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Quantifying and mapping sediment retention ecosystem services in a mountain landscape of Southern Western Ghats, India

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ABSTRACT

Ecosystem services models that are capable of quantifying and mapping the spatial conservation prioritization through the process of simple and scientifically credible methods, in order to conserve protected area is the need of the hour. A sediment retention model based on InVEST was employed to estimate sediment retention, soil loss and sediment export in Periyar Tiger Reserve, a representative in the mountain landscape of Southern Western Ghats, Kerala, India. The analysis included vegetation classes, rainfall erosivity, soil erodibility, watershed boundary, Digital Elevation Model (DEM), biophysical parameters and empirical constants. The estimated sediment retention of PTR was 3574263.9 tonnes/year with 55.45% from Periyar river watershed and 44.55% from Pamba river watershed. Sediment export and potential soil loss were calculated as 40272.66 and 360735.81 tonnes/year respectively. A comparison of sediment retention capacity to the forest ecosystems with different vegetation indicates that there is a decreasing trend from evergreen forest, semi evergreen forest, to grassland-savanna, plantations and moist deciduous forest. It is estimated that 37% of evergreen and 24% of semi evergreen share the major portion of the total sediment retention, 61.12% of PTR. This study reveals the significance of quantifying and mapping the ecosystem services of the Tiger reserve and importance to conserve and required efficient management.

Key words: *Sediment retention, InVEST model, Ecosystem services, Western Ghats, Periyar Tiger Reserve*

Introduction

Ecosystem services are generally defined as the benefits people obtain from ecosystems (MEA 2005). An ecosystem service model has increasingly been used to value ecosystem functions to human benefits (Fisher *et al.,* 2009). The land cover function in soil erosion and hydrological cycle has long been accepted and documented with a special emphasis on forest vegetation (Maes *et al.,* 2012a; Langemeyer *et al.,* 2016). The role of natural vegetation cover in prevention and control of soil erosion has also been recognized recently by all major international ecosystem service classifications (Hilde and Paterson, 2014; Woodruff and BenDor, 2016).

Mountain landscape ecosystem services can make more significant and understandable to decision makers by establishing a wide range of tangible and intangible benefits that people derive from mountain forest ecosystems, and some of them are fresh water and reservoir, habitats for wildlife, protection against natural disasters, carbon sequestra-

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tion and storage, natural resources, tourism and recreation, and biodiversity (Keller *et al.,* 2015; Goldstein *et al.,* 2012; Aiello *et al*., 2015).

Reservoirs are associated with a number of ecosystem services, such as; generation of energy through hydropower, irrigation and recreational activities. Erosion and sedimentation of watersheds are controlled by many factors, including rainfall patterns, soil characteristics, steepness of the hillslope and the type of vegetation cover. Different types of vegetation decrease soil loss and retain sediments from upslope areas to different degrees (Tallis *et al.,* 2011).

Quantification and mapping of ecosystem services are of great importance to identify the risks, impacts and potential trade-offs associated with mountain landscape conservation strategies (Malinga *et al.,* 2015). To perform such assessments, many models have been developed to map, quantify and value the provision of ecosystem services (Fisher *et al.,* 2009; Seppelt *et al.,* 2011; Sharps *et al.,* 2017).

The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model has been developed to quantify and map a range of ecosystem services (Sharp *et al.,* 2015; Tallis *et al.,* 2011). InVEST was developed as part of the Natural Capital Project (www.naturalcapitalproject.org), the aim being an alignment of economic forces with conservation objectives and mainstreaming the approaches. Sediment Delivery Ratio (SDR) model, initially computes the delivery and retention of sediment across the landscape, the service valuation can then be performed in terms of avoided reservoir sedimentation, avoided stream health degradation, avoided water treatment, etc. (Keeler *et al.,* 2012; Sharp *et al.,* 2015). Lake sedimentation and erosion of watersheds can lead to decreased hydropower output, structural damage to reservoirs and other water infrastructure, and flooding. InVEST estimates the capacity of a land parcel to retain sediment using data on geomorphology, climate, vegetation and management practices (Hamel *et al.,* 2015).

In the present study Sediment Delivery Ratio (SDR) model has been used to assess sediment response to different natural vegetation classes in a mountain landscape of Periyar Tiger Reserve (PTR) in the Southern Western Ghats of India. The quantity of eroded sediment reaching the stream network, and thus delivering benefits like maintaining soil and water quality and reservoir functions implies a focus on decisions related to Protected Area (PA) management, thus requiring spatially explicit descriptions of the landscape and associated climatic parameters (Guswa *et al.,* 2014; Meisch *et al.,* 2019).

The aim of this study was to assess sediment retention ecosystem services for the different land-use patterns in PTR. The analysis was based on forest classification, terrain properties, meteorological and biophysical data on InVEST Sediment Delivery Ratio (SDR) model. The specific objectives of this study were to: (1) quantify and map sediment retention ecosystem services provided by different vegetations in PTR and (2) develop a classification framework among these land-use patterns and their spatial distribution. Tropical climatic conditions and highly undulated terrain in Southern Western Ghats, the erosion mitigation and sediment retention services are of great importance to account for conservation strategies in these regions.

Materials and Methods

In this study InVEST (version 3.7.0) SDR is used with input data which include gridded maps of vegetation, terrain properties, climate and some biophysical coefficients.

Study Area

Western Ghats forms a mountain range that extends along the coast of Arabian Sea from south of the Tapti River and ending at Kanyakumari at the southern tip of India. This part is classified and considered as one of the world's richest biodiversity hotspots. The area selected for the study is the PTR in the Periyar-Agasthyamalai landscape. The catchment areas of Periyar and Pamba rivers give livelihoods for many rural and urban communities. The protected area is listed in the UNESCO World Natural Heritage Sites in India (Myers *et al.,* 2000).

PTR is situated in the Western Ghats Hills, specifically Cardamom and Pandalam Hills of the Southern Western Ghats between latitudes 9^{o} 17' 56.04" and 9^{o} 37' 10.2" N and longitudes 76^{o} 56' 12.12" and 77^{o} 25' 5.52" E (Fig.1). PTR covers 925 km^{2} of highly undulating terrain and its elevation ranges from 81m above MSL (lowest) to 2016m (highest) with an average elevation of 1200 m. The climate is cool and humid with an average annual rainfall of 2500 mm. The temperature ranges from 15 ^{o}C to 31^{o}C and the hottest months are April and May, and

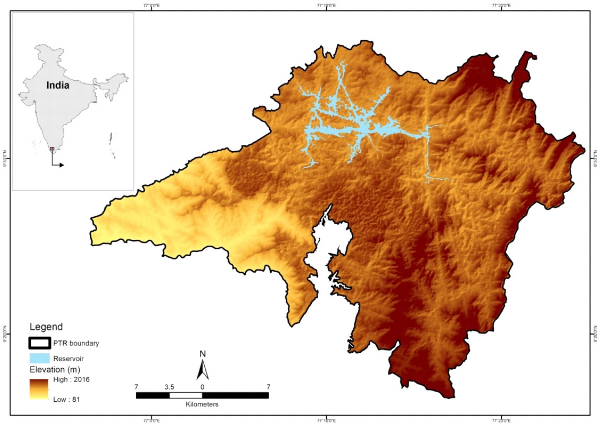

Fig. 1. Location map of Periyar Tiger Reserve

the coolest months are December and January. The forest vegetation ranges from montane evergreen forests at higher elevations to all other major tropical vegetation types along the lower reaches (Satis, 1991).

Sediment retention services modeling - Sediment Delivery Ratio (SDR) model

InVEST software Sediment Delivery Ratio (SDR) model is used to assess the soil retention services (Hamel *et al.,* 2015). The model calculates the average annual soil loss from each parcel of land, determining how much of that soil may arrive at a particular point of interest, estimating the ability of each parcel to retain sediment in the landscape (Sharp *et al.,* 2015).

To identify a land parcel's potential soil loss and sediment transport, the model uses the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) at the pixel scale, which integrates information on vegetation patterns and soil properties, as well as a Digital Elevation Model (DEM), rainfall and climate data.

Revised Universal Soil Loss Equation (RUSLE) is used to calculate the average amount of annual soil loss and presented in equation 1 (Renard *et al.,* 1997):

$$USLE_i = (R \times K \times LS \times C \times P)_i \quad .. (1)$$

where R is the rainfall erosivity, K is the soil erodibility factor, LS is the slope length-gradient factor, C is the land cover management factor and P is the support practice factor.

The SDR is computed as a function of the hydrologic connectivity of the area, as per Vigiak *et al.,* 2012.

The algorithm first computes an index of connectivity IC which determines the degree of hydrological connectivity of a pixel to the stream, based on its upslope contribution and flow path to the stream (Hamel *et al.,* 2015; Sharp *et al.,* 2015; Borselli *et al.,* 2008). The sediment delivery ratio for a pixel i is then directly derived from the conductivity index IC using a sigmoid function (2) (Vigiak *et al.,* 2012).

$$SDR_i = \frac{SDR_{max}}{1+\exp\left(\frac{IC_0-IC_i}{k_b}\right)} \quad .. (2)$$

SDR_{max} is the maximum theoretical SDR, defined as the maximum proportion of fine sediment which can travel to the stream; in the absence of detailed soil information, it has a default value of 0.8 (Vigiak *et al.,* 2012). IC_0 and k_b are calibration parameters that define the shape of the sigmoid function SDR–IC relationship (Hamel *et al.,* 2015). The sediment yield from a given pixel i, sed_export is a direct function of the soil loss and SDR factor (3).

$$sed\_export_i = usle_i \times SDR_i \quad .. (3)$$

The model returns three main outputs that come as both average annual numeric data (amounts for each sub-catchment): (i) total amount of sediment exported to the stream (tonnes/year); (ii) total amount of potential soil loss calculated by the USLE equation (tonnes/year); (iii) sediment retention as the difference in the amount of sediment delivered by the current land cover and a hypothetical watershed where all land use types have been cleared to bare soil (tonnes/year), as well as maps representing the per-pixel contribution to sediment yield (tonnes/pixel)

Its main objectives are to map overland sediment generation and delivery to the stream and to study the service of sediment retention in a catchment, important for reservoir management and in stream water quality. This approach is based on the concept of hydrological connectivity as proposed by Borselli *et al.,* 2008 and has received increasing interest over the past years (Cavalli *et al.,* 2013; López-Vicente *et al.,* 2013; Crema *et al.,* 2015).

Data preparation

InVEST soil retention model require GIS layers, biophysical parameters and empirical constants. GIS layers are DEM, rainfall erosivity, soil erodibility, land cover and watershed boundary spatial data (Sharp *et al.,* 2015). All the input data were resampled at a spatial resolution of 30 m and projected using the World Geodetic System 84 (WGS84).

DEM is a GIS raster data set with an elevation value for each cell and Aster DEM at 30m resolution was used for the model. Rainfall erosivity index (R), reflects climate properties in a raster dataset format and it is calculated using Singh *et al.,* 1981. Soil Erodibility (K) is a pixel dataset, with a soil erodibility value for each cell. It measures the susceptibility of soil particles to detachment and transport by rainfall and runoff. For PTR this was derived from soil texture information provided in the Soil and Land Use Survey of India (SLUSI) data and user table as provided in the InVEST handbook (Sharp *et al.,* 2015).

Land use/land cover statistics were derived from the forest maps of South India in the scale of 1:250,000 with vegetation classifications published by the French Institute of Pondicherry (FIP), 1992. The whole park had been under a strict conservation regime during the map generation and the duration of 25-30 years can be considered as a short period of time for the natural systems to change. Based on knowledge of the land cover and ground truth information, six different land cover classes were identified and are described in Table 1.

Table 1. Land cover statistics and their classification in PTR

Sl. No	Vegetation Class/Land Cover	Area km^2	Area %
1	Evergreen Forest (EGF)	342.12	36.99
2	Semi Evergreen Forest (SEF)	223.2	24.13
3	Moist Deciduous Forest (MDF)	79.48	8.59
4	Plantations	55	5.95
5	Grassland-Savanna	199.2	21.53
6	Waterbody	26	2.81
	Total	925	100

Based on the DEM, the watersheds were generated using ArcGIS. There are nine watersheds and each watershed was given a unique identification number (ws_id). All data sources and values used in the baseline model run are summarized in Table 2.

Results

The sediment retention assessment was performed for the nine sub-basins that cover two major rivers, namely, Periyar and Pamba that are originating from PTR landscape (Table 3) and figures are shown below. The total sediment retention value of the PTR is 3574263.91 tonnes/year with sediment export value of 40272.66 tonnes/year and potential soil loss value of 360735.81 tonnes/year respectively (Fig.2 (a,b,c)).

PTR watersheds absolute values for sediment export, potential soil loss and total sediment retention are shown in Table 4. Watershed no. 7 is the largest contributor to the sediment yield with the highest values for both sediment export (26.12% of the total sediment exported) and potential soil loss of 28.77%. Watershed no.9 has the lowest contribution of 351.23 tonnes/year (1%) of sediment exported and 3072.69 tonnes/year (1%) of potential soil loss.

PTR total sediment retention capacity is 3574263.91 tonnes/year. The highest sediment retention watershed is no. 3 with an absolute value of 997407.02 tonnes/year (27.91% of total sediment retention) followed by the watershed no.7 with 26.68% of the total sediment retention ecosystem services.

Based on the surface area given in Table 4, the highest exporter of sediment is watershed no. 9 with a value of 448.19 tonnes/km^2/year of the Pamba river watershed, followed by no. 4 with 143.18 tonnes/km^2/year of the Periyar river watershed and the lowest values represent watershed no.6 with a rate of 8.43 tonnes/km^2/year.

The highest potential soil loss reported to the surface is also registered in watershed no. 9 with a value of 3809.17 tonnes/km^2/year, almost five times greater than the average for the whole study area of 846.48 tonnes/km^2/year.

Sediment retention services of the different vegetation classes variation are shown in Fig. 3. PTR has 36.99% evergreen, 24.13% semi evergreen and 8.59% moist deciduous forests, then 5.95% plantations, 21.53% grassland-savanna and 2.81% waterbody (Table 1).

Evergreen forest contributes 36.85% (1316830.84 tonnes/year) of the total sediment retention services followed by semi-evergreen forest with 26.50% (947564.25 tonnes/year). Among the forest types, the least sediment retention services are imparted from moist deciduous forest of 4.80% (171993.00 tonnes/year). Other vegetation classes of grasses and plantations carried 22.15% (791938.80 tonnes/

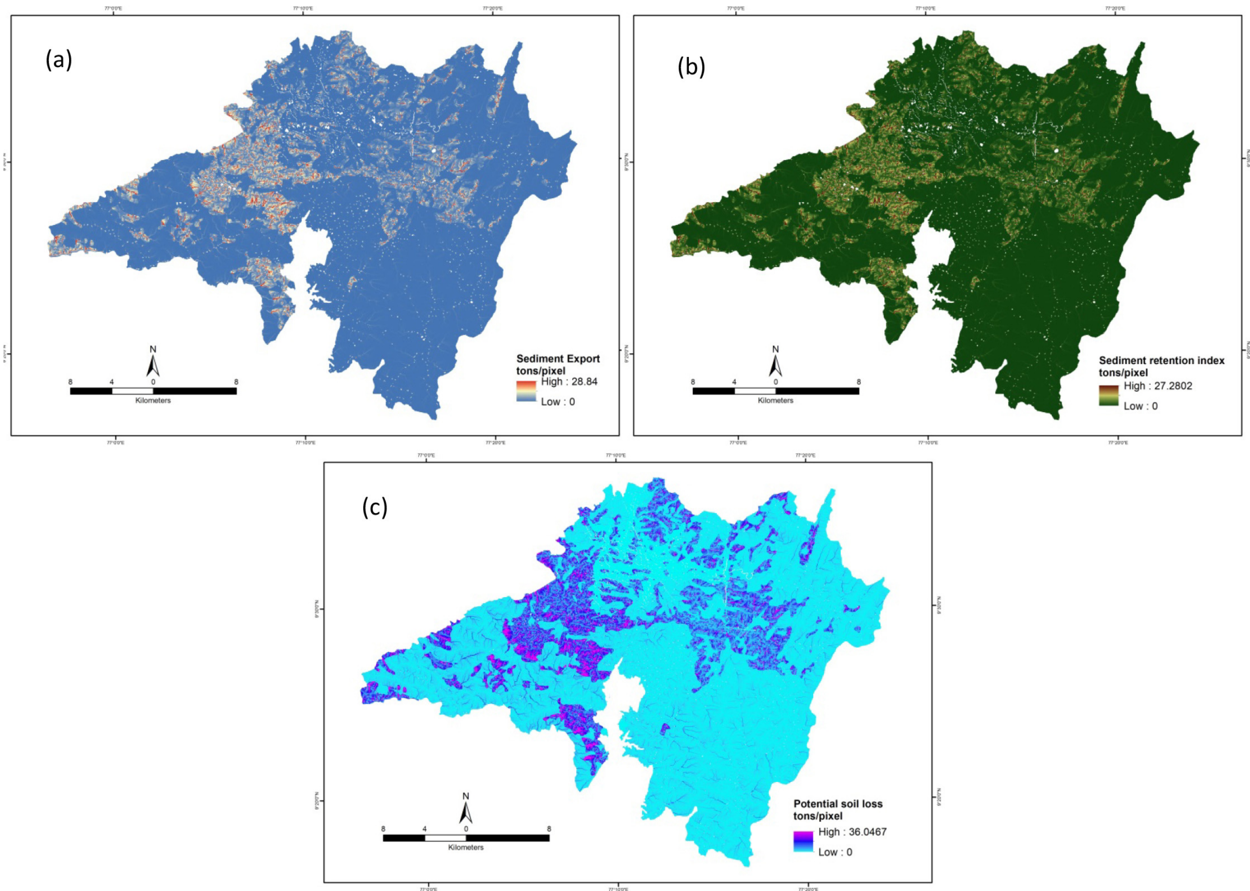

Fig. 2. Sediment retention services assessment for PTR

Table 2. Summary of inputs, baseline values and data sources

Input	Type	Value (Range)	Source
Erosivity layer	Raster (30m)	[581; 1719] MJ·mm/(ha.hr)	PTR and Singh *et al.*, 1981.
Erodibility layer	Raster (30m)	[0.001; 0.41] ton·ha·hr/(ha.MJ.mm)	SLUSI and Sharp *et al.*, 2015
DEM	Raster (30m)	[1; 2016] m	USGS (ASTER)
USLE C factor	Decimal	EGF:0.003 SEF:0.004 MDF:0.003 Plantations:0.06 Grassland:0.054 Water:0.001	Renard *et al.*, 1997
USLE P factor		EGF:1 SEF:1 MDF:1 Plantations:0.8 Grassland:1 Water:1	Renard *et al.*, 1997
Threshold flow accumulation (tfac)	Integer	2000	Verma *et al.*, 2017
k	Decimal	2	Vigiak *et al.*, 2012
IC_0	Decimal	0.5	Vigiak *et al.*, 2012
SDR_{max}	Decimal	0.8	Vigiak *et al.*, 2012

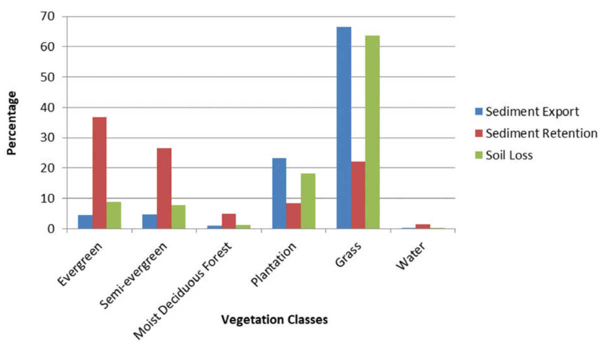

Fig. 3. Sediment retention of different forest ecosystem in PTR

year) and 8.30% (296733.20 tonnes/year) respectively.

Highest sediment export and potential soil loss were reported in the vegetative class of grasses with an amount 26754.75 (66.5%) and 229938.65 (63.70%) tonnes/year respectively. Again moist deciduous forest ranked the least values with 348.68 tonnes/year (0.85%) of the total sediment exported and 4546.13 tonnes/year (1.25%) of potential soil loss of PTR.

Discussion

The highest rates of sediment exported in PTR were recorded in the North-West part with a higher cover of grassland vegetation and also areas having steep slopes characteristic to mountain landscape of Western Ghats environments. Evergreen and semi-evergreen forest regions ranked least for sediment export and soil loss. The higher rates of sediment retention mean the greater amount of forest ecosystem services in the catchment and command areas (Bogdan *et al.*, 2016). The high sediment retention index values of vegetation classes are the result of the strong sediment retention ability of forests (Elliot *et al.*, 1999; Zhao *et al.*, 2013).

The study revealed that the sediment retention ecosystem services of PTR, a natural forest, using the InVEST model and mapping its spatial distribution patterns are important for examining the current distribution and associated ecosystem services assessment (Redhead *et al.*, 2016). This model enables to identify areas of high sediment retention in the PTR, concentrated efforts can also be made by the park management in sustaining such areas and also improve upon areas facing large sediment export and soil loss. Quantifying spatial variations of sediment retention and measuring the volume of soil loss are of great importance to the conservation prioritization of forests in the hilly region (Bai *et al.*, 2013). This research methodology model is a basic guideline for land use planners, park managers, or policymakers to evaluate the different vegetation classification for speciûc sediment retention ecosys-

Table.3. River wise sediment retention ratio of PTR

Sl. No	River name	Sediment export (%)	Sediment retention (%)	Soil loss (%)
1	Periyar	60.85	55.45	57.85
2	Pamba	39.15	44.55	42.15

Table 4. Sediment retention service indicators values for PTR

WS Id	River name	Sediment export (tonnes/year)	Sediment retention (tonnes/year)	Soil loss (tonnes/year)	Export/area km^2/year)	Retention/area (tonnes/(tonnes/km^2/year)	Soil loss/area (tonnes/km^2/year)
1	Periyar	3839.33	225152.35	32777.15	26.55	3081.9	246.57
2	Periyar	3033.17	436014.09	35924.83	23.98	4425.69	209.83
3	Periyar	8593.81	997407.02	79797.15	62.92	5530.8	569.96
4	Periyar	9036.92	323865.73	60143.86	143.18	5131.4	952.93
5	Pamba	2488.42	141044.17	21257.5	21.36	3069.88	252.94
6	Pamba	1855.9	163143.49	16812.12	8.43	4081.97	108.58
7	Pamba	10517.84	953555.81	103788.03	65.26	5916.34	643.95
8	Pamba	556.04	269273.39	7162.49	96.51	5470	824.41
9	Pamba	351.23	64807.86	3072.69	448.19	3081.9	3809.17
	Total	40272.66	3574263.91	360735.81	26.55	36707.97	246.57

tem services (Srichaichana *et al.*, 2019).

Conclusion

The quantification and mapping of sediment retention ecosystem services are of great importance to PA management and conservation planning. We assessed the provision of retention services for each vegetation classes and sub basin configuration, then, compared the results to identify spatial distribution and quantification of ecosystem services of PTR. InVEST ecosystem service model is a potential tool to provide crucial decision and policy making for tiger reserve management.

Our study, coupled with assessments of vegetation with ecosystem services in the mountain landscape of a tiger reserve, can provide the basis for a more informed and conscientious decision making and also better PA management and conservation planning.

The study enables sharing of information to the general public and the policymakers, major evidence to state the positive impacts of a tiger reserve on human wellbeing and it also leads to a useful initial exploration into the research of ecosystem services at a regional scale in a mountain landscape of Southern Western Ghats of India.

Ethical Statement

Compliance with Ethical Standards: I confirm that the research paper is complied with all the Ethical standards prescribed by the Journal Ecology, Environment and Conservation

Funding: There is no external funding for this research

Conflict of Interest: On behalf of all authors, the corresponding author stating that there is no conflict of interest.

Ethical Approval: I confirm that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere.

Informed Consent: I confirm the consent to submit the research paper in the Journal Ecology, Environment and Conservation

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