Estimation of annual soil erosion dynamics (2005 - 2015) in Pakistan using Revised Universal Soil Loss Equation (RUSLE)

Hammad Gilani[1], Adeel Ahmad[2], Isma Younes[2], and Sawaid Abbas [3]

[1]Institute of Space Technology
[2]University of the Punjab
[3]The Hong Kong Polytechnic University

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Abstract

Abrupt changes in climatic factors, exploitation of natural resources, and land degradation contribute to soil erosion. This study provides the first comprehensive analysis of annual soil erosion dynamics in Pakistan for 2005 and 2015 using publically available climatic, topographic, soil type, and land cover geospatial datasets at 1 km spatial resolution. A well-accepted and widely applied Revised Universal Soil Loss Equation (RUSLE) was implemented for the annual soil erosion estimations and mapping by incorporating six factors; rainfall erosivity (R), soil erodibility (K), slope-length (L), slope-steepness (S), cover management (C) and conservation practice (P). We used a cross tabular or change matrix method to assess the annual soil erosion (ton/ha/year) changes (2005-2015) in terms of areas and spatial distriburtions in four soil erosion classes; i.e. Low (<1), Medium (1–5], High (5-20], and Very high (>20). Major findings of this paper indicated that, at the national scale, an estimated annual soil erosion of 1.79 ± 11.52 ton/ha/year (mean ± standard deviation) was observed in 2005, which increased to 2.47 ±18.14 ton/ha/year in 2015. Among seven administrative units of Pakistan, in Azad Jammu & Kashmir, the average soil erosion doubled from 14.44 ± 35.70 ton/ha/year in 2005 to 28.03 ± 68.24 ton/ha/year in 2015. Spatially explicit and temporal annual analysis of soil erosion provided in this study is essential for various purposes, including the soil conservation and management practices, environmental impact assessment studies, among others.

Impacts assessment of land cover and land use changes on soil erosion changes (2005 - 2015) in Pakistan

Hammad Gilani [1, *], Adeel Ahmad [2], Isma Younes [2] and Sawaid Abbas [3] *

[1] Institute of Space Technology, Islamabad 44000, Pakistan

[2] Department of Geography, University of the Punjab, Lahore 54590

[3] Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong

***** Correspondence: hammad.gilani@mail.ist.edu.pk & hammad.gilani@gmail.com

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Abstract

Abrupt changes in climatic factors, exploitation of natural resources, and land degradation contribute to soil erosion and Land Cover and Land Use Changes (LCLUC). This study provides comprehensive analysis of annual soil erosion dynamics in Pakistan for 2005 and 2015 using freely available climatic, topographic, soil type, and land cover geospatial datasets at 1 km spatial resolution. A well-accepted and widely applied Revised Universal Soil Loss Equation (RUSLE) was implemented for the annual soil erosion estimations and mapping by incorporating six factors; rainfall erosivity (R), soil erodibility (K), slope-length (L), slope-steepness (S), cover management (C) and conservation practice (P). We used a cross tabular or change matrix method to assess the annual soil erosion (ton/ha/year) changes (2005 - 2015) in terms of areas and spatial distributions in four soil erosion classes; i.e. Low (<1), Medium (1–5], High (5-20], and Very high (>20). For conservation and effective ecosystem services, at seven administrative units of Pakistan temporal and spatial bivariate analysis were carried out among soil erosion change and LCLUC. Major findings of this paper indicated that, at the national scale, an estimated annual soil erosion of 1.79 $\pm$ 11.52 ton/ha/year (mean $\pm$ standard deviation) was observed in 2005, which increased to 2.47 $\pm$18.14 ton/ha/year in 2015 with total 29,081 km^2 (3.30%) loss and 17,506 km^2(2.00%) gain in LCLUC classes between 2005 - 2015. Spatially explicit and temporal annual analysis of soil erosion and LCLUC could be used for soil conservation and management practices, environmental impact assessment studies, among others.

Keywords: Soil erosion; Geospatial datasets; RUSLE; LCLUC; Soil conservation; Pakistan.

1. Introduction

Injudicious exploitation of natural resources leads to land degradation, droughts, floods, deforestation, etc. The shrinking per capita natural resources lead to intensive land use and resultant in further environmental and land degradation. Land degradation is increasing in severity and extent in many parts of the world, with more than 20% of cultivated areas, 30% of forests, and 10% of grasslands undergoing degradation (Bai*et al.* , 2008). The decline in land quality caused by human activities has been a major global issue since the 20th century and will remain high on the international agenda in the 21st century (Eswaran *et al.* , 2001). Increasing cropping intensity, nutrient mining, traditional agricultural practices, and other human interventions are causing different kinds of land degradation that threaten livelihoods, food security, people's health, and long-term Sustainable Development Goals (SDGs) of promising countries. Land degradation by landslides, soil erosion, and internal biophysical and chemical deterioration are the main constraints for sustainable Land Cover and Land Use (LCLU) management and practices (Kapalanga, 2008).

Soil erosion, considered as an important land degradation process, is the loss of top fertile surface soil as a result of erosive rainfall and consequent runoff, deforestation, sea-land intrusion (Ganasri & Ramesh, 2016; Saha *et al.* , 2018). Soil erosion is a combination of detachment and transport of soil particles and is defined as the amount of soil lost in a specified period over an area of land which has experienced net soil loss (Galdino *et al.* , 2016; Nam *et al.* , 2003; Pimentel, 1993; Saha *et al.* , 2018). Overall, it has negative impacts on the environment through soil nutrient losses, water quality deterioration, and agricultural production, which ultimately leads to economic costs and loss of lives. Assessment and mapping of soil erosion are considered useful information to develop spatial priority areas for controlling and implementing soil erosion mitigation practices.

From simple to complex empirical models have been developed and used to quantify the soil erosion, which includes Zengg equation (Zingg, 1940), Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978), Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1982)), Modified Morgan, Morgan and Finney (MMMF) (Morgan *et al.* , 1984), Agricultural Nonpoint Source model (AGNPS) (Young *et al.* , 1989), Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.* , 1991), Unit Stream Power-based Erosion Deposition (USPED) (Mitasova *et al.* , 1996), European Soil Erosion Model (EUROSEM) (Morgan *et al.* , 1998), etc. The selection and implementation of a particular soil erosion model/equation depends upon the data availability, spatial and temporal scale of the application which may have certain limitations. Among all the soil erosion models/equations, RUSLE is being most widely used due to its simplicity, data requirements, and precision (Ghosal & Das Bhattacharya, 2020; Renard *et al.* , 1991). It was developed and designed with the basic structure of the USLE equation with several improvements in determining factors i.e. rainfall erosivity (R factor), soil erodibility (K factor), slope-length (L factor), slope-steepness (S factor), cover management (C factor) and conservation practice (P factor). Based on geospatial datasets and environments for rapid as well as a detailed assessment of soil erosion at diverse spatial scales these factors can be acquired, processed, and utilized in the RUSLE (El Jazouli *et al.* , 2017; ESA, 2018; Gelagay & Minale, 2016; Uddin *et al.* , 2016, 2018; Ullah *et al.* , 2018).

In South Asia, Pakistan has been continuously suffering from natural disasters (floods, earthquakes, droughts, etc.), morbid socioeconomic activities (increased population, unsustainable land management practices, over-grazing, deforestation, etc.), biophysical factors (unfavorable geology, topographical variations, etc.), and emerging effects of climate change observed through uncharacteristic patterns of weather conditions (Anjum *et al.* , 2010). According to the Global Climate Risk Index (GCRI), Pakistan is the 5^{th} most vulnerable country to climate change (Eckstein *et al.* , 2019). Forest cover removal accelerates surface erosion besides its negative impact on biodiversity and human ecology an increase. Even in the flat to gentle areas of Pakistan, unplanned conversion of agriculture and rangeland to built-up is leading to the severity of soil erosion (Abuzar, 2012; Ahmad *et al.* , 2012). On USLE or RUSLE, Alewell et al., (2019) synthesized and reported peer-reviewed published studies in 40 years (1977 to July 2017), Pakistan contributed only one or two peer-reviewed studies (see figure 1 in Alewell et al., (2019)). Within Pakistan, total four studies over the five sites have been conducted on soil erosion estimation and mapping using the RUSLE at various spatial scales, using multi-resolution geospatial datasets (Abuzar *et al.* , 2018; Ashraf, 2020; Ashraf *et al.* , 2017; Nasir *et al.* , 2006; Ullah *et al.* , 2018). Most of these studies were carried out with one-time assessments with limited spatial coverage (watershed, sub-basin, catchment, etc.) (S1 and Figure S1). Using the RUSLE, Borrelli et al. (2017) produced global scale soil erosion maps at 25 km spatial resolution for the years 2001 and 2012. Global soil erosion maps are spatially too coarse for the national level to sub-national scales decision making and management practices.

In Pakistan, at the national scale, soil erosion dynamic estimations and quantifications are a constraint due to several reasons including lack of data availability and processing willingness, topographical roughness, wilderness, and diversity, etc. The study is designed to cater, at the national scale and seven administrative units (Azad Jammu & Kashmir, Balochistan, Gilgit-Baltistan, Islamabad Capital Territory, Khyber Pakhtunkhwa, Punjab and Sindh) in Pakistan, annual soil erosion dynamics from 2005 to 2015 at 1 km spatial resolution using freely available topographic, biophysical, and climatic variables in the RUSLE. At the national and administrative units, impact assessment of Land Cover and Land Use Changes (LCLUC) on soil erosion was quantified and reported that could be utilized for better management, conservation, and restoration of natural resources through introducing the cost-effective, long term, and equitable ground interventions and practices.

2. Materials and methods

2.1. Study area

Pakistan (Figure 1) spans over an area of 881,913 km^2which extends from 24° N to 37.5° N latitudes and from 62 ° E to 75.5° E longitudes. It is the world's fifth-most populous country with a population exceeding 212.2 million with a population density of 287 per km^2 and 2.08% annual population growth. Pakistan shares administrative borders with India to the east, Afghanistan to the west, Iran to the southwest, and China in the northeast. The lowest and highest elevated points are sea level and K-2 mountain (8,611 meters above sea level) respectively. It comprises total seven administrative units, four provinces (Balochistan, Khyber Pakhtunkhwa, Punjab, and Sindh), two autonomous territories (Azad Jammu & Kashmir, Gilgit-Baltistan) and one federal territory (Islamabad Capital Territory). Pakistan is in the temperate region with an arid and semi-arid climate characterized by hot summers and chilling winters. Pakistan's climate is characterized by extreme variations in temperature and rainfall, because it is located on a great landmass north of the

Tropic of Cancer (between latitudes 25° and 36° N). The agrarian economy of Pakistan is the backbone of the country which is highly dependent upon the Panjnad (Punjab, Jhelum, Chenab, Ravi, Beas, and Sutlej) and Indus river system. The livelihood of almost 70% population is directly or indirectly depends on agriculture and its relevant sectors.

2.2. Data used

In this study, freely available geospatial datasets were utilized for the nationwide annual soil erosion estimation and mapping for 2005 and 2015 in Pakistan at 1 km spatial resolution. Mean monthly rainfall/precipitation (mm) data at 1 km spatial resolution was obtained from the Chelsa-climate web portal (http://chelsa-climate.org) for 2005 and 2015 (Karger *et al.* , 2016). The twelve months raster rainfall/precipitation layers were averaged to calculate the mean annual rainfall/precipitation (mm) for the 2005 and 2015. The global scale 1 km soil map was downloaded from the Food and Agriculture Organization (FAO) harmonized World Soil Database v 1.2 website (http://www.fao.org/land-water/databases-and-software/hwsd/en/) (Fischer *et al.* , 2008). One arc second (˜30 m spatial resolution) Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (Farr *et al.* , 2007) was downloaded from the United States Geological Survey (USGS) Earth Explorer web portal (https://earthexplorer.usgs.gov/). The 30 m spatial resolution DEM was resampled at 1 km grid size, and then further processed to generate slope dataset. Annual Moderate Resolution Imaging Spectroradiometer (MODIS) LCLU datasets (500 m spatial resolution) of 2005 and 2015 were downloaded from the USGS Earth Explorer data web portal (https://earthexplorer.usgs.gov/), which were further resampled at 1 km spatial resolution. For data processing, visualization, and area estimations we used World Geodetic System 1984, Lambert Conformal Conic (LCC) projection system. All the geospatial datasets were truncated at the extent of Pakistan.

2.3. Annual soil erosion modeling and mapping (2005 - 2015)

The inherent soil erosion potential depends on rainfall, soil type, LCLU, and terrain characteristics, which are represented by various factors, such as, rainfall erosivity, soil erodibility, slope length and slope steepness, LCLU management, and conservation practices. At the national scale in Pakistan, in this study RUSLE (equation 1) (Renard*et al.* , 1991) was used to estimate soil erosion at 1 km spatial resolution for 2005 and 2015.

$A = R * K * L * S * C * P$ (1)

where, A = soil erosion (ton/ha/year), R = rainfall erosivity factor (MJ mm/ha/hr/year), K = soil erodibility (ton·ha·hr/ha/MJ/mm), L = slope-length factor (dimensionless), S = slope-steepness factor (dimensionless), C = cover management factor (dimensionless), and P = conservation practice factor (dimensionless).

Equation 2 (Renard & Freimund, 1994) was used to calculate rainfall erosivity factor (R) for 2005 and 2015 using annual mean precipitation data of the respective year. Over the diverse geographical and topographical study areas, several researchers utilized equation 2 to calculate rainfall erosivity factor (Howland *et al.* , 2018; Lamyaa*et al.* , 2018; Uddin *et al.* , 2016, 2018).

$R = 0.0483P1.610$ (2)

where, R = rainfall erosivity factor in Megajoule millimeters per hectare per hour per year (MJ mm/ha/hr/year) and P = annual precipitation in millimeters (mm).

In the FAO soil map, fourteen soil classes were found which behave differently towards soil erosion and hence contain varying soil erodibility (K) factor values that explain the degree of soil erodibility of each soil type. Therefore, for this study, the K factor values were obtained from published research articles, which were assigned to fourteen soil classes to obtain a soil erodibility factor map, used in the RUSLE (Table 1 and Table S1).

In this study, we used equations 3 and 4 to calculate the slope-length (L) and slope-steepness (S) factors respectively which are adopted from variously published studies in the South Asia region (Uddin *et al.* , 2016, 2018) The combined LS-factor describes the effect of topography on soil erosion. As temporal topography data was unavailable for 2005 and 2015, a one-time computed L & S spatial layers were used for annual soil erosion estimations and mapping for 2005 and 2015 over the entire Pakistan.

$L = ([\lambda/22.13]^m)$ (3)

where, L = slope-length factor (dimensionless), λ =grid size (1 km x 1 km) or field slope length, and m = 0.5 for slopes > 4 %; 0.4 for 4% slope; 0.3 for slopes < 3% (Wischmeier & Smith, 1978)

$S = ((0.43 + 0.30\ s + 0.043\ s^2)/6.613)$ (4)

Where, S = slope-steepness factor (dimensionless), s = slope derived from DEM in percentage (%)

In this study, MODIS's seventeen LCLU classes defined according to the International Geosphere-Biosphere Programme (IGBP) classification scheme were clamped/recoded to six LCLU classes ('Cropland', 'Forest land', 'Grassland', 'Other land', 'Settlements' and 'Wetlands/Snow cover') which were defined by Intergovernmental Panel on Climate Change (IPCC) (Table S2). From several published articles on RUSLE, we synthesized average cover management factor (C) values for each IPCC LCLU class, which were assigned to 2005 and 2015 LCLU maps (Table 2 and Table S3).

In this study to determine the soil cover management (C) and conservation practice factor (P) values, we compiled and used average values from previously published studies in Pakistan, India, China, and on a global scale (Table S4). Each LCLU class was assigned an average C and P factor values given in Table 2, to get cover and use management and conservation practice factor (P) maps for 2005 and 2015.

2.4. Quantification of soil erosion factors andannual rate of soil erosion changes (2005 - 2015)

To generate soil erosion maps for 2005 and 2015, the spatially computed soil erosion factors: 'rainfall erosivity (R)', 'soil erodibility (K)', 'slope-length (L)', 'slope-steepness (S)', 'cover management (C)' and 'conservation practice (P)' were inserted in equation 1.

The final annual soil erosion (ton/ha/year) maps were reclassified and renamed into four classes; Low (<1), Medium (1–5), High (5-20), and Very high (>20). In this study, each factor and final annual soil erosion maps were spatially and statistically compared between 2005 and 2015. For the annual soil erosion change assessment, we used a cross tabular or change matrix method in which, diagonal values show the stability of soil classes, while omission and commission values indicate a shift in area or percentage between the four soil erosion classes (adopted from Gilani et al., (2015) used for LCLUC assessment). In this study, using the change matrix method, soil 'loss' (commission) and gain (omission) statistically and spatially were reported between 2005 and 2015.

Latitude wise Pakistan extends from 24° N to 37.5° N. In this study across latitude, mean soil erosion (ton/ha/year) in 2005 and 2015 were plotted to understand eroded intensity linking to spatial distribution of soil erosion areas.

2.5. Land Cover and Land Use Changes (LCLUC) and annual rate of soil erosion changes (2005 - 2015)

For LCLUC mapping (2005 - 2015), we utilized MODIS 1 km LCLU datasets which were reclassified at six IPCC LCLU classes. At the national scale, 2005 and 2015 LCLU maps were compared in terms of area. Like soil erosion change assessment, for LCLUC assessment we used a cross tabular or change matrix method between 2005 and 2015 in which, diagonal values show the stability of LCLU classes while LCLU loss (omission) and gain (commission) statistically and spatially. In the change matrices of soil erosion and LCLUC, the loss and gain values are vice versa.

The estimated annual soil erosion rates against six LCLU categories at seven administrative units of Pakistan were also reported for the identification of soil erosion prone areas where soil conservation practices and ground innervations can be implemented and monitored.

Bivariate analysis is one of the simplest forms of the quantitative analysis. It involves the analysis of two variables, for the purpose of determining the empirical relationship between them. In order to see if the variables are related to one another, it is common to measure how those two variables simultaneously change together (Nandi & Shakoor, 2010). In this study, at 5 km spatial resolution for bivariate analysis mapping, gain, loss and no change in annual soil erosion and LCLU between 2005 and 2015 were spatially plotted using three by three bivariate choropleth map legend.

The overall methodological flow is given in Figure 2.

3. Results

The results of annual soil erosion dynamics in Pakistan consist of two sections: (1) Soil erosion - RUSLE factors, (2) Soil erosion change assessment (2005 - 2015) and (3) Land Cover and Land Use Changes (LCLUC) and soil erosion changes (2005 - 2015).

3.1. Soil erosion – RUSLE factors

At the national scale in this study, six RUSLE factors were calculated at 1 km spatial resolution to compute annual soil erosion for 2005 and 2015. Out of six, soil erodibility (K), and slope-length (L) and slope-steepness (S), factors remained consistent while rainfall erosivity (R), cover management (C), and conservation practice (P) factors varied for the 2005 and 2015 (Figure 3).

In the 2015 rainfall erosivity factor, >200 MJ mm/ha/hr/year was observed over the larger areas of Azad Jammu & Kashmir and Khyber Pakhtunkhwa which was much lower in 2005. Based on the spatial distribution map we observed, overall precipitations of the country increased from 2005 to 2015. The rainfall erosivity factor values remained <11 MJ mm/ha/hr/year in 2005 and 2015 over the entire Sindh province, Southern Punjab, large parts of the Balochistan province and northern sides of Gilgit-Baltistan. A vast area of the country consists of 11 to 130 MJ mm/ha/hr/year rainfall erosivity factor values (Figure 3a).

Based on the LCLUC assessment, in four LCLU classes (Cropland, Grassland, Wetlands/Snow cover, Settlements, and 'Other land') increasing trend observed between 2005 to 2015, while only in 'Forest land' decrease detected. In Punjab and Sindh provinces, a large area was covered by 'Cropland' with 0.27 cover and use management (C) and 0.70 conservation practice (P) factors values. On the national scale, 'Forest land' proportion was tiny as compared to the other LCLU classes. Across Pakistan 'Settlements' are scattered with 0.08 cover management and 0.99 conservation practice factors values (Table 2). A huge area of 'Grassland' LCLU class was viewed across Gilgit-Baltistan, Azad Jammu & Kashmir, Khyber Pakhtunkhwa, and Islamabad Capital Territory with 0.06 cover-management factor value (Figure 3b and 3c).

In the central parts of Punjab, Sindh provinces, slope-length (L), and slope-steepness (S) factors indicated a lower range. Over Gilgit-Baltistan, Azad Jammu & Kashmir, Khyber Pakhtunkhwa, and partial areas of Balochistan, higher values of slope-length and slope-steepness factors were observed with slight variations of low rage values (Figure 3d & 3e).

Figure 3f shows eleven soil erodibility (K) factor classes along with one 'wetlands' LCLU class. In the soil erodibility (K) factor map, based on the literature reviewed, 0.5 ton ha hr/ha/ MJ/mm value was assigned to Cambic Arenosols (Qc) soil class and 0.33 ton ha hr/ha/MJ/mm was assigned to Gleysols (G) soil class. Similar soil erodibility (K) factor value was assigned to Orthic Acrisols (Ao) & Orthic Solonchaks (Zo) soil classes i.e.0.23 ton·ha·hr/ha/MJ/mm, accordingly Haplic Yermosols (Yh) & Calcic Yermosols (Yk) allotted 0.25 ton·ha·hr/ha/MJ/mm soil erodibility (K) factor value and Calcaric Fluvisols (Jc) & Calcic Xerosols (Xk) allocated 0.15 ton·ha·hr/ha/MJ/mm soil erodibility (K) factor value. Lithosols (I) soil class covered the majority of the Balochistan, Khyber Pakhtunkhwa, and Gilgit-Baltistan areas. Cambic Arenosols (Qc) soil was observed in the Sindh and Punjab provinces along the Indian border over the Desertic areas (Thar, Thal, and Kharan). The Calcaric Regosols (Rc) soil class with 0.17 ton ha hr/ha/ MJ/mm lies only in the Potohar plateau.

3.2. Soil erosion change (2005 - 2015)

The annual rate of soil erosion was estimated at 1 km spatial resolution for 2005 and 2015 using the RUSLE (Figure 4). The soil erosion ranges from <1 ton/ha/year to >20 ton/ha/year. In the sloppy high-lands areas of Gilgit-Baltistan, Azad Jammu & Kashmir, Khyber Pakhtunkhwa and Balochistan high (5-20 ton/ha/year) and very high (>20 ton/ha/year) annual rate of soil erosion were detected while from medium (1-5 ton/ha/year) to low (<1 ton/ha/year) values were noticed in the flattened areas of the Punjab and Sindh provinces. The estimated average soil erosion at the national scale in 2005 was 1.79 ± 11.52 ton/ha/year (mean ± standard deviation at 95% confidence interval) which increased to 2.47 ± 18.14 ton/ha/year in 2015. In the Azad Jammu & Kashmir administrative unit 14.44 ± 35.70 ton/ha/year soil erosion was detected in 2005 which increased to 28.03 ± 68.24 ton/ha/year in 2015. In the Balochistan, Islamabad Capital Territory, Punjab, and Sindh, <1 ton/ha/year average soil erosion was perceived in 2005 and 2015. In 2005, average 7.54 ± 20.25 ton/ha/year soil erosion was in Gilgit-Baltistan, which increased to 9.06 ± 29.69 ton/ha/year in 2015. Similarly, in Khyber Pakhtunkhwa province average 8.73 ± 25.55 ton/ha/year soil erosion was 2005 increased to 12.84 ± 39.88 ton/ha/year in 2015 (Table 3). Among all the administrative units, only in Azad Jammu & Kashmir average soil erosion doubled from 14.44 ± 35.70 ton/ha/year in 2005 to 28.03 ± 68.24 ton/ha/year in 2015. In Khyber Pakhtunkhwa province average soil was 8.73 ± 25.55 ton/ha/year in 2005, which increased to 12.84 ± 39.88 ton/ha/year in 2015. Similarly, in the Gilgit-Baltistan administrative unit of Pakistan in 2005 mean soil erosion was 7.54 ± 20.25 ton/ha/year which increased to 9.06 ± 29.69 ton/ha/year in 2015. In Balochistan, Punjab, and Sindh administrative units, the negligible average increase was observed in ten years (2005 - 2015). In Islamabad Capital Territory, mean soil erosion was 0.77 ± 2.22 ton/ha/year in 2005, which rose to 1.57 ± 4.56 ton/ha/year in 2015 (Table 3).

Figure 5 presents latitude wise mean soil erosion in 2005 and 2015. Between 24º - 29.5º latitude as such no soil erosion was observed, from 29.5º (dotted blue line) until 33º (dotted yellow line) latitude very slight erosion detected in 2005 and 2015. Between 33º-37º latitude, a parabolic shape was observed which reflects soil erosion in 2005 and 2015. At 35.5º N latitude (dotted red line), in 2005 mean soil erosion was nearly 17 ton/ha/year, which climbed up to 30 ton/ha/year in 2015.

Through cross tabular or change matrix method, in ten years (2005 - 2015) at the national scale, 35,252 km^2 (4%) area observed under negative change (commission) of soil erosion and 12,108 km^2 (1.37%) area covered under positive change (omission). Out of total area of Pakistan (881,913 km^2), in 834,553 km^2 (94.6%) area no change of soil erosion observed between 2005 and 2015 (Table 4). From 2005 to 2015, 731,863 km^2 (˜83%) area remained intact under the low (<1 ton/ha/year) soil erosion while less than six ton/ha/year remained unchanged under the three soil erosion classes (i.e. medium, high and very high). Between 2005 to 2015, total 451 km^2 (0.05%) area converted from very high (> 20 ton/ha/year) to low (<1 ton/ha/year) soil erosion class following only 43 km^2 area transformed from very high (> 20 ton/ha/year) to medium (1-5 ton/ha/year) and 1,012 km^2 (0.11%) area shifter from very high (> 20 ton/ha/year) to high (5-205 ton/ha/year) soil erosion class. From 2005 to 2015, total 11,734 km^2 (1.33%) area moved from medium (1-5 ton/ha/year) to high (5-20 ton/ha/year) soil erosion. Similarly, 9,730 km^2 (1.10%) soil erosion area moved from high (5-20 ton/ha/year) to very high (> 20 ton/ha/year) soil erosion in ten years (2005–2015) (Table 4).

3.3. Land Cover and Land Use Changes (LCLUC) and soil erosion changes (2005 - 2015)

In ten years of study period (2005 - 2015) at the national scale in Pakistan, overall 'cropland' area increased from 170,761 km^2 (19.36%) in 2005 to 177,474 km^2 (20.12%) while 'forest land' decreased from 2,000 km^2 (0.23%) in 2005 and 1,604 km^2(0.18%) in 2015. At the national scale, in the 'grassland' class 521 km^2 (0.06%), in settlements LCLU class 106 km^2 (0.01%) and in 'wetlands/snow cover' 1,532 km^2 (0. 71%) increased detected between 2005 – 2015 while in 'other' LCLU class an overall area lost from 551,813 km^2 (62.57%) in 2005 to 543,337 km^2(61.61%) in 2015 (Table 5).

Through cross tabular or change matrix method, at the national scale total 29,081 km^2 (3.30%) loss while 17,506 km^2 (2.00%) gain observed in LCLUC classes between 2005 to 2015. Among the LCLU classes, <2% loss and gain detected in ten years of study period (2005 - 2015). In spatial distribution map of LCLU, loss detected prominently in Sindh, Punjab and Khyber Pakhtunkhwa while major gain observed in Balochistan

(Table 6 and Figure 6)

Among all six IPCC defined LCLU classes in the seven administrative units of Pakistan, in the Sindh and Balochistan provinces, the area in the percentage of low annual soil erosion (<1 ton/ha/year) category was observed under the majority of the LCLU classes between 2005 to 2015. In Azad Jammu & Kashmir, Gilgit-Baltistan and Islamabad Capital Territory, a well the distribution of each category of soil erosion against LCLU classes were observed between 2005 to 2015. In the forest, under the high (5-20 ton/ha/year) annual soil erosion class, in the Azad Jammu & Kashmir, Gilgit-Baltistan, Khyber Pakhtunkhwa, and Punjab an increasing trend detected in ten years of study period (2005 - 2015). Among all the administrative units of Pakistan, only in Azad Jammu & Kashmir, under the very high (> 20 ton/ha/year) annual soil erosion class, in all six LCLU classes an increment observed in ten years (2005 - 2015) of the study period. Surprisingly, in the settlement class in 2015, very high (> 20 ton/ha/year) soil erosion was calculated as 10% which was zero in 2005. Even in the Khyber Pakhtunkhwa province and Islamabad Capital Territory, under the high (5-20 ton/ha/year) soil erosion class increase in settlement class observed between 2005 to 2015. In the settlement class, in ten years of the study period (2005 - 2015), no soil erosion occurred in the Gilgit-Baltistan. In the Islamabad Capital Territory, from 2005 to 2015, the other LCLU class completely shifter from medium (1-5 ton/ha/year) to high (5-20 ton/ha/year) annual soil erosion category (Figure 7).

At 5km spatial resolution, bivariate analysis revealed in Pakistan maximum areas covered by 'no change' between soil erosion change and LCLUC classes. Majority LCLUC 'loss' detected in Balochistan, Punjab and Sindh with no-change in soil erosion change. In the Azad Jammu & Kashmir, Gilgit-Baltistan, Islamabad Capital Territory and Khyber Pakhtunkhwa administrative units, 'loss' in LCLUC detected with 'gain' in soil erosion change class. Huge area in Khyber Pakhtunkhwa and Gilgit-Baltistan spreader under 'loss' with few patches of 'gain' in LCLUC and soil erosion change between 2005 - 2015 (Figure 8).

4. Discussion

This study provides the first soil erosion estimations and monitoring from 2005 to 2015 at 1 km spatial resolution at the national scale and seven administrative units of Pakistan. In this study, we adopted a cost-effective and easily replicable methodology, used freely available geospatial datasets (soil, precipitation, LCLU, and elevation) in the widely adopted and proven RUSLE.

4.1. Major finding, ground realties, drivers of soil erosion and LCLUC

The findings of this research revealed, at the national scale in Pakistan in 2005 the estimated average soil erosion was 1.79 $\pm$ 11.52 ton/ha/year which increased 2.47 $\pm$ 18.14 ton/ha/year in 2015 (Table 3) and total 29,081 km^2 (3.30%) loss and 17,506 km^2 (2.00%) gain in LCLUC classes between 2005 - 2015 (Table 5).

. Among seven administrative units, in the Azad Jammu & Kashmir maximum with an increasing rate of soil erosion observed in ten years (2005 - 2015). On 8^{th} October 2005, in the Azad Jammu & Kashmir, Pakistan, the 7.6 Mw earthquake and aftershocks triggered several landslides and soil erosion in the region (Kamp *et al.* , 2008; Shafique *et al.* , 2016). Based on temporal soil erosion assessment between 2005 and 2015 around the earthquake epicenter in ten years annual soil erosion increased (Table 3, Figure S2 & Figure 5). Earthquakes are major cause of soil erosion. Zhang et al., (2009) estimated soil erosion changes in the Wenchuan earthquake of May 12, 2008, results indicated due to earthquake soil erosion area increasing by 279.2 km^2, or 1.9% of the total statistical area. In Pakistan, due to 2010, devastating flood around ˜796,095 square kilometers area of the country came underwater along the Indus River, at least 2,000 people died and almost 20 million people were affected and cost the government US$ 9.7 billion loss. In the subsequent years, in 2011 and 2012, Pakistan was again faced floods. Erosion increases as a function of population growth (Pimentel & Burgess, 2013). According to the 2017 population census, the total population of Pakistan is 212.2 million with 2.08% population growth rate. Population expansion coupled with infrastructural development; LCLUC are intensifying soil erosion. Pakistan has ˜2.5% forest cover with 2.1% of the annual rate of deforestation (FAO, 2010) which is also one of the major drivers of soil erosion causing the instability of sloppy land in the mountainous regions. Due to socioeconomic discrepancies, violation of rules and orders, and lack of awareness and education, the soil conservation practices are hard to implement on the ground. In ten years of the study period (2005 - 2015), soil erosion increased in high altitudes may be due to poor weathering of rocks, increasing surface runoff, landslides, deforestation, forest degradation, natural disasters etc. (Figure 4 and Figure 6).

4.2. Comparison with global and local studies on soil erosion estimation

Using RUSLE, the global scale produced annual soil erosion maps (2001 and 2012) at the 25 km spatial resolution were produced and reported by Borrelli et al. (2017). At the national scale and seven administrative units of Pakistan; the globally produced 2012-annual soil erosion was compared with the 2015-annual soil erosion developed in the study. For the spatial and statistical comparison, the produced soil erosion 2015 map was resampled at 25 km. On the national scale as well as in each administrative unit, the global study reported higher values and spatial variability as compared to national produced soil erosion estimations and maps (Table 7 & Figure 9). In few areas of Punjab, Sindh, Balochistan, and Gilgit-Baltistan, in the global soil erosion map, no data observed, even where this study reported low (<1 ton/ha/year) annual soil erosion, the global study reported medium (1-5 ton/ha/year) annual soil erosion. For the annual soil erosion, within Pakistan at the watershed level and basin-scale, using the RUSLE, four studies over the five sites were reported, which were compared with this study by comparing mean soil erosion rate (ton/ha/yr) (Figure S1). Over the Rawal watershed and the Simly watershed we observed the finding of this study are matching well while in the Ghabbir watershed, Potohar region and Soan river basin, this study reported very low mean annual soil erosion values (ton/ha/year) as compared to sub-national scale studies (Table S5). This might be because of input data sources, spatial resolutions, variation in factor equations, and study scales.

4.3. Limitations of this study

This study was carried out in quite a detail including, literature review, geospatial data collection, calculation of RUSLE factors, implementation of RUSLE at the national scale, and spatial analysis conducted to the best of the authors' knowledge and experience. There may be some flaws, errors, or uncertainty in data that may affect results and methodology, so there are some limitations of this study.

For the estimation and monitoring of annual soil erosion over Pakistan, all the globally produced spatial datasets and comprehensive literature reviewed estimated values were utilized. Unfortunately, Pakistan is data-scarce, indeed medium spatial resolution (10 - 30 m) geospatial datasets are freely available to produce basic products (e.g. LCLU maps, soil characteristic maps) but unavailable at the national scale due to several reasons e.g. lack of willingness, technological lacks, and financial constraints. Although across Pakistan nearly 50 meteorological stations are installed most of the time rainfall data is unavailable, those are available are in hardcopy and confidential for the public and researchers.

Although in this study we tried to validate our soil erosion estimates with the previously conducted local/ small scale studies, we noticed that all the five studies were conducted in one big region (i.e. Potohar plateau).

Despite these limitations, spatially explicit and temporal soil erosion provided in this study is essential for various purposes, including the soil conservation and management practices, environmental impact assessment studies, among others.

5. Conclusions

This study presents a spatial quantitative evaluation of decadal (2005 - 2015) annual soil erosion change on the national and subnational levels of Pakistan using freely available remotely sensed data and easy-to-perform RUSLE. It provides baseline information about soil erosion intensities on seven administrative units of Pakistan. There was a lack of a scientific study in Pakistan on soil erosion dynamics and a current approach is a viable option as compared to field-based assessments and evaluations.

The results of this study would be utilized to identify the soil erosion prone areas and conversion of LCLU at the national scale that would help in planning the watershed management activities. International and national reporting on soil and LCLU change dynamics in Pakistan can be drawn from these results. Reported soil erosion and soil change dynamics on highly prone latitude windows would help planners, policy and decision-makers to devise mechanisms to control/ reduce soil erosion and to set conservation priorities. A bivariate analysis between soil erosion change and LCLUC (2005 - 2015) was assessed in this study which is an indication of the need for soil erosion control measures on a national scale.

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Table 1. Soil erodibility factor (K) values compiled through the literature review (Details given in table S1).

FAO soil type (Soil acronym)	**K factor value (**ton·ha·hr/ha/MJ/mm)
Orthic Acrisols (Ao)	0.23
Eutric Cambisols (Be)	0.24
Gleysols (G)	0.33
Lithosols (I)	0.27

FAO soil type (Soil acronym)	K factor value (ton·ha·hr/ha/MJ/mm)
Calcaric Fluvisols (Jc)	0.15
Orthic Luvisols (Lo)	0.26
Cambic Arenosols (Qc)	0.05
Calcaric Regosols (Rc)	0.17
Haplic Xerosols (Xh)	0.19
Calcic Xerosols (Xk)	0.15
Haplic Yermosols (Yh)	0.25
Calcic Yermosols (Yk)	0.25
Gleyic Solonchaks (Zg)	0.16
Orthic Solonchaks (Zo)	0.23

Table 2. Soil cover management factor (C) and conservation practice factor (P) values compiled through literature review (Details given in Table S2 & S3 for cover management factor (C) and conservation practice factor (P) respectively).

IPCC land cover class	C factor value	P factor value
Forest land	0.02	0.99
Cropland	0.27	0.70
Grassland	0.06	0.95
Wetlands	0	1
Settlements	0.08	0.99
Other land	0.32	0.96

Table 3. Annual soil erosion estimation (mean ± standard deviation) in 2005 and 2015 at the national and seven administrative units of Pakistan.

Administrative unit name	2005	2015
	Mean ± Standard deviation ton/ha/year	Mean ± Standard deviation ton/ha/
National scale	1.79 ± 11.52	2.47 ± 18.14
Azad Jammu & Kashmir	14.44 ± 35.70	28.03 ± 68.24
Balochistan	0.28 ± 1.88	0.26 ± 1.77
Gilgit-Baltistan	7.54 ± 20.25	9.06 ± 29.69
Islamabad Capital Territory	0.77 ± 2.22	1.57 ± 4.56
Khyber Pakhtunkhwa	8.73 ± 25.55	12.84 ± 39.88
Punjab	0.11 ± 1.22	0.17 ± 2.02
Sindh	0.02 ± 0.28	0.03 ± 0.35

Table 4. Soil erosion change matrix from 2005 to 2010 in Pakistan

Soil erosion class (ton/ha/year)	Low (<1)	Medium (1-5)	High (5-20)	Very high (> 20)	Total 2015
	km^2 (%)	km^2 (%)	km^2 (%)	km^2 (%)	km^2 (%)
Low (<1)	731,863 (82.99)	12,967 (1.47)	439 (0.05)	126 (0.01)	745,395 (84.52)

Soil erosion class (ton/ha/year)	Low (<1)	Medium (1-5)	High (5-20)	Very high (> 20)	Total 2015
Medium (1-5)	7,064 (0.80)	49,191 (5.58)	11,734 (1.33)	256 (0.03)	68,245 (7.74)
High (5-20)	553 (0.06)	2,985 (0.34)	31,512 (3.57)	9,730 (1.10)	44,780 (5.08)
Very high (> 20)	451 (0.05)	43 (0.00)	1,012 (0.11)	21,987 (2.49)	23,493 (2.66)
Total 2005	739,931 (83.90)	65,186 (7.39)	44,697 (5.07)	32,099 (3.64)	881,913 (100.00)
Negative change (loss)	Negative change (loss)	35,252 (4.00)	Positive change (gain)	Positive change (gain)	12,108 (1.37)

Table 5. Land Cover and Land Use (LCLU) assessment between 2005 and 2015 (MODIS seventeen land cover classes were recoded into six IPCC land cover classes detail give in Table S4).

IPCC Land cover class	2005	2015
	km^2 (%)	**km^2 (%)**
Cropland	170,761 (19.36)	177,474 (20.12)
Forest land	2,000 (0.23)	1,604 (0.18)
Grassland	134,496 (15.25)	135,017 (15.31)
Other land	551,813 (62.57)	543,337 (61.61)
Settlements	6,298 (0.71)	6,404 (0.73)
Wetlands/Snow cover	16,545 (1.88)	18,077 (2.05)
Total	881,913 (100)	881,913 (100)

Table 6. Land Cover and Land Use Change (LCLUC) matrix from 2005 to 2010 in Pakistan

IPCC LCLU class	Cropland	Forest land	Grassland	Other land	Settl
	km^2 (%)	**km^2 (%)**	**km^2 (%)**	**km^2 (%)**	**km^2**
Cropland	164,880 (18.70)	2 (0.00)	11,148 (1.26)	1,442 (0.16)	0
Forest land	0	1,080 (0.12)	517 (0.06)	6 (0.00)	0
Grassland	5,545 (0.63)	145 (0.02)	113, 838 (12.91)	15,479 (1.76)	0
Other land	288 (0.03)	769 (0.09)	8,634 (0.098)	533,172 (60.46)	0
Settlements	29 (0.00)	0	60 (0.01)	17 (0.00)	6,298
Wetlands/Snow cover	19 (0.00)	4 (0.00)	299 (0.03)	1,697 (0.19)	0
Total 2005	170,761 (19.36)	2,000 (0.23)	134,496 (15.20)	551,813 (62.57)	6,298
Negative change (loss)	Negative change (loss)	29,081 (3.30)	Positive change (gain)	Positive change (gain)	17,506

Table 7. A statistically (mean ± standard deviation) comparison between the globally produced 2012-annual soil erosion (Borrelli*et al.* , 2017)) and 2015-annual soil erosion developed in the current study over the Pakistan.

Administrative unit name	**Global study** (Borrelli *et al.*, 2017)	**Current study***
	Mean ± Standard deviation ton/ha/year	**Mean ± Standard deviation ton/ha/**
National scale	12.36 ± 30.21	2.59 ± 10.17
Azad Jammu & Kashmir	40.88 ± 54.72	22.25 ± 20.27

Administrative unit name	**Global study** (Borrelli *et al.*, 2017)	**Current study***
Balochistan	12.98 ± 21.82	0.41± 1.57
Gilgit-Baltistan	25.48 ± 51.72	8.72 ± 13.08
Islamabad Capital Territory	15.62 ± 3.49	0.34 ± 0.28
Khyber Pakhtunkhwa	29.16 ± 49.59	11.78 ± 21.97
Punjab	5.88 ± 12.40	0.35 ± 0.01
Sindh	4.95 ± 13.67	0.02 ± 3.46

*rescaled at 25 km spatial resolution

Captions of Figures:

Figure 1. Study area map showing locations and topography of Pakistan.

Figure 2. Methodological flow chart.

Figure 3. Soil erosion - RUSLE factor maps (a). Rainfall erosivity factor (R) for 2005 & 2015, (b). Cover management factor (C) for 2005 & 2015, (c). Conservation practice factor (P) for 2005 & 2015, (d). Slope-length factor (L), (e). Slope-steepness factor (S), and (f). Soil erodibility factor (K).

Figure 4. Annual soil erosion and change assessment maps 2005 – 2015.

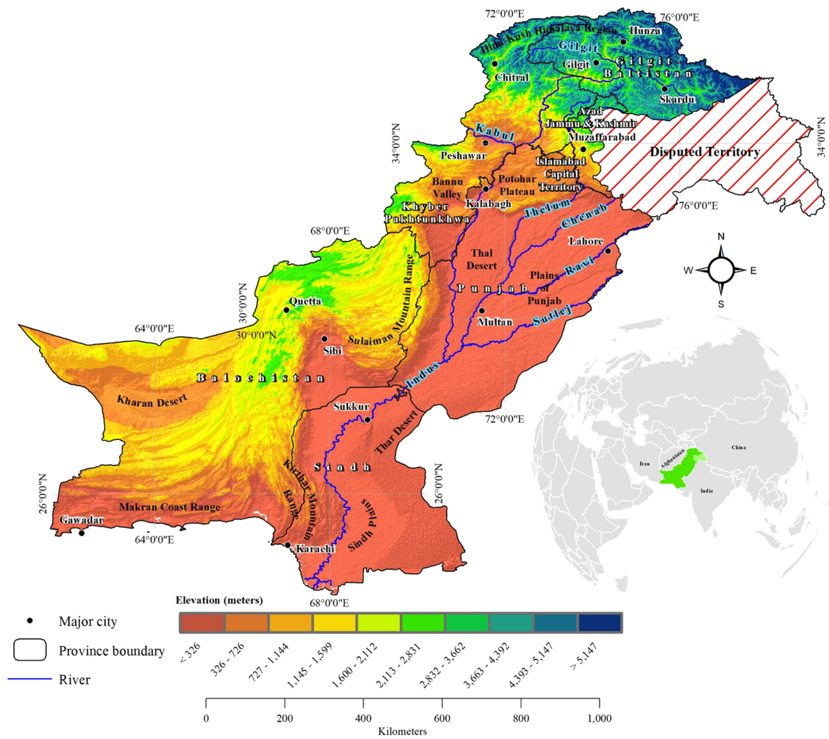
Figure 5. Mean soil erosion (ton/ha/yr) variations along latitude.

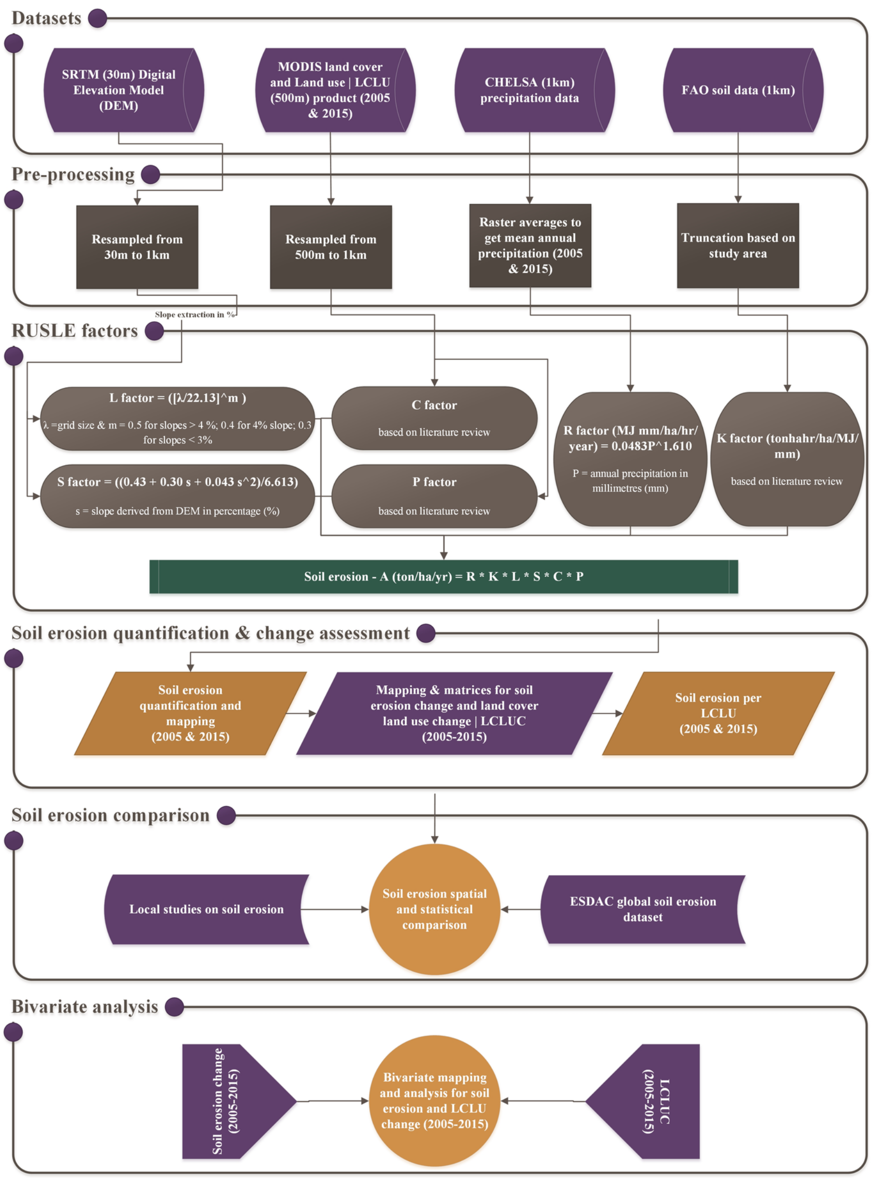
Figure 6. Land Cover and Land Use (LCLU) and change assessment maps 2005 and 2015.

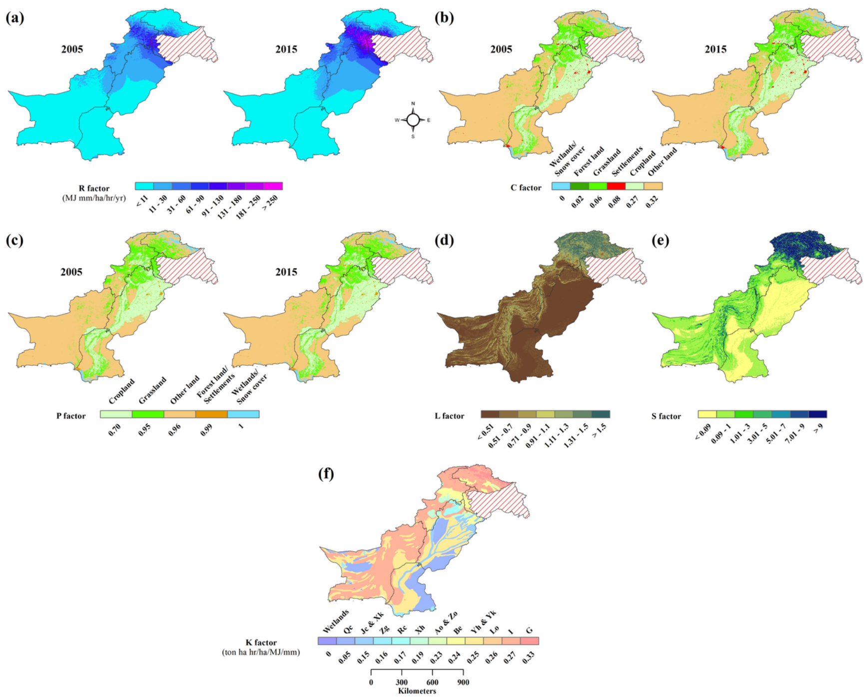
Figure 7. LCLU level annual soil erosion distribution for 2005 and 2015.

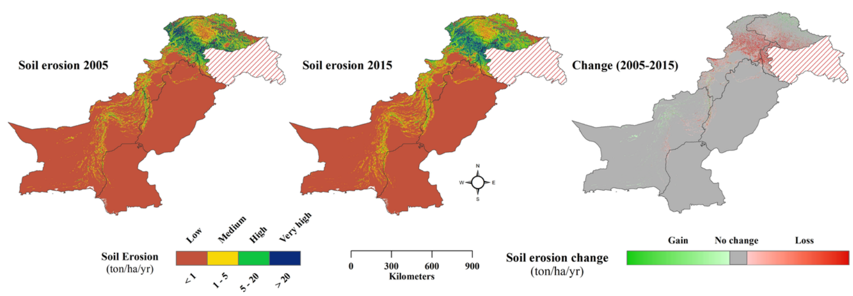
Figure 8. A bivariate spatial analysis map among soil erosion change and LCLUC 2005 and 2015.

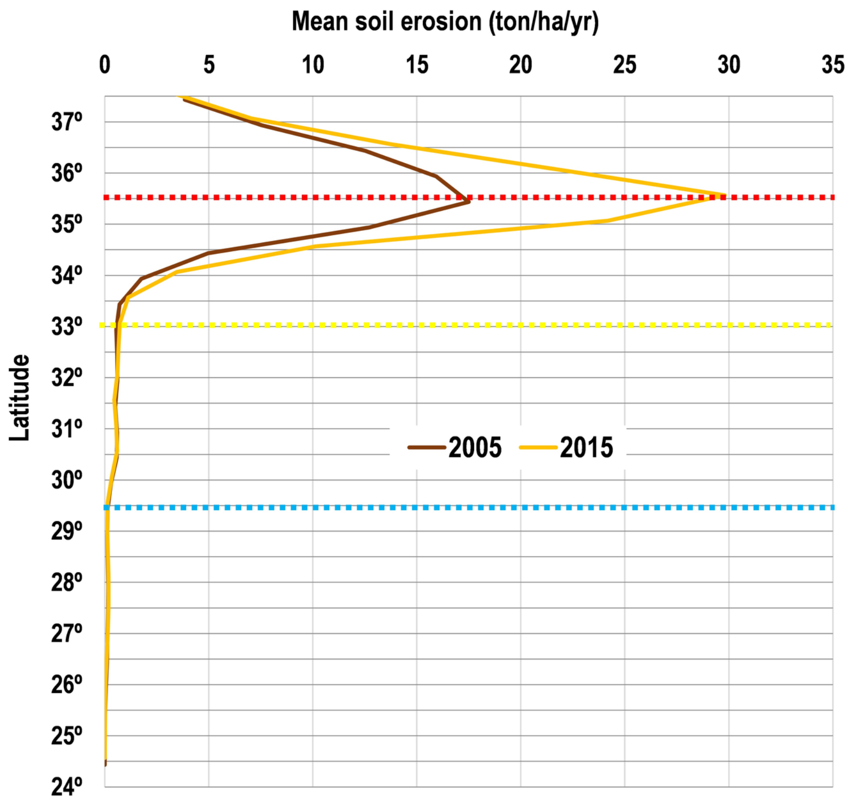
Figure 9. Spatial comparison between Borrelli et al. (2017) and current study over Pakistan for 2015.

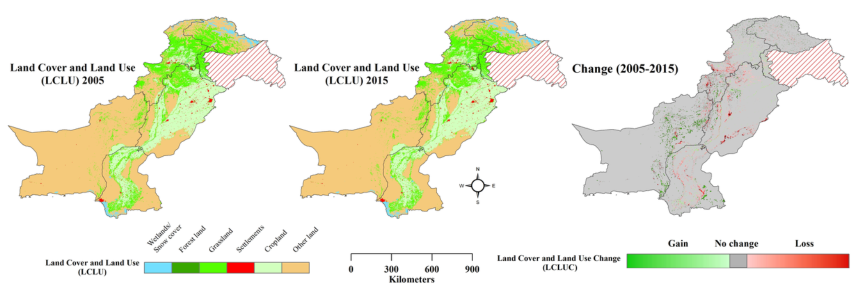

72°0'0"E
76°0'0"E
Hindu Kush Himalaya Region
Hunza
Gilgit
Gilgit
Gilgit Baltistan
Chitral
Skardu
Azad Jammu & Kashmir
Muzaffarabad
Disputed Territory
34°0'0"N
Kabul
Peshawar
Islamabad Capital Territory
Bannu Valley
Potohar Plateau
Kalabagh
Khyber Pakhtunkhwa
Jhelum
Chenab
76°0'0"E
68°0'0"E
Thal Desert
Lahore
Ravi
Plains of Punjab
Punjab
Quetta
30°0'0"N
Sulaiman Mountain Range
Multan
Sutlej
64°0'0"E
Sibi
Balochistan
Indus
Kharan Desert
Sukkur
72°0'0"E
Thar Desert
Sindh
Kirthar Mountain Range
Sindh Plains
26°0'0"N
Makran Coast Range
Gawadar
64°0'0"E
Karachi
68°0'0"E
N
W
E
S
China
Iran
Afghanistan
India
Elevation (meters)
Major city
Province boundary
River
< 326
326 - 726
727 - 1,144
1,145 - 1,599
1,600 - 2,112
2,113 - 2,831
2,832 - 3,662
3,663 - 4,392
4,393 - 5,147
> 5,147
0
200
400
600
800
1,000
Kilometers

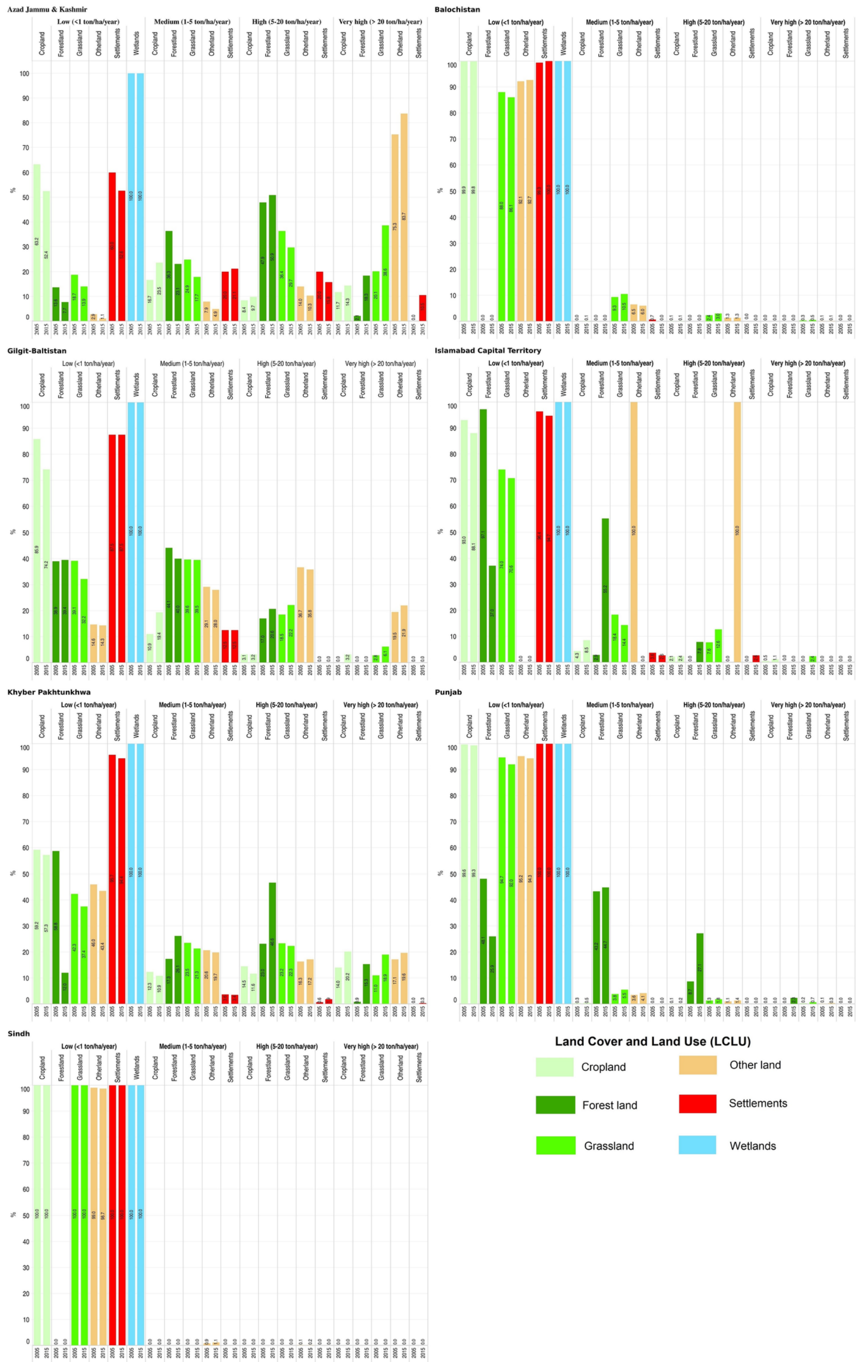

Datasets
SRTM (30m) Digital Elevation Model (DEM)
MODIS land cover and Land use | LCLU (500m) product (2005 & 2015)
CHELSA (1km) precipitation data
FAO soil data (1km)
Pre-processing
Resampled from 30m to 1km
Resampled from 500m to 1km
Raster averages to get mean annual precipitation (2005 & 2015)
Truncation based on study area
Slope extraction in %
RUSLE factors
L factor = ([λ/22.13]^m)
λ =grid size & m = 0.5 for slopes > 4 %; 0.4 for 4% slope; 0.3 for slopes < 3%
C factor
based on literature review
R factor (MJ mm/ha/hr/year) = 0.0483P^1.610
P = annual precipitation in millimetres (mm)
K factor (tonhahr/ha/MJ/mm)
based on literature review
S factor = ((0.43 + 0.30 s + 0.043 s^2)/6.613)
s = slope derived from DEM in percentage (%)
P factor
based on literature review
Soil erosion - A (ton/ha/yr) = R * K * L * S * C * P
Soil erosion quantification & change assessment
Soil erosion quantification and mapping (2005 & 2015)
Mapping & matrices for soil erosion change and land cover land use change | LCLUC (2005-2015)
Soil erosion per LCLU (2005 & 2015)
Soil erosion comparison
Local studies on soil erosion
Soil erosion spatial and statistical comparison
ESDAC global soil erosion dataset
Bivariate analysis
Soil erosion change (2005-2015)
Bivariate mapping and analysis for soil erosion and LCLU change (2005-2015)
LCLUC (2005-2015)

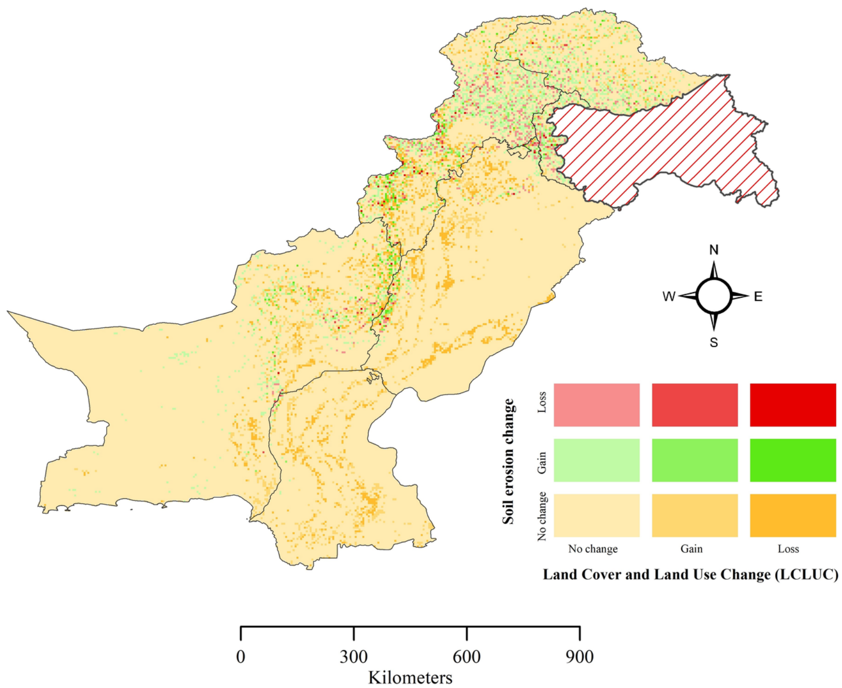

(a)
2005
2015
R factor
(MJ mm/ha/hr/yr)
< 11
11 - 30
31 - 60
61 - 90
91 - 130
131 - 180
181 - 250
> 250
N
W
E
S
(b)
2005
2015
Wetlands/ Snow cover
Forest land
Grassland
Settlements
Cropland
Other land
C factor
0
0.02
0.06
0.08
0.27
0.32
(c)
2005
2015
Cropland
Grassland
Other land
Forest land/ Settlements
Wetlands/ Snow cover
P factor
0.70
0.95
0.96
0.99
1
(d)
L factor
< 0.51
0.51 - 0.7
0.71 - 0.9
0.91 - 1.1
1.11 - 1.3
1.31 - 1.5
> 1.5
(e)
S factor
< 0.09
0.09 - 1
1.01 - 3
3.01 - 5
5.01 - 7
7.01 - 9
> 9
(f)
Wetlands
Qc
Jc & Xk
Zg
Rc
Xh
Ao & Zo
Re
Yh & Yk
Lo
I
G
K factor
(ton ha hr/ha/MJ/mm)
0
0.05
0.15
0.16
0.17
0.19
0.23
0.24
0.25
0.26
0.27
0.33
0
300
600
900
Kilometers

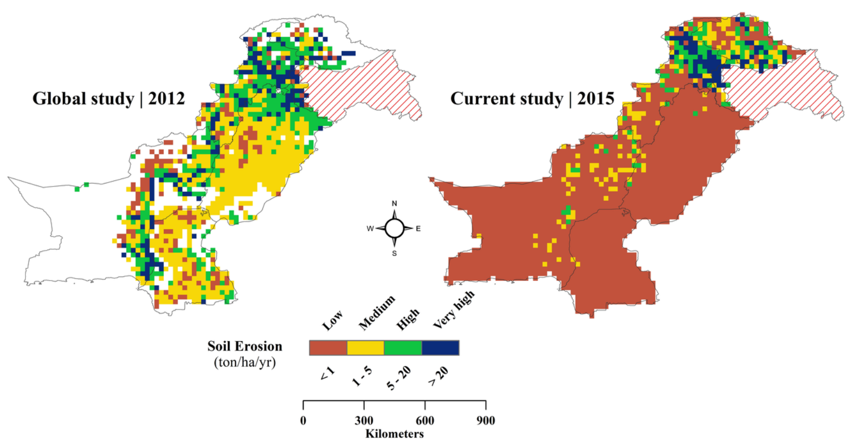

Soil erosion 2005
Soil erosion 2015
Change (2005-2015)
N
W
E
S
Low
Medium
High
Very high
Soil Erosion
(ton/ha/yr)
< 1
1 - 5
5 - 20
> 20
0
300
600
900
Kilometers
Gain
No change
Loss
Soil erosion change
(ton/ha/yr)


Mean soil erosion (ton/ha/yr)
0
5
10
15
20
25
30
35
Latitude
37°
36°
35°
34°
33°
32°
31°
30°
29°
28°
27°
26°
25°
24°
2005
2015


Land Cover and Land Use (LCLU) 2005
Land Cover and Land Use (LCLU) 2015
Change (2005-2015)
Land Cover and Land Use (LCLU)
Wetlands/ Snow cover
Forest land
Grassland
Settlements
Cropland
Other land
0
300
600
900
Kilometers
Land Cover and Land Use Change (LCLUC)
Gain
No change
Loss


Azad Jammu & Kashmir
Balochistan
Gilgit-Baltistan
Islamabad Capital Territory
Khyber Pakhtunkhwa
Punjab
Sindh
Low (<1 ton/ha/year)
Medium (1-5 ton/ha/year)
High (5-20 ton/ha/year)
Very high (> 20 ton/ha/year)
Cropland
Forestland
Grassland
Otherland
Settlements
Wetlands
%
Land Cover and Land Use (LCLU)
Cropland
Other land
Forest land
Settlements
Grassland
Wetlands


N
W
E
S
Soil erosion change
Loss
Gain
No change
No change
Gain
Loss
Land Cover and Land Use Change (LCLUC)
0
300
600
900
Kilometers


Global study | 2012
Current study | 2015
N
W
E
S
Low
Medium
High
Very high
Soil Erosion
(ton/ha/yr)
< 1
1 - 5
5 - 20
> 20
0
300
600
900
Kilometers