Overview of Ecosystem Service: Landslide Regulation

Abstract

This study develops the first global methodology to quantify landslide regulation as an ecosystem service, focusing on avoided human mortality. Using a coupled modeling approach that integrates sediment export modeling, historical landslide data, and population exposure assessment, we estimate the economic value of landslide prevention provided by natural forest vegetation. Our framework links land use decisions to mortality impacts through the InVEST Sediment Delivery Ratio model and empirical mortality functions derived from the Emergency Events Database.

## 1 Description

Landslide regulation represents a critical regulating ecosystem service provided by forests through slope stabilization and erosion control. Forests reduce landslide risk through multiple mechanisms: root systems bind soil particles together, canopy cover reduces surface erosion from precipitation, and vegetation slows water infiltration rates. This ecosystem service is particularly valuable in mountainous and hilly regions where human populations are exposed to landslide hazards.

Our framework centers on estimating the human death toll from landslides to assign a monetary value to landslide prevention provided by natural vegetation. We recognize other benefits of landslide regulation that have measurable value, such as reduced infrastructure damage or prevented agricultural losses, but focus on deaths because they represent the most significant cost of landslide hazards. Our analysis quantifies this service specifically in terms of avoided landslide mortality, measuring how forest cover prevents human fatalities that would otherwise occur due to landslide events.

## 2 Methods

Building on the methodology outlined in (Brander et al. 2018), we develop a three-step modeling approach to estimate how changes in land use affect human health through changes in landslide risk. The approach couples models of sediment export, landslide occurrence, and mortality outcomes to link land use decisions to mortality impacts. The framework consists of three linked components: the InVEST Sediment Delivery Ratio (SDR) model, which estimates how changes in land use affect sediment export and erosion processes; a mortality function that relates sediment export to historical landslide deaths; and an approach to estimating health impacts that quantifies how changes in landslide risk affect population exposure and mortality.

### 2.1 Data Sources and Variables

| Data | Source | Variable Description |
| --- | --- | --- |
| LULC | ESA-CCI (ESA 2017) | Land use/land cover including forest extent |
| Population | WorldPop (WorldPop 2020) | Gridded population data accounting for human exposure |
| Landslide Mortality | EM-DAT - The international disaster database (Delforge et al. 2025) | Annual records of landslide-related fatalities |
| Admin 2 Borders | FAO GAUL 2015 (FAO 2015) | Administrative boundaries linked to EM-DAT |
| Precipitation | ERA5 (Hersbach et al. 2023) | Annual precipitation data for weather variation |
| Value of Statistical Life (VSL) | USDOT (U.S. Department of Transportation, Office of the Secretary 2025) | GDP-adjusted VSL for economic valuation |
| SDR inputs | NatCap TEEMs | Basins, elevation, soil data for sediment export modeling |

### 2.2 Sediment Export Modeling

We used the InVEST Sediment Delivery Ratio (SDR) model to estimate sediment export, which serves as a proxy for landslide risk. The SDR model is a spatially explicit tool that maps soil erosion and sediment delivery to streams based on the Revised Universal Soil Loss Equation (RUSLE) framework. The model operates in two main steps:

**Step 1: Soil Erosion Estimation**  
We estimated soil loss on each pixel using the RUSLE equation:

Where:

* : Slope length and steepness factor, derived from digital elevation model (DEM)
* : Rainfall erosivity factor, representing the erosive power of precipitation
* : Soil erodibility factor, indicating the susceptibility of soil particles to detachment
* : Vegetation cover factor, reflecting the protective effect of vegetation
* : Conservation practices factor, accounting for erosion control measures

**Step 2: Sediment Delivery Ratio Calculation**  
For each pixel, we calculated how much eroded sediment actually reaches streams using the Sediment Delivery Ratio (SDR):

The SDR is calculated based on land cover characteristics and the degree of hydrological connectivity between upslope areas and streams. Areas with dense vegetation have lower SDR values due to their capacity to trap sediment, while areas with sparse vegetation or high connectivity have higher SDR values.

**Input Data Requirements:**

* Digital elevation model (DEM)
* Rainfall erosivity raster derived from precipitation data
* Soil erodibility raster from soil surveys
* Land use/land cover raster classification
* Watersheds shapefile for hydrological routing
* Biophysical table assigning C and P factor values to different land use classes

### 2.3 Mortality Function Development

We developed an empirical relationship between sediment export and landslide mortality using historical data. The mortality function links sediment export rates (as estimated by the SDR model) to observed landslide deaths, allowing us to predict mortality risk under different land use scenarios.

**Historical Landslide Death Data**: We compiled historical landslide mortality data from the Emergency Events Database (EM-DAT), which provides comprehensive records of natural disasters and their impacts. The database includes information on landslide events, casualties, and affected populations at national and subnational scales.

**Population Exposure Assessment**: We used gridded population data from the WorldPop dataset to estimate population exposure to landslide risk. The WorldPop dataset provides population counts at high spatial resolution (approximately 1 km at the equator) for 2000-2020.

**Precipitation Assessment**: We used gridded monthly precipitation data from the Copernicus Climate Change Service’s ERA5 dataset to control for the impact of precipitation on landslide risk. The ERA5 dataset provides monthly averaged precipitation levels at a resolution of 0.25 degrees for 2000-2020.

### 2.4 Analytical Approach

We construct a historic panel dataset at the administrative-2 level combining mortality data from EM-DAT with sediment export estimates from InVEST’s SDR model, which incorporates forest cover effects. The analysis accounts for population exposure using WorldPop data and weather variability through ERA5 precipitation records.

From this integrated dataset, we estimate a mortality function using:

where:

* = count of landslide-related mortalities in region at time
* = natural log of sediment export sum
* = natural log of total population
* = natural log of total precipitation
* = year fixed effects
* = error term

Each observation represents an administrative-2 region in year . The function is estimated using a generalised Poisson loglinear model since the dependent variable is count data; sediment export is treated as the primary predictor while controlling for population density and precipitation patterns that influence landslide susceptibility.

### 2.5 Estimating Avoided Mortality

To measure the economic value of avoided landslide deaths, we estimate the mortality function parameters for 2000-2020. For 2019, the year of interest, we use those coefficients to estimate the predicted mortality using two scenarios:

1. SDR values based on observed LULC maps, and
2. SDR values based on LULC maps where the sediment retention properties of forest have been reduced to zero.
   * Specifically, the C factor in the SDR model is set reduced to the same level as urban

This allows for a comparison between predicted mortality under observed conditions and predicted mortality under counterfactual conditions. The difference represents avoided mortality due to forest cover.

### 2.6 Valuation Method

To estimate the economic value of landslide regulation, we employ a GDP-adjusted Value of Statistical Life (VSL) approach. Country adjusted VSL amounts are estimated for each country based on the total avoided mortality estimates, aligning with other VSL calculations used in GEP estimates. Using the estimated coefficients from the mortality function, we calculate avoided mortality by comparing predicted mortality under a counterfactual scenario (without forest cover) to the observed scenario (with current forest cover). The difference in mortality is then valued using country-specific VSL estimates.

## 3 Validation

in progress…

## 4 Results

### 4.1 Tables

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| Table 1: Results by Country 2019   | Country (ee\_r264\_name) | Avoided Mortality | Avoided Mortality Value USD | | --- | --- | --- | | Aruba | 0 | 0 | | Afghanistan | 0.525081 | 43574 | | Angola | 3.20196 | 1.17172e+06 | | Aland | 0.11542 | 932706 | | Albania | 0.333534 | 304340 | | Andorra | 0.0307292 | 211861 | | United Arab Emirates | 0.000439683 | 3251.32 | | Argentina | 1.56277 | 2.6e+06 | | Armenia | 0.195466 | 150162 | | American Samoa | 0 | 0 | | Antigua and Barbuda | 0.00512097 | 16170.5 | | Australia | 1.99995 | 1.83721e+07 | | Austria | 1.06663 | 8.89172e+06 | | Azerbaijan | 0.445581 | 357834 | | Burundi | 0.245398 | 8621.27 | | Belgium | 0.0631062 | 492648 | | Benin | 0.325365 | 61483.3 | | Burkina Faso | 0.154676 | 19769.4 | | Bangladesh | 0.393297 | 139975 | | Bulgaria | 0.574171 | 995246 | | Bahrain | 0.00181847 | 8283.65 | | Bahamas | 0 | 0 | | Bosnia and Herzegovina | 0.520271 | 532282 | | Belarus | 0.103114 | 117821 | | Belize | 0.113344 | 117243 | | Bermuda | 0 | 0 | | Bolivia | 2.64399 | 1.54812e+06 | | Brazil | 17.4416 | 2.63183e+07 | | Barbados | 0 | 0 | | Brunei | 0.046706 | 237475 | | Bhutan | 1.14144 | 682261 | | Bouvet Island | 0.62172 | 7.94063e+06 | | Botswana | 0.0525511 | 62982.6 | | Central African Republic | 1.14427 | 85899 | | Canada | 2.82523 | 2.18838e+07 | | Cocos Islands | 1.99995 | 1.83721e+07 | | Switzerland | 0.696956 | 9.79732e+06 | | Chile | 1.3104 | 3.17421e+06 | | China | 60.4321 | 1.04449e+08 | | Cote d’lvoire | 0.734741 | 262966 | | Cameroon | 2.91016 | 756316 | | Democratic Republic of the Congo | 7.54294 | 702139 | | Republic of the Congo | 0.651979 | 271113 | | Colombia | 12.6574 | 1.36903e+07 | | Comoros | 0 | 0 | | Cabo Verde | 0.0154509 | 11310.9 | | Costa Rica | 1.56091 | 3.36081e+06 | | Cuba | 0.785711 | 1.21217e+06 | | Christmas Island | 1.99995 | 1.83721e+07 | | Cayman Islands | 0 | 0 | | Cyprus | 0.0448995 | 222862 | | Czechia | 0.316455 | 1.27247e+06 | | Germany | 1.13034 | 8.99549e+06 | | Djibouti | 0.00114497 | 542.842 | | Dominica | 0 | 0 | | Denmark | 0.0160583 | 159408 | | Dominican Republic | 1.04135 | 1.42398e+06 | | Algeria | 0.695909 | 519640 | | Ecuador | 3.4431 | 3.57017e+06 | | Egypt | 1.47459e-05 | 7.30118 | | Eritrea | 0.20515 | 0 | | Western Sahara | 0.592764 | 347493 | | Spain | 2.67786 | 1.33291e+07 | | Estonia | 0.0228037 | 91536.5 | | Ethiopia | 6.89824 | 955285 | | Finland | 0.11542 | 932706 | | Fiji | 0.465969 | 463369 | | France | 2.03809 | 1.37621e+07 | | Faroe Islands | 0.000300964 | 3171.83 | | Micronesia | 0 | 0 | | Gabon | 0.633752 | 788050 | | United Kingdom | 0.305305 | 2.18328e+06 | | Georgia | 0.716794 | 567914 | | Ghana | 0.82193 | 300337 | | Gibraltar | 0.0465084 | 0 | | Guinea | 1.3882 | 239248 | | Guadeloupe | 2.03809 | 1.37621e+07 | | Gambia | 0.00937356 | 1156.28 | | Guinea-Bissau | 0.0867294 | 11702 | | Equatorial Guinea | 0.193569 | 220091 | | Greece | 0.589111 | 1.90345e+06 | | Grenada | 0 | 0 | | Greenland | 0 | 0 | | Guatemala | 4.07588 | 3.07315e+06 | | French Guiana | 2.03809 | 1.37621e+07 | | Guam | 0 | 0 | | Guyana | 0.212067 | 227008 | | Hong Kong | 0.00219814 | 17763.4 | | Honduras | 3.46572 | 1.44921e+06 | | Croatia | 0.282117 | 733733 | | Haiti | 0.357525 | 80785 | | Hungary | 0.106551 | 302920 | | Indonesia | 24.925 | 1.71059e+07 | | Isle of Man | 0 | 0 | | India | 27.4896 | 9.37767e+06 | | Ireland | 0.0776822 | 1.06199e+06 | | Iran | 0.952742 | 609974 | | Iraq | 0.0960419 | 91028.8 | | Iceland | 0.00710155 | 81233.2 | | Israel | 0.0392629 | 290331 | | Italy | 3.44212 | 1.94491e+07 | | Jamaica | 0.337231 | 315987 | | Jordan | 0.0046169 | 3217.3 | | Japan | 11.1311 | 7.51766e+07 | | Kazakhstan | 0.381624 | 603097 | | Kenya | 1.226 | 401632 | | Kyrgyzstan | 0.317792 | 75515.4 | | Cambodia | 1.16787 | 434398 | | Kiribati | 0 | 0 | | Saint Kitts and Nevis | 0.0602986 | 237755 | | South Korea | 2.06644 | 1.10164e+07 | | Kuwait | 0 | 0 | | Laos | 2.54306 | 1.10036e+06 | | Lebanon | 0.0866244 | 128917 | | Liberia | 0.280902 | 30894.5 | | Libya | 0.00842408 | 14025.4 | | Saint Lucia | 0.00353019 | 6957.51 | | Liechtenstein | 0.0163382 | 455695 | | Sri Lanka | 1.30191 | 888058 | | Lesotho | 0.179232 | 32408.4 | | Lithuania | 0.0486169 | 159305 | | Luxembourg | 0.114333 | 2.15315e+06 | | Latvia | 0.0487383 | 140858 | | Macao | 0 | 0 | | Morocco | 0.592764 | 347493 | | Monaco | 2.78361e-07 | 9.01229 | | Moldova | 0.0216383 | 15929.3 | | Madagascar | 4.43574 | 370486 | | Maldives | 0.0106542 | 20902.2 | | Mexico | 13.6428 | 2.36405e+07 | | Marshall Islands | 0 | 0 | | North Macedonia | 0.288171 | 323548 | | Mali | 0.291017 | 47266.7 | | Malta | 0.0183242 | 99278.9 | | Myanmar | 5.96858 | 1.42226e+06 | | Montenegro | 0.163913 | 242203 | | Mongolia | 2.49818 | 1.81493e+06 | | Northern Mariana Islands | 0 | 0 | | Mozambique | 2.64476 | 229416 | | Mauritania | 0.0128706 | 3800.55 | | Martinique | 2.03809 | 1.37621e+07 | | Mauritius | 0.000236313 | 450.308 | | Malawi | 0.735061 | 71352.6 | | Malaysia | 4.52098 | 8.25002e+06 | | Mayotte | 2.03809 | 1.37621e+07 | | Namibia | 0.0864529 | 68361.2 | | New Caledonia | 0.130651 | 729458 | | Niger | 0.0761291 | 7145.64 | | Nigeria | 4.79525 | 1.8151e+06 | | Nicaragua | 1.66479 | 544883 | | Netherlands | 0.0378608 | 338829 | | Norway | 0.62172 | 7.94063e+06 | | Nepal | 5.14212 | 1.03384e+06 | | Nauru | 0.0137939 | 24841.1 | | New Zealand | 0.601204 | 4.29781e+06 | | Oman | 0.00672236 | 21546 | | Pakistan | 2.38394 | 553903 | | Panama | 1.18304 | 3.25758e+06 | | Peru | 5.92022 | 6.96175e+06 | | Philippines | 5.85123 | 3.32521e+06 | | Palau | 0 | 0 | | Papua New Guinea | 5.16094 | 2.22141e+06 | | Poland | 0.502996 | 1.33431e+06 | | Puerto Rico | 0.359235 | 1.9108e+06 | | North Korea | 2.33396 | 0 | | Portugal | 0.616537 | 2.405e+06 | | Paraguay | 0.540206 | 525489 | | Palestine | 0.0392629 | 290331 | | French Polynesia | 0.0232662 | 83911.6 | | Qatar | 0.0117778 | 131554 | | Reunion | 2.03809 | 1.37621e+07 | | Romania | 0.871032 | 1.89105e+06 | | Russia | 6.94758 | 1.32906e+07 | | Rwanda | 0.27303 | 36958.6 | | Saudi Arabia | 0.0255646 | 126309 | | Sudan | 0.382682 | 45401.9 | | Senegal | 0.142865 | 34167.4 | | Singapore | 0.0389337 | 429089 | | Svalbard and Jan Mayen | 0.62172 | 7.94063e+06 | | Solomon Islands | 0 | 0 | | Sierra Leone | 0.287542 | 40556.6 | | El Salvador | 0.977555 | 705715 | | San Marino | 0 | 0 | | Somalia | 0.114144 | 10298 | | Serbia | 0.538866 | 698378 | | South Sudan | 0.845903 | 0 | | Sao Tome and Principe | 0.00018664 | 60.3594 | | Suriname | 0.0990015 | 109680 | | Slovakia | 0.472067 | 1.53085e+06 | | Slovenia | 0.438155 | 1.89007e+06 | | Sweden | 0.360159 | 3.11596e+06 | | Swaziland | 0.143155 | 93610.3 | | Seychelles | 0.00345183 | 11041.3 | | Syria | 0.13846 | 25672 | | Turks and Caicos Islands | 0 | 0 | | Chad | 0.32796 | 48958.6 | | Togo | 0.336276 | 46430.8 | | Thailand | 4.97751 | 6.32621e+06 | | Tajikistan | 0.144966 | 21100.3 | | Tokelau | 0.601204 | 4.29781e+06 | | Turkmenistan | 0.00218813 | 2430.86 | | Timor-Leste | 0.276629 | 72222.5 | | Tonga | 0 | 0 | | Trinidad and Tobago | 0.0936744 | 270705 | | Tunisia | 0.0628574 | 37066.8 | | Turkey | 3.37435 | 5.19636e+06 | | Tuvalu | 0 | 0 | | Tanzania | 3.03923 | 540034 | | Uganda | 0.931888 | 128032 | | Ukraine | 0.460836 | 278761 | | Uruguay | 0.0812563 | 248699 | | United States | 17.8832 | 1.94927e+08 | | Uzbekistan | 0.097653 | 33312.2 | | Saint Vincent and the Grenadines | 0.000701766 | 1025.01 | | Venezuela | 4.54839 | 0 | | British Virgin Islands | 0 | 0 | | Virgin Islands, U.S. | 0 | 0 | | Vietnam | 6.15107 | 3.53684e+06 | | Vanuatu | 0.0825888 | 44266.3 | | Samoa | 0 | 0 | | Akrotiri and Dhekelia | 0.305305 | 2.18328e+06 | | Clipperton Island | 2.03809 | 1.37621e+07 | | Kosovo | 0.538866 | 698378 | | Paracel Islands | 60.4321 | 1.04449e+08 | | Yemen | 0.156352 | 16287.2 | | India | 27.4896 | 9.37767e+06 | | China | 60.4321 | 1.04449e+08 | | China | 60.4321 | 1.04449e+08 | | India | 27.4896 | 9.37767e+06 | | India | 27.4896 | 9.37767e+06 | | Pakistan | 2.38394 | 553903 | | India | 27.4896 | 9.37767e+06 | | China | 60.4321 | 1.04449e+08 | | India | 27.4896 | 9.37767e+06 | | South Africa | 1.71052 | 1.86759e+06 | | Zambia | 1.97253 | 414989 | | Northern Cyprus | 0.0448995 | 222862 | | Zimbabwe | 0.881238 | 247974 | |

### 4.2 Figures

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| Figure 1: Avoided Mortality 2019 — Administrative Level 2 |

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| Figure 2: Avoided Mortality 2019 — Country Level |

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| Figure 3: Economic Value of Avoided Mortality 2019 - Administrative Level 2 |

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| Figure 4: Economic Value of Avoided Mortality 2019 - Country Level |

## 5 References

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