Analysis of changes in soil erosion under climate change in Fiji

FAO Investment Centre

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Contents

1 Introduction

The Food and Agriculture Organization of the United Nations (FAO) is currently designing a forest landscape restoration (FLR) project for Fiji. The project is expected to benefit upland farmers and land stewards in Fiji through forest ecosystem restoration and climate-smart farming. At the same time, the World Wildlife Fund (WWF) is also working on a reef conservation project in the country.

It is well-known that sedimentation and polluted runoffs are one of the main threats to coral ecosystem[1]. Hence, it is important to assess whether FAO's upland work would harm or benefit WWF's project in the coastal areas. In this analysis, erosion risks across the landscape of Fiji is assessed given the climate trends and land cover types.

A commonly used empirical model for erosion is used in the analysis, namely the RUSLE or the Revised Universal Soil Loss Equation (Borrelli et al., 2021[2]). While RUSLE does not take into account the physical processes of erosion to coastal areas (sedimentation, runoffs, transfers, etc.), it can provide an estimate of soil loss (Igwe et al., 2017[3]) based on the landscape features. Any changes in soil loss would translate into changes in sedimentation and runoff.

Our analysis focused in the two main islands of Fiji: Viti Levu and Vanua Levu (Figure 1). These are the locations where both projects would take place, and should provide a good representation of climates and soil types in Fiji. Changes in soil erosion rates was examined for the major hydrological basins under current and future climates.

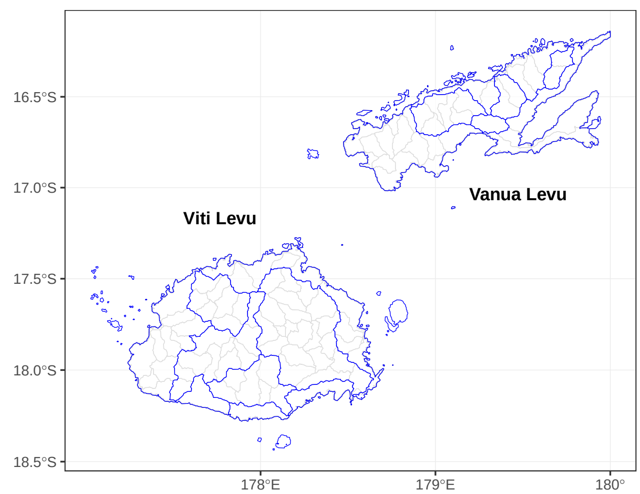

Figure 1: Fiji's main islands and the major hydrological basins

2 Findings

2.1 Overall summary

The RUSLE methodology was used to calculate average soil loss by water in Fiji. The results show that soil erosion rates is relatively higher in the provinces of Ba, Ra, and Nadroga (Viti Levu) and the provinces of Bua and Macuata (Vanua Levu) (Figure 2). Inspection of the RUSLE parameters revealed that erosion rates in Viti Levu are driven mainly by climate and topography, whereas the land cover type, especially croplands, contributed the most to the erosion rates in Vanua Levu.

[1] https://coral.org/en/coral-reefs-101/direct-threats/

[2] https://www.sciencedirect.com/science/article/pii/S004896972101562X

[3] https://dx.doi.org/10.22161/ijaers.4.12.22

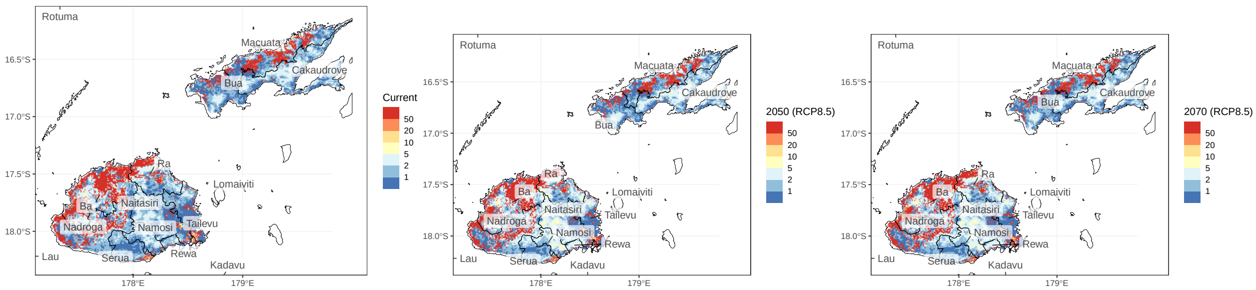

Figure 2: Average soil loss in t/ha/year

Examination of the values by districts (Figure 3) and by major basins (Figure 4) further emphasize this spatial trends in erosion risks. It also confirms that Viti Levu has higher rates compared to Vanua Levu. Soil loss by water is in general higher in Fiji with rates by pixel (10 x 10 meter) ranging from 0 to 21,505 t/ha/year (maximum found in Viti Levu). The average by districts or major basins vary from 3.9 to 137.4 t/ha/year. Our calculation is in line with similar studies conducted in the Pacific (Ram and Terry, 2014[4] both in terms of the range and the average values. Thammadi and Pisini (2022[5]), for example, estimated the average rates around the Rewa river at 4,400 t/ha/yr.

Under RCP 8.5, the two islands show different trends in terms of the average rates. In Viti Levu, a decrease is expected where the current rates are high and an increase for the rest. Whereas in Vanua Levu, the rates are expected increase across the island. A significant decrease of up to 8% by 2050 and up to 16% by 2070 is expected in the provinces of Ba, Ra, and Nadroga. However, their average rates will remain highest in the country. On the other hand, the rest of the country will see an increase of up to 60% in the average rates. The southeastern provinces of Viti Levu will experience the most significant increase.

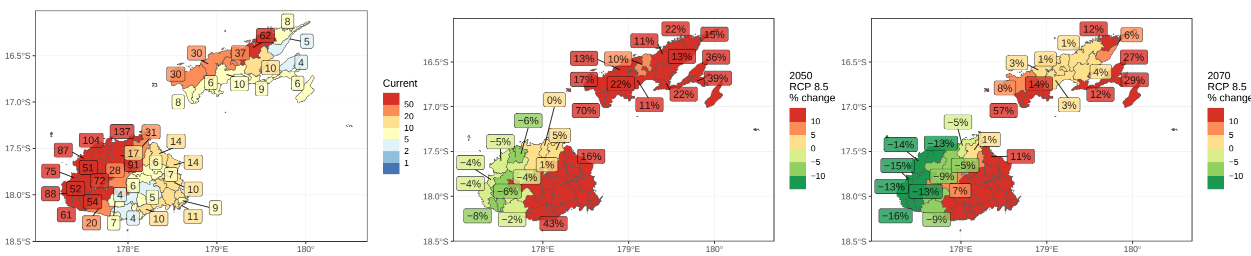

Figure 3: Average soil loss by districts in t/ha/year

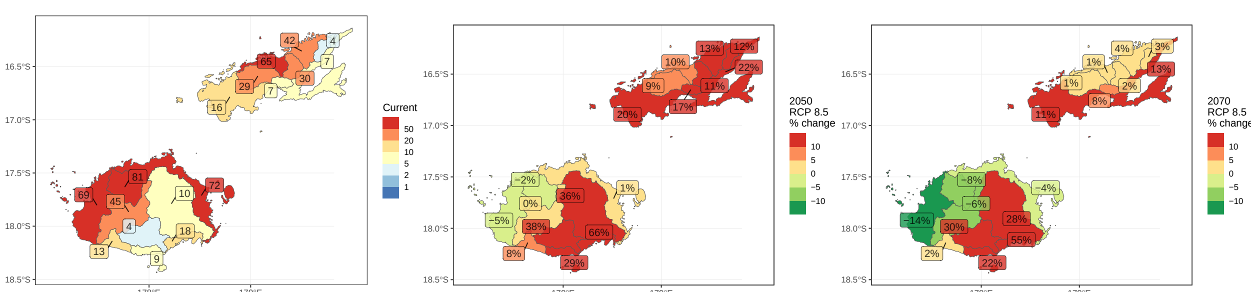

Figure 4: Average soil loss by major basins in t/ha/year

[4]https://www.researchgate.net/profile/Arishma-Ram/publication/280712383_Land_use_and_erosion_risk_in_small_forest_catchments_on_the_Coral_Coast_of_Fiji_baseline_estimates_of_sediment_inputs_to_coastal_lagoons/links/55c1e6b908aed9dff2a5bc8f/Land-use-and-erosion-risk-in-small-forest-catchments-on-the-Coral-Coast-of-Fiji-baseline-estimates-of-sediment-inputs-to-coastal-lagoons.pdf

[5]https://iopscience.iop.org/article/10.1088/1755-1315/1084/1/012050/pdf

Table 1: Soil erosion rates by land cover type (t/ha/year)

Land cover	Viti Levu	Vanua Levu
Cropland / Agriculture	195.52	151.25
Grassland	94.47	48.23
Shrubland	73.28	39.33
Trees	1.66	1.49

2.2 Inspection of the erosion rates within the country

Using data from the World Database of Protected areas[6], we investigated the erosion rates for the terrestrial protected areas within the country (Figure 5, $left$). The rates are relatively lower in general compared to the rest of the country, except for Draunibota and Labiko, Qaranibuluti Nature Reserve, and Koroyanitu Heritage Park.

The data further reveals that the erosion rates are highly correlated with the tree cover (Figure 5, $right$). The water dams appears to be outliers because of the low tree cover due the water extent within these protected areas. Analysis of the soil erosion rates by land cover type further confirm this correlation (Table 1). Cropland areas have the highest rates with values more than twice the rates of the other land covers.

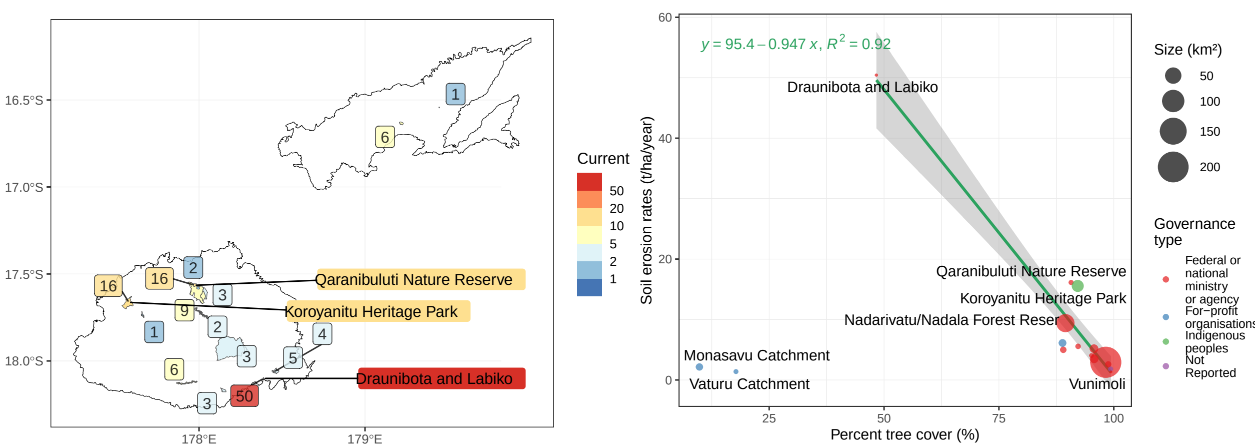

Figure 5: Soil erosion rates within protected areas

We further investigated the rates in the upstream areas of the croplands within each major basin and each district (Figure 6). The risks to the croplands are highest in Ba river basin with the average rates amounting up to 64 t/ha/year. This high erosion rates could translate into both damages to croplands and polluted runoffs to the coastal areas. The following district are where the risks to the croplands are highest: Ba, Magodro, Nawaka, Tavua, Vuda, Malomalo, Nasigatoka, Navosa, Ruwailevu, Rakiraki, Saivou, and Labasa (Figure 7).

2.3 Project scenarios

The project is a forest landscape restoration and will mainly take place in non-forest areas by planting trees on croplands, grasslands, or shrublands. In our scenario analysis, we investigated how the erosion rates will change if the project takes place only on the cropland basins. Here, the aim is to reduce erosion damages to croplands and the polluted sedimentation to coastal and reef areas. We assume that the project will increase the average annual NDVI by 10% by 2050 and by 20% by 2070 on the following land cover types upstream of croplands: croplands, grasslands, and shrublands.

[6] https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA

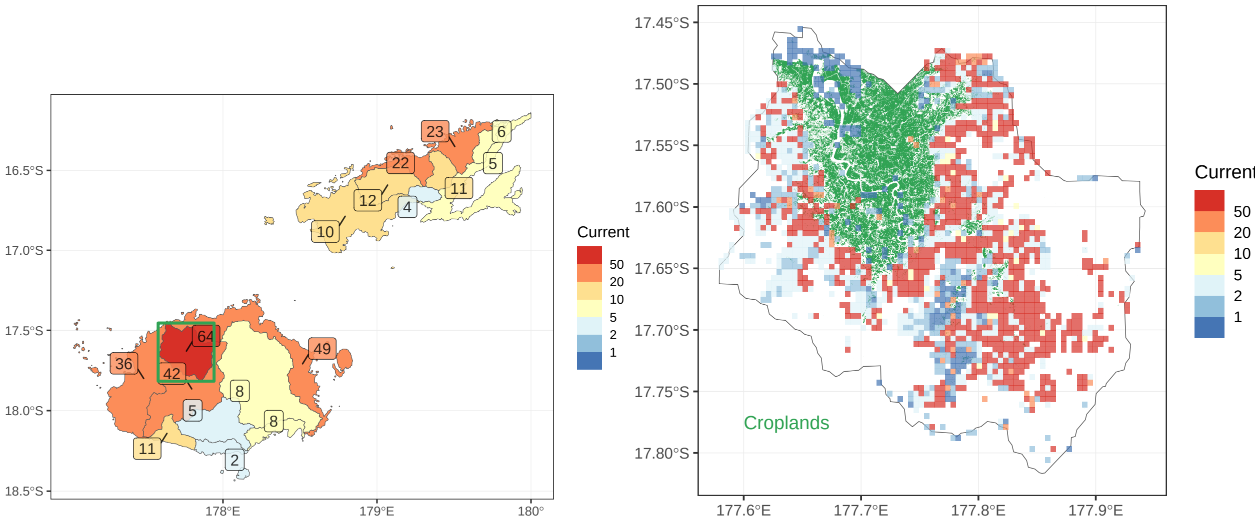

Figure 6: Average soil loss in cropland basins in t/ha/year

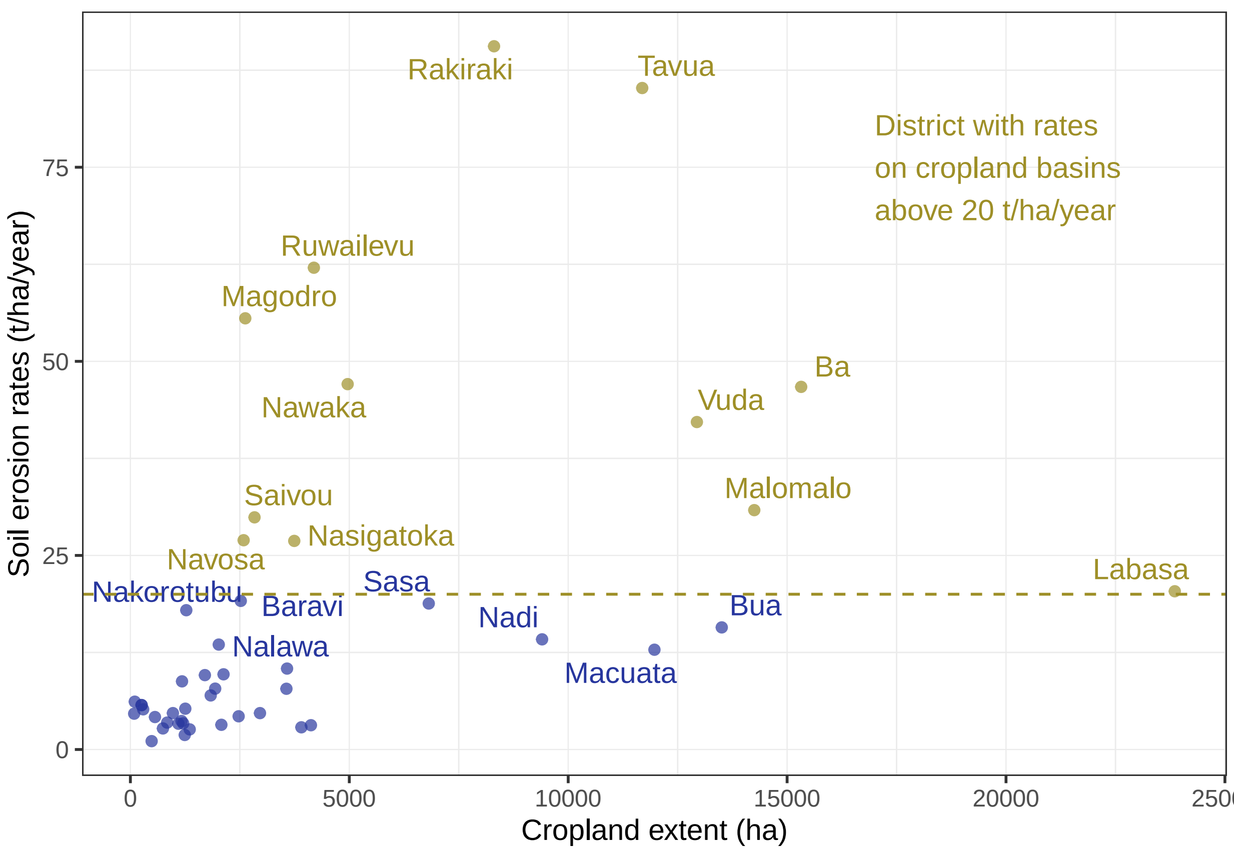

Figure 7: Average soil loss in cropland basins in t/ha/year - by district

Under this scenario, the rates are projected to significantly decrease if the project contribute to NDVI increase on croplands, grasslands, and bare lands (Figure 8, 9, and 10). Up to 14 t/ha/year could be saved with a 10% increase in NDVI and up to 28 t/ha/year with a 10% increase. It is important to note though that the potential effects of land preparation on erosion rates were not studied. It is recommended that the project put in place support practices that will reduce soil erodibility during the land preparation activities. Support practices should mitigate the potential negative effects of the project in its first years of implementation, especially in Viti Levu.

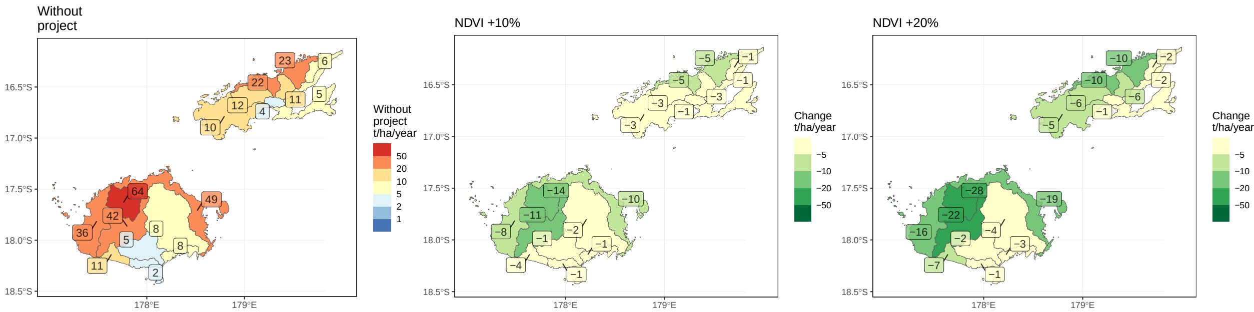

Figure 8: Change in erosion risks on croplands - with the project (Current)

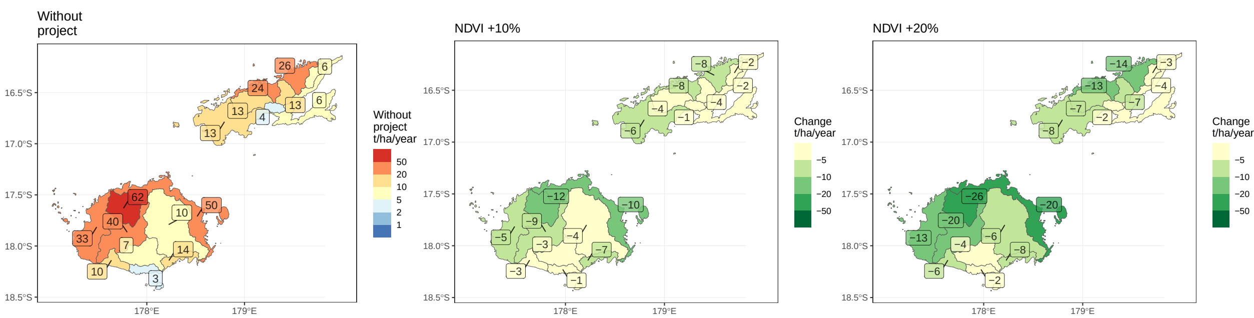

Figure 9: Change in erosion risks on croplands by 2050 - with the project (RCP 8.5)

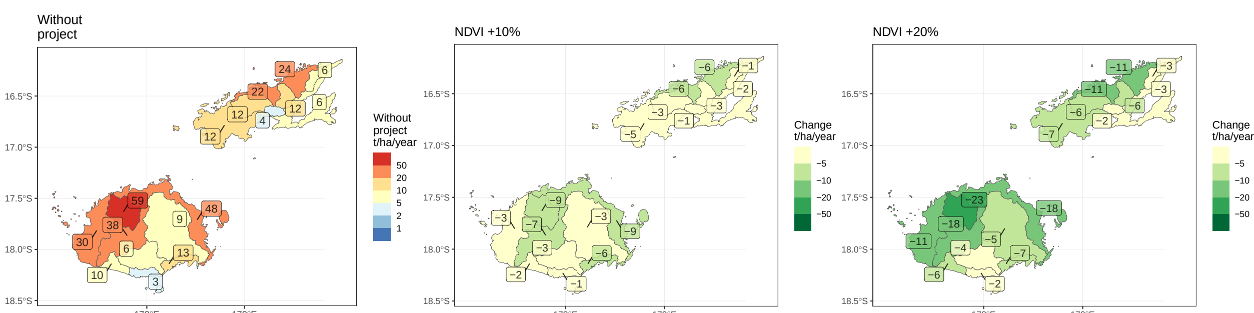

Figure 10: Change in erosion risks on croplands by 2070 - with the project (RCP 8.5)

3 Approach

The RUSLE is an erosion model for predicting average annual soil loss (A) resulting from raindrop splash and runoff (Reynard et al., 1997[7]). The model takes into account several factors, namely the rainfall erosivity (R), the soil erodibility (K), the slope length and steepness (LS), the cover management (C), and the

[7] https://www.ars.usda.gov/arsuserfiles/64080530/rusle/ah_703.pdf

support practice (P). The average annual erosion can be computed using Equation (3) and is given in $t/ha/year$.

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

Data processing and calculations were done in R, ArcGIS and Google Earth Engine depending on the data type.

3.1 Rainfall Erosivity Factor

The R factor describes the power of rainfall to cause soil erosion. It can be calculated based on the intensity and the duration of a rainstorm (Reynard et al., 1997; Nearing, 2017[8]). The annual average can be calculated as the average of the product of the total rainstorm energy (E) and the maximum 30-min intensity (I_{30}) for all the rainstorm n during the year (See Equation (3.1)). Given its importance in soil erosion assessment, a Global Rainfall Erosivity Database or GloREDa has already been developed by Panagos et al (2017) at 1-km spatial resolution.

$$R = \frac{\sum E \cdot I_{30}}{n}$$

The GloREDa data is made available by the European Soil Data Centre (ESDAC)[9] and we used it for our calculation. In addition, ESDAC also provides data on future R factor values data under climate change (Future Global Rainfall Erosivity in 2050 and 2070[10]), as calculated by Panagos et al. (2022[11]).

Overall, the current rainfall erosivity is among the highest in the world. The values are relatively higher in the western parts of the country's main islands (Figure 11). On the other hand, the southeastern part of Viti Levu has the lowest R factor. Under RCP8.5, the rainfall erosivity is expected to increase significantly in the central areas in 2050 but then stabilizing between 15,000 to 20,000 MJ mm/h/ha/year in 2070.

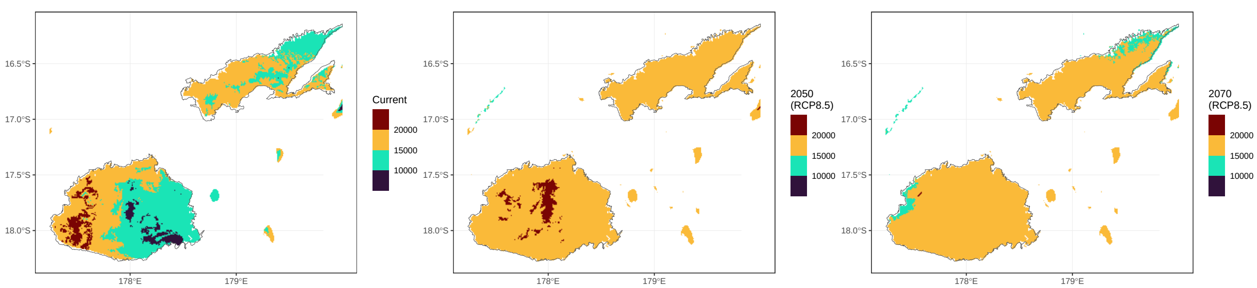

Figure 11: Average rainfall erosivity in MJ·mm/h/ha/year

3.2 Soil Erodibility Factor

The soil erodibility factor measures the inherent erodibility of a particular soil, i.e., it quantifies the susceptibility of soil particles to detachment and transport by rainfall and runoff. The calculation of the K factor depends on soil contents, structure, and permeability. Reynard et al. (1997) suggested a formula Equation (3.2) for computing the soil erodibility factor per unit of rainfall erosivity.

[8] https://www.sciencedirect.com/science/article/abs/pii/S0341816217301960
[9] https://esdac.jrc.ec.europa.eu/themes/global-rainfall-erosivity
[10] https://esdac.jrc.ec.europa.eu/themes/future-global-rainfall-erosivity-2050-and-2070
[11] https://www.sciencedirect.com/science/article/pii/S0022169422004401

Table 2: Conversion of drainage classes into structure and permeability values

Drainage class	Structure (s)	Permeability (p)
Very poorly-drained	4	7
Poorly-drained	4	6
Imperfectly or somewhat poorly-drained	3	5
Moderately well-drained	3	4
Well-drained	3	3
Somewhat excessively-drained	2	2
Excessively-drained	1	1

$$K = \frac{1}{7.59} \cdot \frac{[2.1 \cdot 10^{-4}\,(12 - OM)\,M^{1.14} + 3.25(s-2) + 2.5(p-3)]}{100}$$

where

$$M = (\%_{very\ fine\ sand} + \%_{silt}) \cdot (100 - \%_{clay})$$

In Equation (3.2), OM is the organic matter content (%), M the textural factor, s the structure class, and p the permeability class. M can be estimated in several ways based on the soil texture (Reynard et al., 1997; ESDAC[12]; PNNL[13]). Overall, the K factor is more dependent on the physical properties of the soil than on climates. Its values can change depending on the granularity[14], the presence of organic matter, etc.

In this analysis, the dominant soil values from the Harmonized World Soil Database verision 2 (HWSD2) was used to calculated the K factor in Fiji. HWSD2 already have data on OM, $\%_{silt}$, and $\%_{clay}$. The fraction of very fine sand is assumed to be 20% of the fraction of sands[15]. For the structure (s) and the permeability (p) class, their values (see Table 2) were approximated using the drainage class available in HWSD2 and following the information in the USDA Soil Survey Manual[16], ESDAC[17], and the Minnesota Stormwater Manual[18].

The estimated K factor across Fiji, at 1-km grid, is shown in Figure 12. Overall, the soil erodibility uniformly varies from 0.03 to 0.035. The southeastern soils of Viti Levu have the highest erodibility. The estimated values are slightly higher but preferred to the coarse ESDAC data (at 25 km spatial resolution). And in terms of climate scenarios, it is assumed that the soil erodibility will remain unchanged under climate change.

3.3 Slope length and Steepness factors

The slope length (L) and steepness (S) factors or combined as the topographic factor (LS) measures the effects of topography on soil erosion by water. Both an increase in soil length and steepness would increase the erosion rates. Moore & Burch (1986[19]) proposed a GIS-based approach for calculating LS using digital elevation models (DEM).

Their estimation was based on the below equation (3.3) which account for the hydrological processes that affect runoff and erosion. In addition, we also included the slope limit of 50% (26.6 degrees) suggested by Panagos et al. (2015[20]). And in similar to soil erodibility, it is assumed that the topographica factor will

[12] https://esdac.jrc.ec.europa.eu/themes/soil-erodibility-europe
[13] https://mepas.pnnl.gov/mepas/formulations/source_term/5_0/5_32/5_32.html
[14] https://hal.science/hal-01602205/
[15] https://www.researchgate.net/publication/258844532_Genesis_of_textural_contrasts_in_subsurface_soil_horizons_in_the_Northern_Pantanal-Brazil
[16] https://naldc.nal.usda.gov/catalog/CAT87208319
[17] https://esdac.jrc.ec.europa.eu/themes/soil-erodibility-europe
[18] https://stormwater.pca.state.mn.us/index.php?title=Soil_erodibility
[19] https://acsess.onlinelibrary.wiley.com/doi/abs/10.2136/sssaj1986.03615995005000050042x
[20] https://www.mdpi.com/2076-3263/5/2/117

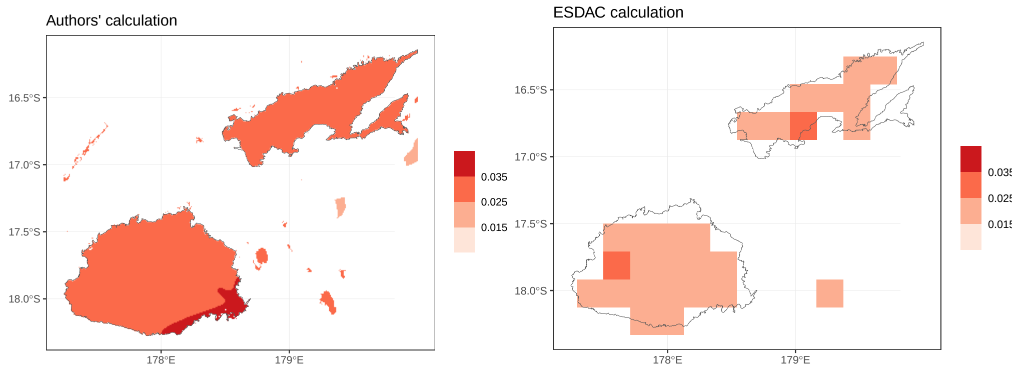

Figure 12: Soil erodibility in t·ha·h/(ha·MJ·mm)

remain unchanged under climate change.

$$LS = (\frac{Acc \cdot D}{22.13})^{0.4} \cdot (\frac{sin\theta}{0.0896})^{1.3}$$

where: Acc is the flow accumulation, D the grid cell size, and θ is the slope angle.

The LS factor for Fiji is shown in Figure 13. The values were computed using SRTM DEM at 30 meter resolution.

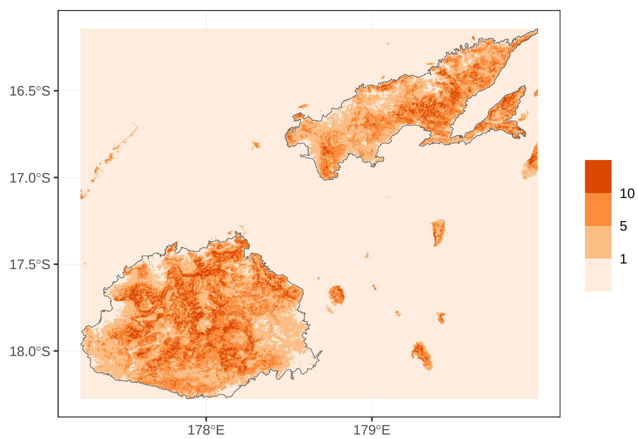

Figure 13: Topopgrahic factor

3.4 Cover-Management factor

The C factor represents the effect of cropping and management practices on erosion rates. Hence, it is the most used to compare the relative impacts of management options of conservation plans. The C factor can be estimated based on the land cover information. Several approaches exist for calculating the C factor (Phinzi & Ngetar, 2019[21]), but opted for the one proposed by Panagos et al. (2015[22]) because it combines both land cover and NDVI information.

In their analysis, Panagos et al. (2015) provided the C factor values per land cover type and the formula to adjust for the vegetation cover. We modified this approach to use the Normalized Difference Vegetation

[21] https://www.sciencedirect.com/science/article/pii/S2095633918300583#bib47
[22] https://www.sciencedirect.com/science/article/pii/S0264837715001611

Table 3: Default C factor values per land cover type in USP land cover

USP Land Cover - values	USP Land Cover - classes	C min	C range
1	Water	0.0000	0.0000
2	Mangroves	0.0000	0.0000
3	Bare soil / Rock	0.0000	0.0000
4	Urban / Impervious	0.0000	0.0000
5	Cropland / Agriculture	0.1500	0.3500
6	Grassland	0.0100	0.0900
7	Shrubland	0.0030	0.0970
8	Trees	0.0001	0.0029

Index (NDVI) as proxy for vegetation cover instead. Li et al. (2010[23]) has already proposed that min-max normalization of NDVI values is a good proxy for identify dense vs poorly vegetated areas. After investigation NDVI values from the 16-day MODIS Terra product in Fiji, we determined that the maximum average NDVI for the period 2017-2022 (past 5 years) is 0.94.

Hence, the cover-management equation is given in Equation (3.4), where $C_{land\ cover}$ are the C values by land cover proposed by Panagos et al. (2015) and summarized in Table 3. The C factor will reach its maximum value when NDVI is smallest (or 0), and with full vegetation cover (highest NDVI), the C values will be minimal.

$$C = Min(C_{land\ cover}) + Range(C_{land\ cover}) \cdot (1 - \frac{NDVI}{0.94})$$

In this study, the Fiji land covers[24] produced by the University of the South Pacific was used to extract the landcover classes. As of August 2023, the dataset had annual land cover for the years 2019 to 2022. We used the most recent land cover from the year 2022. The dataset is considered adequate as its approach was specifically design for Fiji[25].

The C factor values are summarized in Table 3 and the calculated values across Fiji are shown in Figure 14. With the project, these C factor values are projected to improve given both the increase in vegetation cover and the projected shift in land cover classes. Per Panagos et al. (2015), soil conservation practices such as crop cover, no-tillage, and crop residues can reduce erosion rates ranging from 10% to 75%.

3.5 Support practice factor

The P factor accounts for control practices (contour farming, strip cropping, terracing, etc.) on soil loss, as those practices affect water erosion by modifying the flow pattern, grade, or direction of surface runoff and by reducing the volume and rate of runoff. Generally, the presence of support practices reduce erosion and runoff.

Approaches for computing the P factor and the default values are available from the literature (Phinzi & Ngetar (2019) and Wenner (1980[26] for reference on a few commonly used approach). Because of the ex-ante nature of this analysis, we assumed the support practice to be constant at 1 for the without project scenario. On the other hand, based on information on the ground, project sites are expected to have reduced P factors, ranging from 0.2 to 0.6 per Ebabu et al. (2022)[27].

[23] https://link.springer.com/article/10.1007/s12583-010-0147-4
[24] https://pacificdata.org/data/organization/livelihoods-and-landscapes-project
[25] https://pacificdata.org/data/dataset/agu-lulc
[26] https://edepot.wur.nl/480199
[27] https://www.sciencedirect.com/science/article/pii/S2095633921001039

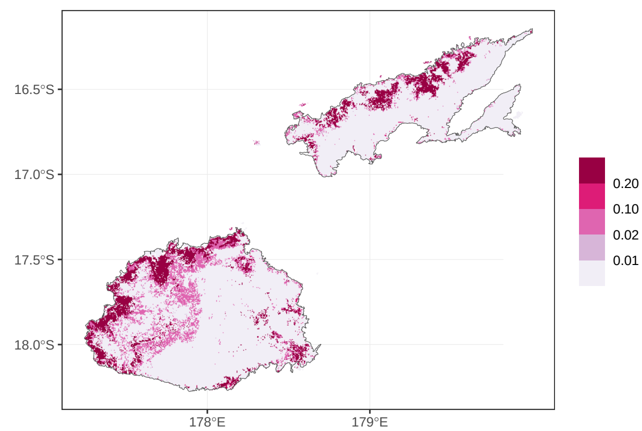

Figure 14: Cover-management factor