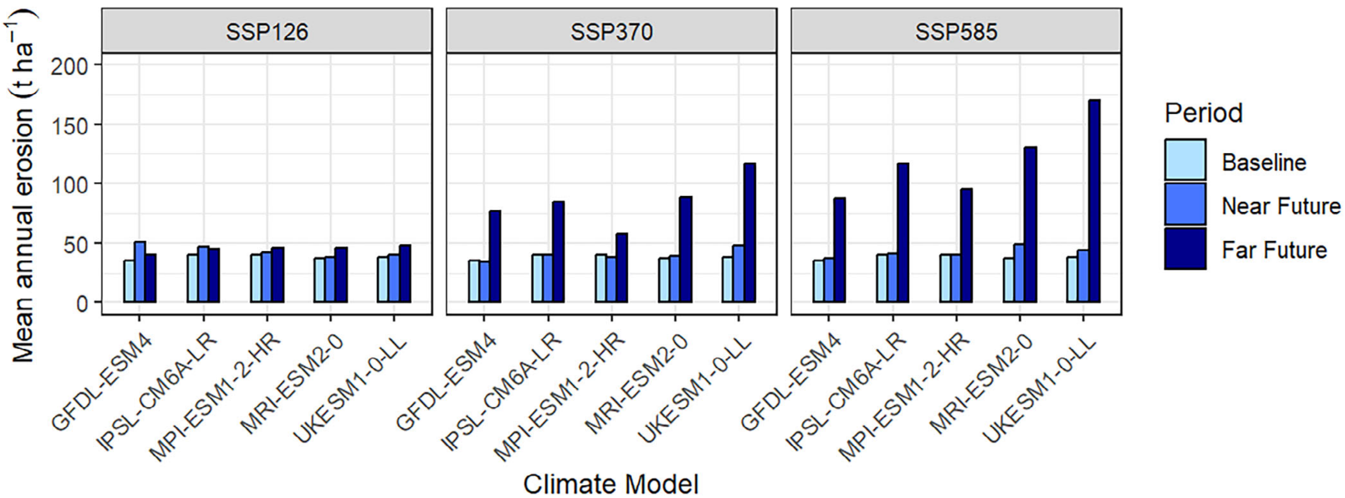

FIGURE 5 Mean annual soil erosion rates for SSP126, SSP370, and SSP585 for five climate models. Results show mean values of all simulated slopes and fallow lengths. [Colour figure can be viewed at wileyonlinelibrary.com]

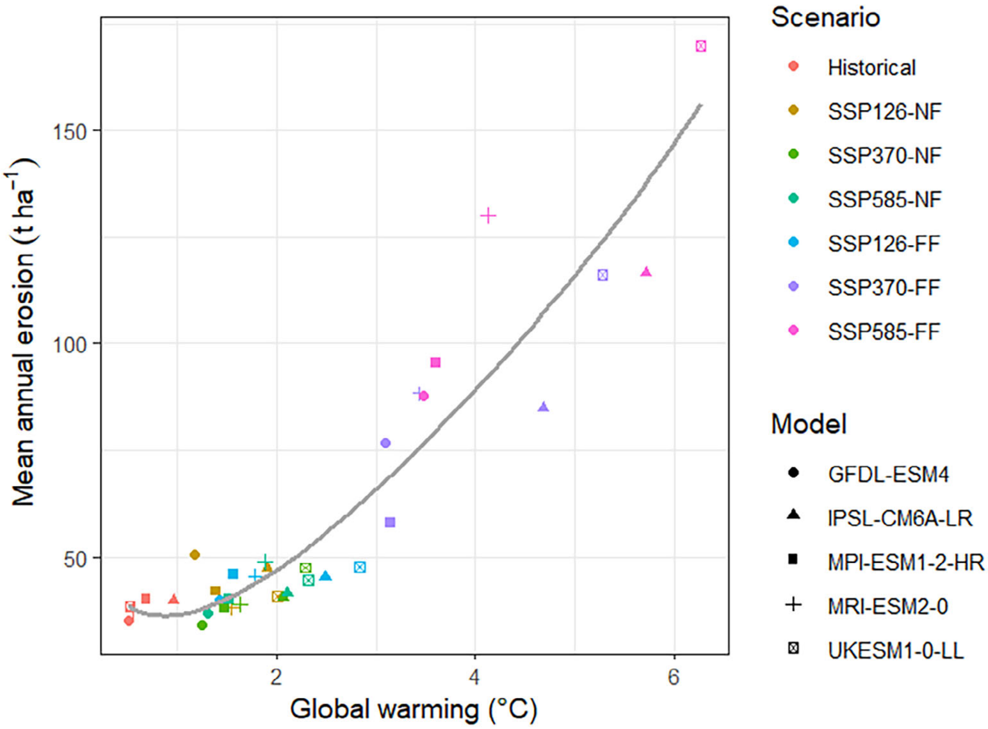

FIGURE 6 Mean annual soil erosion rates in relation to global warming. The model is described as $f(x) = 76.31 + 45.91x + 0.01\ \exp(x) - 85.81\sqrt{x}$ with $p < 0.001$ and $R^2 = 0.88$. The model is applicable for warming levels between 0.52 and 6.27°C. FF, far future; NF, near future. [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | Future intensity and seasonality of erosion

The simulated increase in annual soil erosion can be attributed to an increase in high-intensity erosion events. While during the historical baseline, in all near-future scenarios and the SSP126 far future, erosion per day rarely exceeds 0.3 t ha^{-1}, far-future scenarios of SSP370 and SSP585 indicate a clear increase of days with soil losses between 0.3 and 2.0 t ha^{-1} (Figure 7a). Under these scenarios, days with erosion exceeding 0.3 t ha^{-1} constitute more than 50% of all erosion days. Increases in high-intensity erosion days are also determined by slope and fallow periods. With rising slopes and decreasing fallow periods, the share of erosion days above 0.5 and 1 t ha^{-1} clearly increases for the SSP370 and SSP585 far future, respectively (Figure 7b,c). We conclude that climate change-induced increments in annual erosion are largely due to an increase in high-intensity erosion events, while the quantity

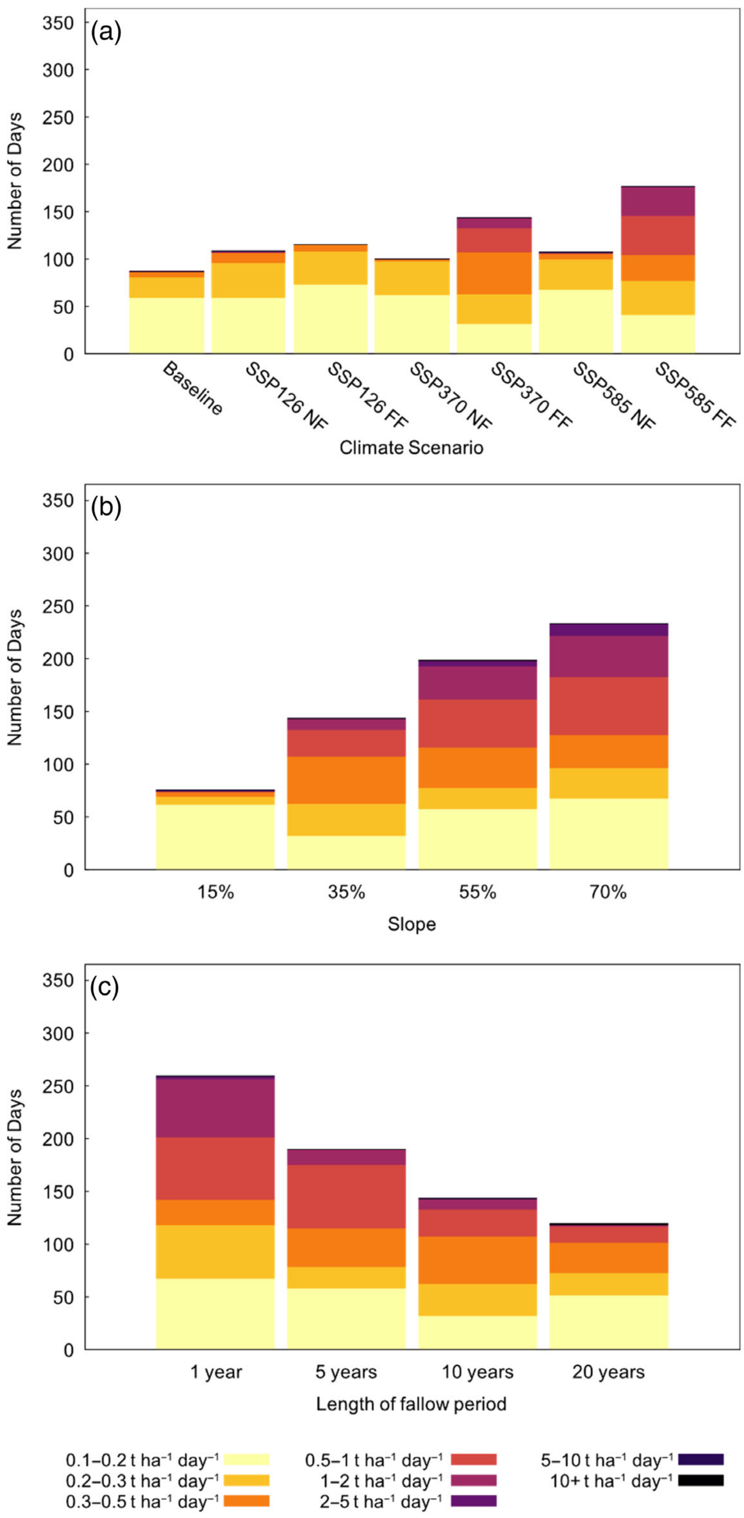

FIGURE 7 Frequency of different daily soil erosion intensities per (a) climate scenario and time period, (b) 15%, 35%, 55%, and 70% slope steepness, (c) 1-year, 5-year, 10-year, and 20-year fallow regimes. Values for (a) are based on 35% slope steepness and a 10-year fallow regime. Values for (b) are based on the SSP370 far future and a 10-year fallow regime. Values for (c) are based on the SSP370 far future and 35% slope steepness. Results show the mean values of the five climate models. FF, far future; NF, near future. [Colour figure can be viewed at wileyonlinelibrary.com]

of days with lower erosion intensities (<0.2 t ha^{-1}) shows slight decreases.

Our results further indicate that the increase in erosion intensities will mostly occur in the pre-monsoon season between March and April and the high monsoon season between July and September. Figure 8 shows that all erosion peaks, except the spring peak under fallow, are substantially higher under the SSP370 and SSP585 far futures. For the autumn peak under fallow, this increase is extreme. In addition, maximum erosion in spring and increases in erosion during summer occur about 1 month earlier under both rice and fallow under these scenarios. Changes in the magnitude and timing of erosion can be related to an increasing precipitation intensity during the early and high monsoon season. Particularly during the pre-monsoon season between the mid of March and the beginning of June, four out of five

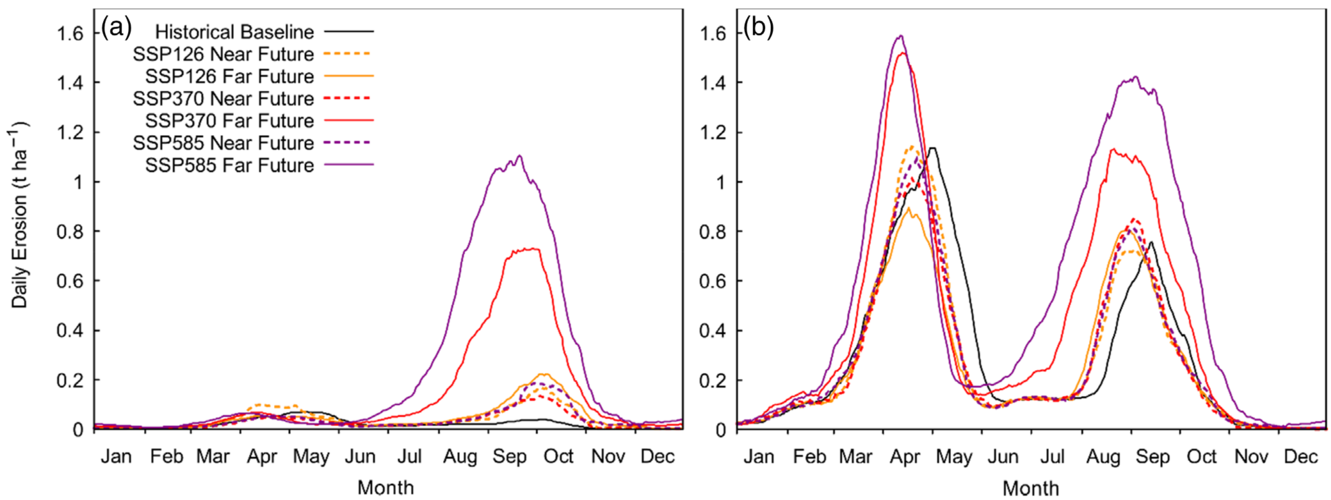

FIGURE 8 31-Day moving average of intra-annual soil erosion dynamic for (a) fallow and (b) rice cultivation. The *x*-axis indicates the month; the *y*-axis indicates erosion per day in t ha^{-1}. Results were averaged over the five climate models and 30 simulated years per period and are based on 35% slope steepness and a 10-year fallow regime. The 35% slope was selected because this slope range contains the most shifting cultivation areas; the 10-year fallow regime corresponds to the mean simulated fallow period. [Colour figure can be viewed at wileyonlinelibrary.com]

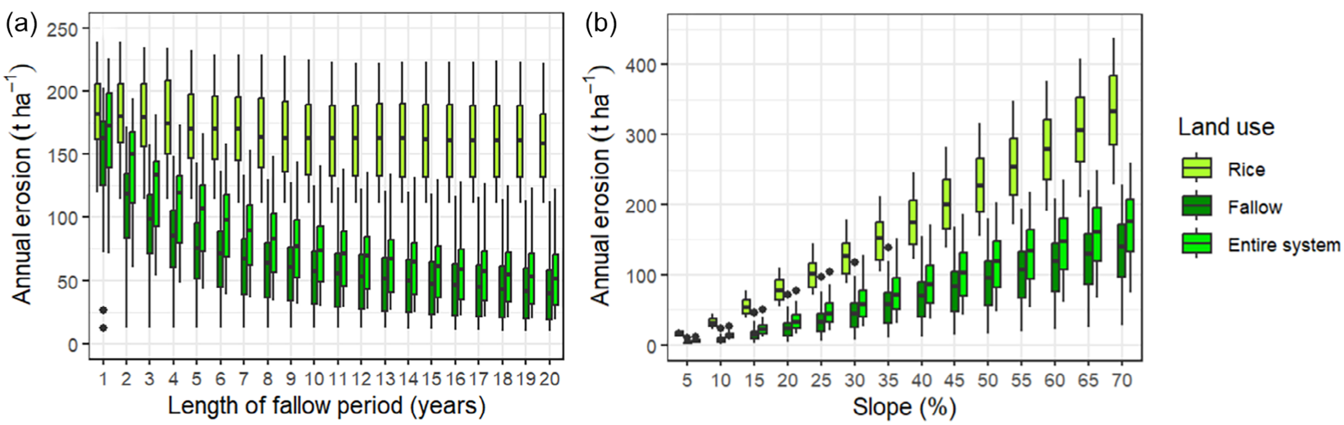

FIGURE 9 Relationship between (a) fallow period length and erosion and (b) slope and erosion for the far future. Boxplots show median, first and third quartile, and the range of values excl. outliers. Outliers are indicated by points. The average of SSP126, SSP370, and SSP585 scenarios of five climate models is shown. [Colour figure can be viewed at wileyonlinelibrary.com]

climate models indicate substantial increases in precipitation (see Figure A3 in Supplementary Material). However, a simple translation from precipitation to erosion increases would fall short, since the latter also depends on other factors, such as the distribution of rainfall across days and changes in vegetation cover.

3.3 | Future soil erosion for different slopes and fallow periods

Our results reveal a negative relationship between fallow period length and soil erosion, which is stronger during the fallow period itself than during rice cultivation (Figure 9a). During cultivation, the relation is linear, while it is nonlinear during fallow. This pattern can be explained by the fact that soil erosion during fallow is highest during the early years after rice cultivation. The shorter the fallow period, the higher the share of erosion-prone years at the beginning of the fallow phase. With increasing fallow length, the share of less erosion-intensive years increases, hence overall erosion during the fallow period decreases. When the fallow periods are longer than 10 years, the strength of the relationship diminishes. Considering the fallow–erosion relationship for the entire system, soil erosion is 1.6 times higher under a 1-year compared with a 5-year fallow regime and even 2.2 times higher when compared with a 10-year fallow regime.

Our results confirm the expectable distinct, positive linear relation between slope and soil erosion, which is more pronounced during rice cultivation than during fallow (Figure 9b). During rice cultivation in the

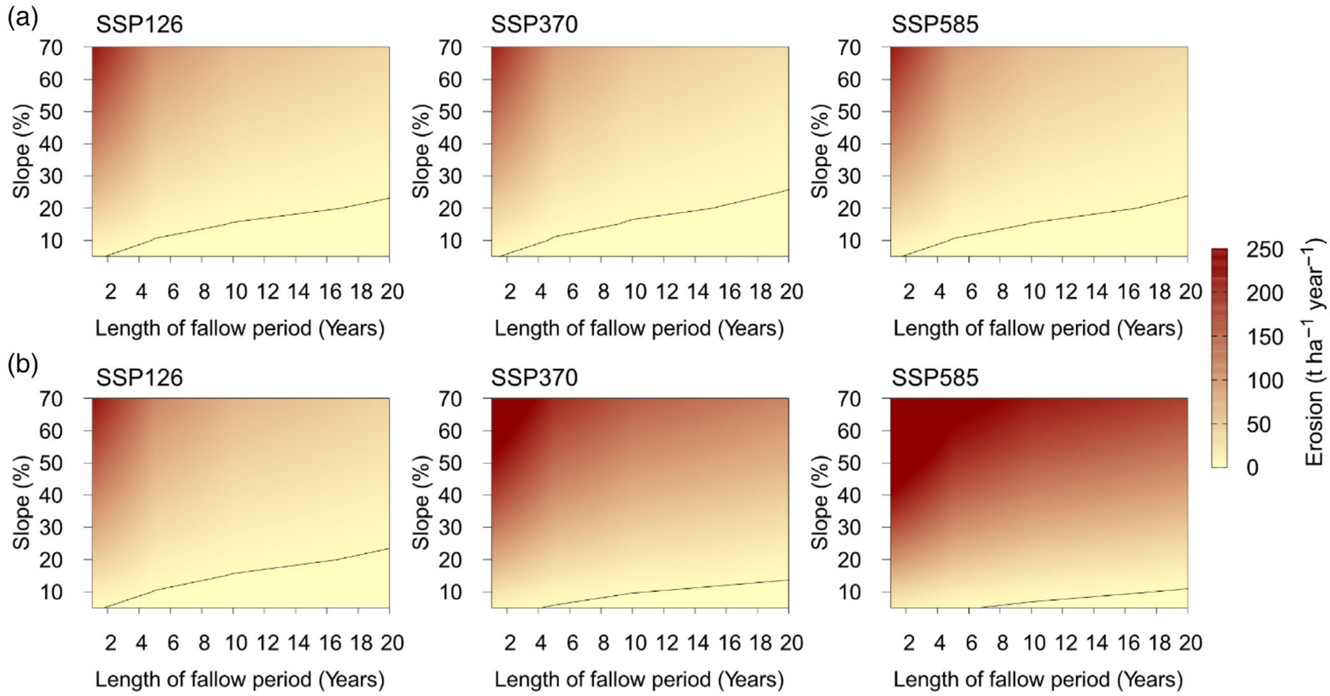

FIGURE 10 Combined effects from the slope inclination and fallow period on erosion for the (a) near and (b) far future of SSP126 (left), SSP370 (center), and SSP585 (right) scenarios. The average erosion values (in t ha^{-1} year^{-1}) of five climate models are shown. The number of fallow years is indicated on the *x*-axis. Slope values (in %) are given on the *y*-axis. The black line indicates the soil loss tolerance of 10 t ha^{-1} year^{-1} given for Nagaland in Mandal and Sharda (2011). [Colour figure can be viewed at wileyonlinelibrary.com]

far future, annual erosion increases by 4.9 t ha^{-1} per each additional percent slope. Rice cultivation on slopes of 20% steepness hence leads to annual erosion rates more than twice as high as on slopes of 10% steepness (79 and 32 t ha^{-1}, respectively). Under fallow, erosion increases per additional percent slope are still prominent, but with 2.1 t ha^{-1} less strong.

Our results show that erosion under shifting cultivation is influenced not only by the slope gradient but also by the length of the fallow period, and suggest that short fallow periods favor erosion for two reasons: First, frequent cultivation cycles result in poor physical characteristics of the soil, and second, the proportion of highly erosion-prone fallow years within the total cycle is larger when fallow periods are short.

3.4 | Combined effects of slope inclination, fallow period, and climate change

Our results indicate that climate change will reduce the sustainable possibility space for shifting cultivation toward the end of the century, particularly under the SSP370 and SSP585 scenarios (Figure 10). Under these scenarios, the same slope inclinations will require longer fallow periods than during the first half of this century when erosion rates are to remain largely unchanged.

When the often used soil loss tolerance of 10 t ha^{-1} year^{-1} is taken as a reference value not to be exceeded, shifting cultivation during the far future of SSP370 and SSP585 would require minimum fallow periods of 4 (SSP370) and 7 years (SSP585) on a 5% slope, and 11 (SSP370) and 17 years (SSP585) on a 10% slope. Under the far future of SSP126, 5% and 10% slopes could be cultivated under a 2 and 5-year fallow regime, respectively, while slopes of 15% and 20% would require fallow periods of at least 10 and 16 years, respectively. On slopes steeper than 20%, mean annual soil loss would exceed 10 t ha^{-1} year^{-1} under all fallow periods and far future scenarios.

In the near future, slopes of 5% and 10% could be cultivated under a 2 and 5-year fallow regime under all scenarios. Slopes of 15% and 20% would require a minimum fallow length of 10 and 16 years, respectively, under both SSP126 and SSP585, while under SSP370, 9 and 14 years would be required.

We conclude that an increase in the slope gradient from 5% to 10% multiplies the required years of fallow period by a mean factor of 2.5, hence increasing the length of the fallow period can, albeit to a limited extent, compensate for cultivating steeper slopes. In the far future of the medium-high and high-end emission scenarios, a soil loss tolerance of 10 t ha^{-1} year^{-1} would already be exceeded at 10% slope gradients when fallow periods of 11 and 17 years, respectively, are not met. We note that the soil loss tolerance of 10 t ha^{-1} year^{-1} is used here only as an example, without claiming that losses below this threshold would be sustainable.

4 | DISCUSSION

4.1 | Future changes in soil erosion

This is, to our knowledge, the first study estimating future soil erosion for shifting cultivation systems. Through comprehensive scenario simulations consisting of 14 slopes, 20 fallow periods, three climate scenarios, and two future periods, we assess the combined effects of climate change and agricultural intensification on future erosion dynamics of traditional smallholder production systems in the Himalaya region.

Our results indicate substantial increases in soil erosion at the field scale toward the end of the century, which are particularly strong under the SSP370 and SSP585 scenarios. For these scenarios, our study suggests increasing erosion intensities and slight seasonal shifts, which were not yet shown by other studies. Our results highlight the dependence of future erosion increments on global warming rates and show that exceeding global temperature targets will have significant consequences for hillside agriculture. Under a 3°C warmer world, annual erosion in shifting cultivation in Northeast India will increase by more than 70% from 38 to about 66 t ha^{-1}, while erosion increases can be limited to 5% if the 1.5°C global warming scenario as aimed for in the Paris Agreement is reached.

Several previous studies have indicated reduced fallow periods as a reason for increased soil erosion, suggesting depletion of organic carbon and impaired physical soil properties (e.g., soil porosity and aggregate stability) due to short fallow cycles leading to increased soil erodibility (Grogan et al., 2012; Mishra & Ramakrishnan, 1983; Prokop & Poreba, 2012; Ziegler et al., 2009). However, we are not aware of a study that systematically analyzed the relationship between fallow length and erosion. Our research fills this gap, showing that short fallow periods indeed increase erosion rates of shifting cultivation systems and that a 10-year fallow system could potentially halve erosion compared with a 1-year fallow regime.

Our simulations confirm the significant positive relationship between slope inclination and erosion reported in many previous studies from diverse contexts (Elhassanin et al., 1993; Mondal et al., 2016; Setyawan et al., 2019; Shen et al., 2019). With rice showing a stronger slope–erosion correlation than fallow, our study is likewise in line with previous studies indicating the relationship to be land cover dependent (El Kateb et al., 2013; Sun et al., 2014).

By linking the slope–erosion with the fallow–erosion relationship, we could demonstrate that long fallow periods can compensate to a limited extent for steep slopes, which previous studies did not consider. Beyond that, our modeling approach allowed the analysis of potential, hypothetical future scenarios, such as highly unsustainable management on steep slopes and under extremely short fallow cycles, which cannot be found yet but might eventually evolve in the future, for example, as a consequence of increasing demographic pressure. That way, our analysis revealed not only the realistic but the entire possibility space of future soil erosion.

Our findings complement previous studies on climate change effects in India, suggesting an increasing trend in soil erosion that has already been predicted for other places and land uses in the country (Chakrabortty et al., 2020; Choudhury et al., 2022; Gupta & Kumar, 2017; Khare et al., 2017; Kumar et al., 2022; Mondal et al., 2015; Rajbanshi & Bhattacharya, 2021; Sooryamol et al., 2022). However, concerning the magnitude of soil erosion increases, our estimates can hardly be compared with previous studies, as these were carried out at the entire watershed scale instead of the field scale, for different regions and/or land uses, and sometimes earlier-generation climate change scenarios. Still, our findings are in line with previous studies regarding slight changes in soil erosion in the near future, while our estimated increases for the late 21st century exceed those of previous studies (Choudhury et al., 2022; Gupta & Kumar, 2017; Mondal et al., 2015; Sooryamol et al., 2022). On a global level, our results are consistent with many other case studies, together indicating a wide range of soil erosion increases between 1.2% and 1614% during the 21st century when compared with the late 20th century (Li & Fang, 2016).

4.2 | Implications for land degradation and management

Future increases in soil erosion will accelerate land degradation and thus productivity losses in uphill regions. Soil erosion and degradation processes are strongly interlinked, as erosion leads to a reduction in root zone depth and displacement of the nutrient and carbon-rich top soil, thus diminishing soil water availability and plant growth (Lal, 2001; Sidle et al., 2006; Zhang et al., 2021). Although quantification of the soil erosion–fertility relationship has proven to be difficult due to its dependence on the experimental methodology (Bakker et al., 2004) and its nonlinear shape (Zhang et al., 2021), previous studies have confirmed the organic matter and nutrients depletion due to erosion under shifting cultivation (Gafur et al., 2003) and estimated substantial associated reductions in crop productivity for Nagaland and other mountainous regions of India (Sharda et al., 2010). Based on these and our findings, we expect substantial declines in the productivity of uphill farming systems under climate change, particularly where steep slopes combined with short fallow periods will boost increasing soil erosion.

Lestrelin et al. (2012) have claimed that the effect of carbon and nutrient depletion due to intensified management could be more important for productivity declines than soil erosion. We argue that soil erosion plays an essential role in this process chain, as erosion exacerbates the loss of soil organic carbon, thereby promoting soil erodibility, further organic carbon depletion, and degradation. Moreover, we assume that the contribution of soil erosion to degradation processes will rise in the future, not only because of likely increments in erosion but also because of cumulative effects over time. While a certain amount of soil loss in 1 year may not significantly affect productivity, cumulative erosion over several years may significantly influence soil fertility. This assumption is supported by findings from Zhang et al. (2021), who reported crop yields drop significantly once a critical top soil depth has been eroded.

To limit adverse effects on future soil productivity, our study recommends maintaining sufficiently long fallow periods, which should be longer on steeper than on shallower slopes. In addition, a wide application of soil conservation measures is advised. Besides contouring practices, previous research recommends measures that provide a continuous soil cover, such as cover crops and mulching (Anantha et al., 2021; Kaye & Quemada, 2017; Ngangom et al., 2020; Sidle et al., 2006), intercropping, and a change in crop mix from upland rice to maize and soybean (Sharma et al., 2017; Singh et al., 2011). Further research will be needed on sustainable management practices for uphill shifting cultivation.

4.3 | Implications for policies

This research contributes to the ongoing political debate on agricultural intensification in South and Southeast Asia, where population growth and the propagation of settled agriculture through various government programs and initiatives have recently increased land competition, resulting in intensified cultivation cycles and expansion of cultivation to steeper slopes (Castella et al., 2013; Feng et al., 2021; Fox et al., 2014; Lestrelin et al., 2012; Nongkynrih et al., 2018).

Our research shows that (1) the increasing competition and scarcity of cultivable lands will lead to significant erosion increments due to the combined effects from cultivation expansion on steeper slopes and decreasing length of fallow periods and that (2) these dynamics will intensify under increasing global warming scenarios. Under these scenarios, land degradation in uphill areas will proceed at an increasing pace, thereby further pushing land scarcity, ultimately leading to a reinforcing cycle of migration of tribal farmers to barely cultivable lands and land degradation. To break this cycle, our research recommends, on a global level, limiting increasing climate forcing as much as possible and, on a regional level, avoiding increasing competition among land uses in future development plans. Therefore, further studies will be needed to investigate the possibilities of integrating shifting cultivation with other land uses, thus reducing land competition and further displacement of tribal farming communities.

4.4 | Limits and uncertainties

While providing important insights into future erosion dynamics of uphill agricultural systems, several limitations of our approach should be noted. First, we only represented one crop and fallow plant in our simulations and not the entire plant diversity, which is typical for shifting cultivation systems.

Further, we note that because this research was conducted at field scale, the outlined dynamics refer specifically to erosion processes at the sloping field, such as gully and interrill erosion; hence estimated erosion is higher than if measured at the catchment scale. A simple aggregation of our results to the catchment scale should therefore be avoided, also because sedimentation processes were not captured in this study.

Our results depend strongly on future precipitation patterns and, thus, on the projected climate data used for the simulations. As the future occurrence of high-intensity precipitation events is uncertain, the magnitude of future erosion outlined here remains uncertain as well. However, by applying a combination of five bias-corrected and statistically downscaled climate models and three climate scenarios, we were able to present a range of possible future erosion pathways, accounting for the uncertainties related to future climate.

As soil property analyses are time intensive, costly, and rarely available, our study was limited to six soil profiles, which cannot represent the full diversity of soils in the region nor the range of slopes implemented in the model. Future studies could extend this research to additional sites.

Lastly, we emphasize that this research focuses on a case study region; thus, the applied modeling approach was tailored to the specific conditions of this region. We expect that our results on the general dynamics between slope steepness, fallow periods, and erosion will be similar in other uphill shifting cultivation regions, but recognize that the analyzed relationships depend on the soil, climatic, and management conditions. In particular, climate change will manifest differently in distinct mountain regions; hence, climate change effects on upland soil erosion presented here should not be extrapolated to other regions.

5 | CONCLUSION

This study identifies possible future trends in soil erosion for uphill shifting cultivation systems. Our results demonstrate that slope cultivation under short fallow cycles and climate change will lead to increasing soil erosion in the Himalayas. Increases will be particularly strong under the medium-high (SSP370) and high-end (SSP585) climate change scenarios, leading to mean erosion increases by a factor of 2.2 and 3.1 toward the end of the century, respectively, compared with the historical baseline (1985–2014). These increases occur especially between March and April and between July and September and are associated with a rising number of high-intensity erosion events. We conclude that an increase in global average temperatures by 3°C will increase erosion rates by more than 60%, compared with erosion rates when the 1.5°C goal of the Paris Agreement is reached.

Our results further show that, in order to maintain tolerable erosion rates, steeper slopes require longer fallow periods. An increase in slope inclination from 5% to 10% multiplies the minimum fallow period length by a mean factor of 2.5 when a soil loss tolerance of 10 t ha^{-1} year^{-1} is taken as a reference. When erosion rates above this soil loss tolerance are to be avoided in the far future, shifting cultivation under medium-high and high-end climate change scenarios should reach fallow periods of at least 4 and 7 years, respectively, for slope inclinations of 5%, and 11 and 17 years, respectively, for slope inclinations of 10%. From our findings, it follows that climate change limits the possibility space of future shifting cultivation in terms of the cultivable slope range and the required fallow period lengths.

In order to prevent increasing land degradation of uphill regions in Northeast India and other places in South and Southeast Asia, we recommend (1) on a global level, to limit warming to the 1.5°C temperature target of the Paris Agreement; (2) on a regional level, to avoid an increasing competition among land uses resulting in the displacement of tribal farmers to higher altitudes and/or the shortening of fallow periods; and (3) on a field scale, to adopt diverse soil conservation practices.

For future studies, our findings reveal the need to investigate options for sustainable integration of shifting cultivation with other land uses. Also, upcoming studies could focus on the potential of soil conservation measures to reduce erosion in shifting cultivation systems, particularly on the steeper slope range.

This is the first study analyzing soil erosion of shifting cultivation systems under climate change. Our results contribute to increasing the understanding of uphill land degradation dynamics, revealing impacts on erosion resulting from the interplay of climate change and agricultural intensification.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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