Spatial assessment of soil erosion using the revised universal soil loss equation (RUSLE) model for sustainable marine ecosystems in the coastal of northern part, Aceh Province

Muhammad Nanda[1,2,3,4*], *Muhammad* Alwan[1], *Muhammad* Ghufran[1], *M. Iqbal Ichsan* Fahlefy[1], *Ismail* Husein[1], *Haekal Azief* Haridhi[1,2,3], *Badrul* Munir[5,6], *Intan Mulia* Sari[5], *Amir* Asyqari[3,4,5], *Tarmizi* Hasyem[6], *Muhammad* Muhammad[7], *Indah* Permatasari[8], *Sayed* Yunus[9]

[1]Department of Marine Sciences, Faculty of Marine and Fisheries, Universitas Syiah Kuala, Banda Aceh, Aceh 23111, Indonesia
[2]Research Center for Marine Sciences and Fisheries, Universitas Syiah Kuala, Banda Aceh, Indonesia
[3]Tsunami and Disaster Mitigation Research Center, Universitas Syiah Kuala, Banda Aceh, Indonesia
[4]Research Center Ethnosciences, Universitas Syiah Kuala, Banda Aceh, Aceh 23111, Indonesia
[5]Physics Department, Universitas Syiah Kuala, Banda Aceh, Aceh 23111, Indonesia
[6]Geophysical Engineering Department, Universitas Syiah Kuala, Banda Aceh, Aceh 23111, Indonesia
[7]Department of Fisheries Resource Utilization, Faculty of Marine and Fisheries, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia
[8]Department of Production Technology of Seed and Feed fish, Polytechnic of Indonesia Venezuela (POLIVEN), Aceh Besar, Indonesia.
[9]Regional Disaster Management Agency (BPBD) of Banda Aceh City.

Abstract. Coastal erosion presents a significant danger to sustainable marine ecosystems, especially in the northern coastal area of Aceh Province, Indonesia. This research combines the Revised Universal Soil Loss Equation (RUSLE) model with GIS and remote sensing to provide an innovative spatial evaluation of soil erosion risks. This study produces high-resolution maps of erosion risk and sediment yield by integrating precipitation patterns, soil properties, topography, and land use data. The results indicate substantial areas of soil erosion that contribute to sediment accumulation in coastal regions, which may affect marine ecosystems and increase land-sea connectivity issues. This methodology enhances the utilization of RUSLE in coastal environments and offers practical guidance for erosion mitigation and sustainable land management. The study highlights the significance of mitigating soil erosion as an important factor in attaining SDG 14 (Life Below Water), emphasizing the necessity for integrated policies to reduce land degradation and its subsequent effects on marine ecosystems. The findings highlight the significance of geospatial tools to encourage evidence-based decision-making for sustainable management of coastal and marine resources.

* Corresponding author: m.nanda@usk.ac.id

1 Introduction

Coastal ecosystems consist of important resources, including fisheries, tourism, urban areas and harbour construction, all of which depend on the soil [1]. However, The soil is subjected to physical and anthropogenic pressures, and erosion has slowly become a key issue over time [2]. In the coastal areas, land degradation occurs due to soil erosion, reduced agricultural output, and reduced sedimentation, adversely affecting the marine ecosystem's biology and water quality [3].

The northern coast of Aceh Province (**Fig 1**) has been identified and characterized as being prone to erosion due to the region's geomorphology and climatic conditions [4]. The hilly landscape patterns of the region, seasonal monsoons [5] and land use changes aggravate the erosion problem [6], leading to sediment deposition in coastal waters. These activities adversely affect marine biodiversity and the fishing sector, as sufficient erosion may bury coral reefs, decrease water quality, and disturb marine ecosystems [7]. Recent studies indicate significant land loss, increased sediment ratio, and decreased ecosystem services, threatening ecological and economic dependence on marine and coastal resources [8]. Therefore, it is crucial to understand and manage soil erosion in these coastal regions to ensure the sustainable exploitation of the ocean environments, which are vital for our marine resources.

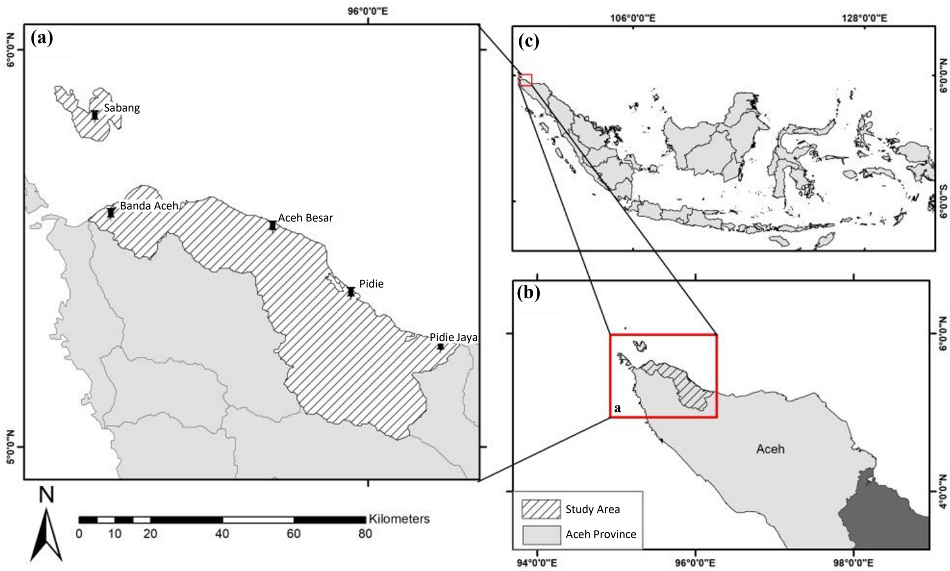

Fig. 1. (a) The location map of the study area at (a) The northern coast of (b) Aceh Province, (c) Indonesia

The Revised Universal Soil Loss Equation (RUSLE) has been proven useful in estimating and predicting soil loss rates in diverse environments such as sensitive coastal zones [6-7]. This model involves the linkage of the rainfall pattern, soil type, topography, land use, and conservation to evaluate erosion risk better [11]. Thus, this study attempts to configure erosion risk prediction more accurately by utilizing the RUSLE model in combination with GIS and remote sensing data. Such maps will be useful for designing appropriate soil conservation and management practices to maintain desired soil qualities and reduce erosion impacts [12].

In addition, sediment yield as a result of soil erosion directly contributes to sediment budgets and coastal morphodynamics, which are important in planning and carrying out coastal zone management strategies [13]. Using spatial data, assessment and management of

these risks can greatly promote sustainable development and conservation in line with the Sustainable Development Goals, particularly SDG 14 [14], for the sustainability and well-management of the oceans, seas, and marine resources [15]. By filling critical knowledge and methodological gaps, this study aims to support sustainable development efforts and enhance the resilience of coastal ecosystems in northern Aceh Province.

2 Methods

This research developed a Geographic Information System (GIS) based application of the Revised Universal Soil Loss Equation (RUSLE) to determine the extent of annual soil erosion and its map location in the northern coastal region. It encompasses five main components, i.e., rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and support practices (P) [7, 13]. This study used the Google Earth Engine (GEE), an open-source cloud computing platform, for data processing, storage analysis, visualization, and results display. GEE is a cloud-based open-source platform that makes it easy to access and process large geospatial data collection [17]. According to each character of coastal conditions of northern Aceh, specifically developed approaches in estimating R, K, LS, C and P were applied. Each factor was estimated utilizing methods modified to suit the coastal area of northern Aceh. A model layers file was created in the GIS system, where each layer was integrated to create a probabilistic erosion potential map. This spatial information enables the understanding of erosion in the study area, which is useful in formulating guidelines for the management of the marine ecosystem.

2.1 RUSLE Data

A combination of rainfall, soil, land slope, land use, and conservation methods were used to estimate the soil erosion. The soil erosion was estimated using the methodological framework displayed in **Fig. 2**. Rainfall intensity and frequency both contribute to erosion, and the R-factor measures the kinetic energy of raindrops [18]. Climate Hazards Center InfraRed Precipitation with Station (CHIRPS) data rainfall data with 5566 m spatial resolution [19] were used to extract annual rainfall totals; these values were then interpolated with inverse distance weighting (IDW) [20] to continuously distribute R-factor values according to [21] regression equation.

The K-factor indicates the soil erodibility according to texture, organic matter, structure and permeability [22]. A table of soil properties was extracted from the Soil texture classes (USDA system) [23]. Specific K values were determined based on empirical equations [24] and interpolated over the entire study area using an inverse distance weighting (IDW) method to capture spatial heterogeneity [20].

The LS factor considers the impact of a slope's length and steepness on the potential for erosion. Topographic data derived from a 30-meter resolution DEM [25] for slope and flow accumulation calculations. An empirical total slope (LS) factor was calculated from slope degree and flow accumulation to delineate locations where the combination of longer, steeper slopes increase erosion hazard [26]. The C-factor stands for the role of vegetation and ground cover in protecting soil from being washed away. C-factor values were derived from NDVI and the transformation C-factor [27]. The C-factor map identified the regions with the lowest and highest values, reflecting high vegetation cover that needs to be prioritized for conservation [28].

In the end, the P-factor reflects the impact of conservation practices. Where detailed field data on local practices were absent, P-values corresponding to slope classes were estimated based on conventional values in the literature [24 - 25]. Separate slope data was derived from the DEM before classifying to produce a P-factor map [30], which evaluates areas where less

erosion control is required, with the expectation that these are mainly situated on areas of greater slope. The spatial alignment of these RUSLE layers created the spatial consistency needed for accurate soil erosion estimates. Our integrated method results in a continuous erosion risk across the coastal landscape, useful for conservation and land management.

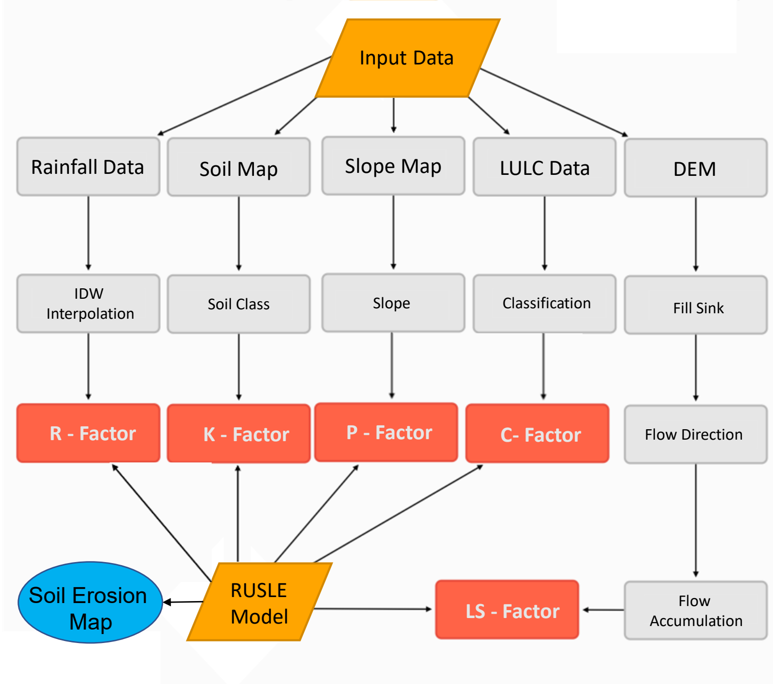

Fig 2. Schematic outline of the methodological framework applied to assess soil erosion.

2.2 Estimation RUSLE Model

The coastal soil erosion can be modeled using sediment transport models. One of the widely used empirical models among these is the Revised Universal Soil Loss Equation (RUSLE) [31]. The success of RUSLE is due to its lower data requirements, ease of access to the datasets it employs, and compatibility with GIS database systems [32]. With the help of the RUSLE model, soil erosion assessment can be undertaken for major river basins, specific coastal sites, and crop fields [16].

However, it is important to note that RUSLE does not consider some significant land degradation processes, such as gully erosion and landslips. The soil erosion was estimated using the methodological framework displayed in **Fig. 2.** The RUSLE model estimates soil loss by the formula [21] as follows:

$$A = R \times K \times LS \times C \times P \qquad (1)$$

where A is annual eroded soils (Ton ha $^{-1}$yr^{-1}), R factor of rainfall erosivity (MJ mm ha^{-1} yr^{-1}), K specific soil classification, LS slope-length and steepness effect factors (%), C is vegetation or plant coverage- management and P is support practices used to reduce erosion in this research.

3 Results and discussion

The research shows the application of the RUSLE model for soil erosion assessment in the northern coastal province of Aceh. The R-factor map in Fig 3a provides information on high rainfall erosivity, particularly in the coastal zones because of the monsoon winds. The intensity of rainfall was established as an important factor in tropic erosion [33]. The K – factor is represented in Fig 3b in the sandy soils, which are usually porous and hence more prone to erosion since they have low cohesion [34].

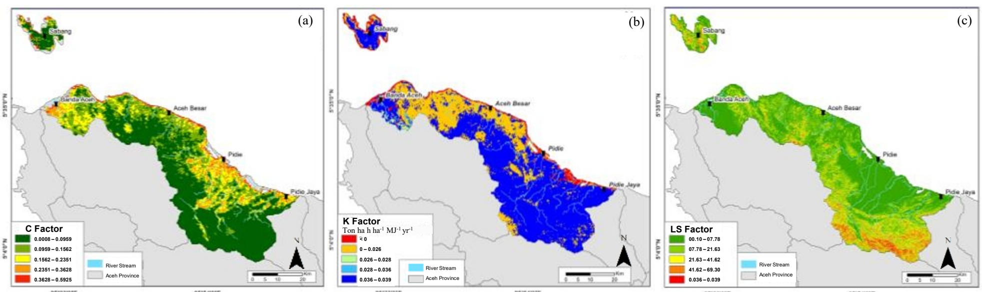

Fig 3. Data on (a) R- Factor (b) K - Factor (c) and LS - Factor estimated in this study

The LS factor (Fig 3c) shows that steeper angles are more vulnerable to erosion because runoff is faster than the lower angles, which agrees with the erosion models. C-factor maps (Fig 4b) demonstrate that zones of high vegetation distribution are less exposed to erosion than zones with a lower abundance of grass cover or bare soils. In the end, the P-factor Fig 4a. Stresses the purpose of implementing measures against erosion, such as terracing and contour farming, which substantially lowers erosion risk.

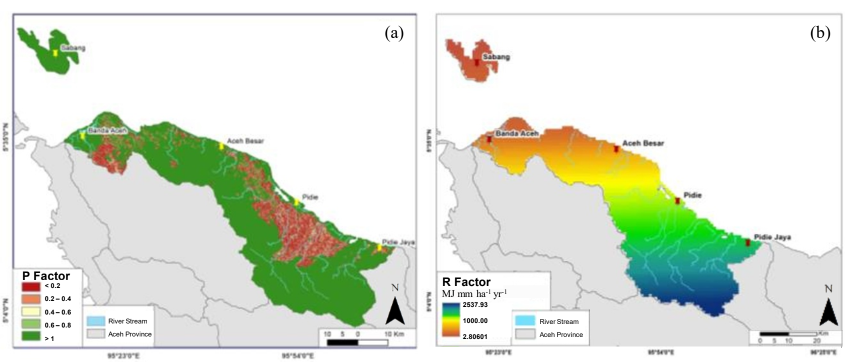

Fig 4. Spatial distribution of (a) P - factor and (b) C - factor estimated in this study

However, the spatial pattern of soil erosion shows (Fig 5) that the most eroded areas are steep, have high rainfall and have low or no conservation measures. These areas are predominantly located in the northern section of the country's coastal belt. Since most of them are eroded, the available sediments are washed away into marine waters (> 40 tons/ yr). This is a major threat to marine habitats since degrading sediments may cause decreased water quality and harm the marine ecosystem.

Therefore, the results of this research highlight the criticality of taking proactive soil conservation measures in areas where the risk is assessed to be very high to protect both land and marine ecosystems. Applying the RUSLE model in this regard has facilitated mapping erosion-prone areas, which will help in future land use planning and erosion control

measures. These findings, along with the earlier studies on coastal erosion, advocate for an integrated land management approach to soil conservation and the sustainability of marine resources.

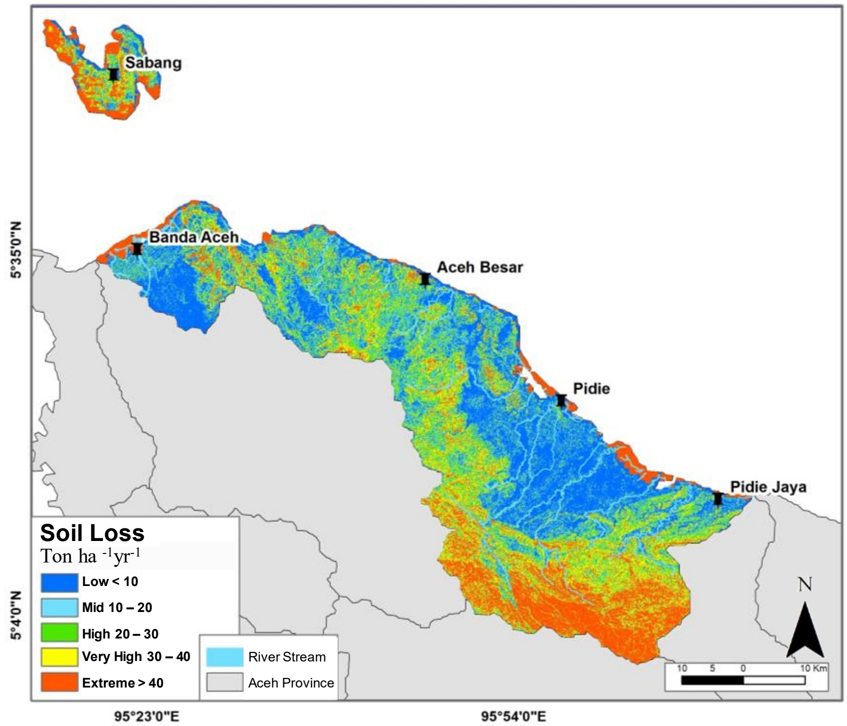

Fig 5. Spatial distribution of soil erosion estimated in this study

4 Conclusions

This research successfully applied the RUSLE model to determine the erosion risk in the northern coastal region of the Aceh Province. The integration of RUSLE factors - rainfall erosivity, soil erodibility, slope length and steepness, cover management and support practices - made it possible to develop a comprehensive spatial erosion risk map and identify areas that are highly at risk, thus indicating areas that need interventions as a matter of priority.

The results show that regions with high rainfall intensity, type and number of sandy soils, steepness or grade of slopes, number of vegetation cover and conservation practices such as tree planting (afforestation) are highly prone to erosion. These regions, especially found along the northern coast, are also responsible for a sizeable amount of sediment loading in the marine waters and thus pose threats to the land and aquatic environments.

The research clearly indicates that restoring areas such as marginal land or those that are regarded as highly degraded through measures like terracing and afforestation remains crucial. Such erosion control measures will minimize sediment runoff, soil loss, and marine environment pollution. More ever, the RUSLE model is a useful framework for identifying areas prone to soil erosion and formulating appropriate land use strategies to enhance sustainable land utilization while reducing erosion. This work reinforces the case for an integrated approach to soil and land management that conserves both soil and water resources to enhance the sustainability of Aceh's coastal ecosystems in the long run.

References

1. V. Ayyam, S. Palanivel, S. Chandrakasan, *Coastal ecosystems of the Tropics-adaptive management*. Springer (2019)
2. Y. Malhi, et al., Climate change and ecosystems: threats, opportunities and solutions. *Philos. Trans. R. Soc. B* **375**, 20190104 (2020)
3. C.R. Nichols, J. Zinnert, D.R. Young, Degradation of coastal ecosystems: causes, impacts, and mitigation efforts. *Tomorrow's Coasts: Complex and Impermanent*, 119–136 (2019)
4. S. Chapkanski, et al., Fluvial and coastal landform changes in the Aceh River delta (northern Sumatra) during the century leading to the 2004 Indian Ocean tsunami. *Earth Surf. Process. Landforms* **47**, 1127–1146 (2022)
5. R. Sinha, R. Chandrasekaran, N. Awasthi, Geomorphology, land use/land cover and sedimentary environments of the Chilika Basin. *Ecol. Conserv. Restor. Chilika Lagoon India*, 231–250 (2020)
6. B.M.R. Faisal, Y.S. Hayakawa, Geomorphological processes and their connectivity in hillslope, fluvial, and coastal areas in Bangladesh: A review. *Prog. Earth Planet. Sci.* **9**, 41 (2022)
7. C.M. Crain, B.S. Halpern, M.W. Beck, C.V. Kappel, Understanding and managing human threats to the coastal marine environment. *Ann. N.Y. Acad. Sci.* **1162**, 39–62 (2009)
8. R.K. Turner, I. Lorenzoni, N. Beaumont, et al., Coastal management for sustainable development: analysing environmental and socio-economic changes on the UK coast. *Geogr. J.*, 269–281 (1998)
9. R. Benavidez, B. Jackson, D. Maxwell, K. Norton, A review of the (Revised) Universal Soil Loss Equation (RUSLE): With a view to increasing its global applicability and improving soil loss estimates. *Hydrol. Earth Syst. Sci.* **22**, 6059–6086 (2018)
10. K. Ghosal, S. Das Bhattacharya, A review of RUSLE model. *J. Indian Soc. Remote Sens.* **48**, 689–707 (2020)
11. Y. Farhan, S. Nawaiseh, Spatial assessment of soil erosion risk using RUSLE and GIS techniques. *Environ. Earth Sci.* **74**, 4649–4669 (2015)
12. D. Arrouays, V.L. Mulder, A.C. Richer-de-Forges, Soil mapping, digital soil mapping and soil monitoring over large areas and the dimensions of soil security–A review. *Soil Secur.* **5**, 100018 (2021)
13. B.G. Thom, et al., National sediment compartment framework for Australian coastal management. *Ocean Coast. Manag.* **154**, 103–120 (2018)
14. U. Nations, Transforming our world: the 2030 agenda for sustainable development (2015)
15. L.R. Virto, A preliminary assessment of the indicators for Sustainable Development Goal (SDG) 14 'Conserve and sustainably use the oceans, seas and marine resources for sustainable development.' *Mar. Policy* **98**, 47–57 (2018)
16. K.Y. Saketa, E.N. Tamene, S.B. G., et al., Modeling soil erosion using RUSLE and GIS at watershed level in the upper Beles, Ethiopia. *Environ. Challenges* **2**, 100009 (2021)
17. M. Amani, et al., Google Earth Engine cloud computing platform for remote sensing big data applications: A comprehensive review. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **13**, 5326–5350 (2020)
18. D.T. Meshesha, A. Tsunekawa, N. Haregeweyn, Influence of raindrop size on rainfall intensity, kinetic energy, and erosivity in a sub-humid tropical area: A case study in the northern highlands of Ethiopia. *Theor. Appl. Climatol.* **136**, 1221–1231 (2019)
19. C. Funk, et al., The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Sci. Data* **2**, 1–21 (2015)

20. F.-W. Chen, C.-W. Liu, Estimation of the spatial rainfall distribution using inverse distance weighting (IDW) in the middle of Taiwan. *Paddy Water Environ.* **10**, 209–222 (2012)
21. K.G. Renard, J.R. Freimund, Using monthly precipitation data to estimate the R-factor in the revised USLE. *J. Hydrol.* **157**, 287–306 (1994)
22. Y. Ostovari, S. Ghorbani-Dashtaki, H.-A. Bahrami, et al., Modification of the USLE K factor for soil erodibility assessment on calcareous soils in Iran. *Geomorphology* **273**, 385–395 (2016)
23. T. Hengl, Soil texture classes (USDA system) for 6 soil depths (0, 10, 30, 60, 100, and 200 cm) at 250 m. *Zenodo* (2018)
24. W.H. Wischmeier, D.D. Smith, Predicting rainfall erosion losses: A guide to conservation planning. Department of Agriculture, Science and Education Administration, (1978)
25. E. Rodriguez, C.S. Morris, J.E. Belz, A global assessment of the SRTM performance. *Photogramm. Eng. Remote Sens.* **72**, 249–260 (2006)
26. P. Bircher, H.P. Liniger, V. Prasuhn, Comparing different multiple flow algorithms to calculate RUSLE factors of slope length (L) and slope steepness (S) in Switzerland. *Geomorphology* **346**, 106850 (2019)
27. S. Huang, L. Tang, J.P. Hupy, et al., A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. *J. For. Res.* **32**, 1–6 (2021)
28. L. Matas-Granados, M. Pizarro, L. Cayuela, et al., Long-term monitoring of NDVI changes by remote sensing to assess the vulnerability of threatened plants. *Biol. Conserv.* **265**, 109428 (2022)
29. S.W. Correa, C.R. Mello, S.C. Chou, et al., Soil erosion risk associated with climate change at Mantaro River Basin, Peruvian Andes. *Catena* **147**, 110–124 (2016)
30. J.H. Abdulkareem, B. Pradhan, W.N.A. Sulaiman, et al., Prediction of spatial soil loss impacted by long-term land-use/land-cover change in a tropical watershed. *Geosci. Front.* **10**, 389–403 (2019)
31. K.G. Renard, Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). US Department of Agriculture, Agricultural Research Service (1997)
32. A.Y. Yesuph, A.B. Dagnew, Soil erosion mapping and severity analysis based on RUSLE model and local perception in the Beshillo Catchment of the Blue Nile Basin. *Environ. Syst. Res.* (2019)
33. D.L. Dunkerley, Rainfall intensity bursts and the erosion of soils: An analysis highlighting the need for high temporal resolution rainfall data. *Earth Surf. Dyn.* **7**, 345–360 (2019)
34. J.M. Hall-Spencer, B.P. Harvey, Ocean acidification impacts on coastal ecosystem services due to habitat degradation. *Emerg. Top. Life Sci.* **3**, 197–206 (2019)