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Regional spatial patterns of three water ecosystems services

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ABSTRACT

Water ecosystem services are benefits obtained from natural processes held by terrestrial vegetation in relation to hydrologic systems. These benefits have implications for human wellbeing through the mitigation of flood risk, management of stormwater runoff, and removal of pollutants from water systems that ultimately supply drinking and irrigation water. Assessing national and regional stocks of these important ecosystem services is crucial for the sustainable development of the land and for conservation purposes. In this study, we applied three models from the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool to map the production of flash-flood risk mitigation, stormwater retention, and nitrogen retention. Our findings were consistent with impact assessments on local communities. Through the three ecosystem services mapped, we demonstrated the role of existing terrestrial vegetation in processing hydrologic systems in the Republic of Ecuador. The results from this modeling also provided insights into potential planning pathways for future management using the InVEST software.

Introduction

Ecosystem services are recognized as the benefits people obtain from nature (Reid, et al., 2005). Some examples of ecosystem services that are associated with water processes include water purification through nutrient retention (such as nitrogen), reduced flood risk after an extreme weather event, and stormwater management through runoff retention (Reid et al., 2005). Water (or hydrological) ecosystem services that are produced through terrestrial ecosystem processing of hydrologic systems are a good measure of the current role of terrestrial vegetation in maintaining a healthy and resilient landscape (Brauman et al., 2007).

Ecosystem services offer a valuable means for people to relate to and value nature (Grizzetti et al., 2016). Living in areas with poor amounts of healthy vegetation decreases access to the production of ecosystem services, decreasing human wellbeing (Brauman, 2015). This is because ecosystem services such as water purification remove large amounts of pollutants from inland and coastal waters. The prevention of flash flooding reduces the risk of human communities to extreme rainfall. Stormwater retention reduces strain over local gray infrastructure and property damage from slow floods.

The role that nature plays in ensuring viable and healthy environments for people to live in, accentuate its importance during economic development and planning (Grizzetti et al., 2016). Numerous nations throughout the world manage their land for extraction and development purposes (Salvia et al., 2019). This is because of the increasing demand for extractive products and urbanization (Larrea, 2013; Shade, 2015). However, many of these management processes do not employ sustainable development nor conservation practices to ensure the protection of key ecosystem provisioning areas, especially those that support hydrologic systems the most.

Having current stocks of the role of terrestrial systems in providing key water ecosystem services can support land managers and policymakers in the decision-making process (Grizzetti et al., 2016). A clear understanding of the role of nature in this regard can help justify the costs associated with its preservation and restoration (Grizzetti et al., 2016). For this reason, this study maps three key ecosystem services generated through terrestrial ecosystem processing of hydrologic systems. We hold this assessment for the Republic of Ecuador in South America.

Methodology

Study site

The Republic of Ecuador is one of the smallest countries in South America. It has a total land area of 283,560 square kilometers, of which more than half is tree cover (Zanaga et al., 2021). Despite its large amount of forestland (Figure 1), Ecuador has suffered through major fluctuations in management due to changes in political power and dominant industries (Larrea, 2013; Shade, 2015). Ecuador has for three regions inland, which are known as the "oriente" or Amazonian region, the coastal region, and the "sierra" or highland region.

Few studies have assessed multiple water ecosystem services for Ecuador throughout and within its inland regions. It is no surprise that Amazonian regions of the country, which count with the largest amounts of protected land (United Nations' Environment Programme and the International Union for Conservation of Nature, 2020), generally excel in the provisioning of ecosystem services (Montoya et al., 2019), but understanding patterns associated with land within other regions of the country can also be beneficial for promoting distributive justice according to recent studies (Rodriguez Gonzalez & Torres Garrido, 2023).

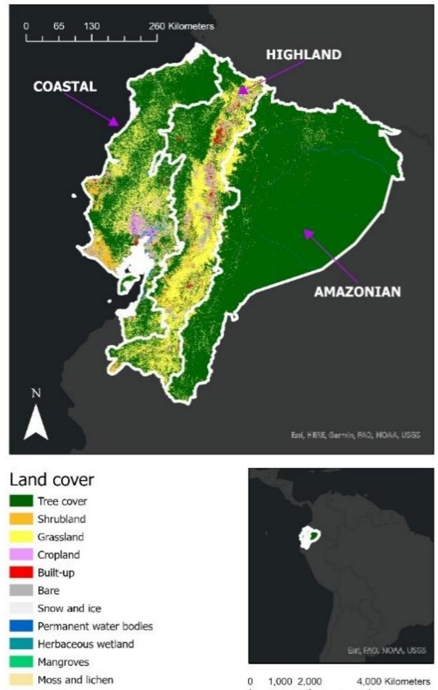

Figure 1. Study site. Map shows the Republic of Ecuador and its location relative to the rest of South America, as well as land cover distribution across its three inland regions.

InVEST modeling

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) 3.13.0 Workbench is the desktop interface for a land-cover based mapping tool that allows the user to incorporate local biophysical conditions through model parameters, with sufficient flexibility for relying on literature values when the data is not locally and readily available (Natural Capital Project, 2022). InVEST's nutrient delivery, flood risk mitigation, and stormwater retention can be used to assess patterns of water purification, flash-flood prevention, and runoff control by vegetated landscapes. These three models were used to assess terrestrial ecosystem processing of hydrologic systems in Ecuador at a 30m spatial resolution. In the following paragraphs, we provide a brief description of the process behind each of the three models, and list all data inputs used in Table 1. All spatial data was processed through ArcGIS Pro 3.0.0 (Esri, 2022). Unless specified, default model parameters were used.

The natural nutrient cycle is crucial to maintaining healthy hydrologic systems. Anthropogenic point and non-point pollutant sources increase nitrogen (N) loads coming from degraded land covers. Natural vegetation is crucial for retaining these before they enter streams. The InVEST Nutrient Delivery model represents the surface flow of N runoff downslope (according to precipitation and elevation) and the retention efficiency of the land from a starting raster pixel until reaching the stream. The latter is based on various land-cover specific biophysical characteristics such as N loading, N retention efficiency, and the distance at which a given land-cover type retains N at its maximum capacity. For these land-cover specific biophysical characteristics, we relied on InVEST suggested values (Natural Capital Project, 2022).

Vegetated land is crucial to retaining water from rainfall. In rapidly urbanizing areas, where pervious surfaces decrease quickly, runoff can accumulate and cause strain over local sewage and drainage systems while also causing damage to property. Meanwhile, in areas where extreme rainfall events are increasing due to global climate change, the risk of landslides and fatalities is constant. Whether shorter and consistent rain events over an inadequate gray infrastructure or extreme and unexpected rainfall, the presence of vegetated land can act as a buffer to damages and prevent disasters. The InVEST Stormwater Retention and the Flood Risk Mitigation models estimate the amount of precipitation retained per raster pixel according to the ability of the land cover type if falls in to do so, which varies throughout hydrologic soil groups (biophysical values for models obtained from United Stated Department of Agriculture – Natural Resources Conservation Service, 2007, and based on recommendations from the InVEST User Guide – see Natural Capital Project, 2022). The difference between both models is that the first focuses on gradual accumulation of water runoff while the second focuses on runoff from extreme unexpected rainfall.

Summary statistics (minimum, maximum, mean and standard deviation) were calculated for all model outputs at national and regional scales using ArcGIS Pro (Esri, 2022). Model outputs were also aggregated at the level-5 watershed scale for visualization. Administrative boundaries of regions were downloaded from the Humanitarian Data Exchange (v1.60.3) (https://data.humdata.org/) (United Nations' Office for the Coordination of Humanitarian Affairs – Latin America and the Caribbean, 2020), and watershed boundaries were downloaded from the *Sistema Nacional de Información* of the *Secretaría Nacional de Planificación* for the Republic of Ecuador (https://sni.gob.ec/) (Secretaría Nacional del Agua, 2011).

Table 1. Sources for geospatial data inputs used in InVEST models.

Data input	**Source**	**Applies to model?**		
		Nutrient delivery	*Flood risk mitigation*	*Stormwater retention*
Land cover	European Space Agency WorldCover product (10-meter spatial resolution) (Zanaga et al., 2021)	Yes	Yes	Yes
Digital Elevation Model	Institut de Recherche pour le Développement (Souris, 2018)	Yes	No	No
Precipitation	Huffman et al. (2019)	Yes (called nutrient runoff proxy)	No	Yes
Watersheds	Secretaría Nacional del Agua (2011)	Yes	Yes (used as area of interest)	Yes (used as area of interest)
Soil hydrologic group	United States of America National Aeronautics and Space Administration Earth Observing System Data and Information System (Ross et al., 2018)	No	Yes	Yes
Rainfall depth	World Bank (2023)	No	Yes	No

Discussion and results

Most of the Amazonian region of Ecuador excels in the provisioning of all three water ecosystem services mapped (above the national mean – see Table 2). This pattern is consistent with other national assessment of hydrologic services (Montoya et al., 2019), and comes as no surprise: the Amazonian region counts with the largest amounts of forested (Figure 1) and protected land (United Nations' Environment Programme and the International Union for Conservation of Nature, 2020) in Ecuador. However, when observed at the watershed scale (Figure 2), it better captures how southern areas of the Amazonian region of Ecuador have poor provisioning of water ecosystem services. The location of these low-provisioning areas is consistent with the highest number of people in the region affected per flood events (Bucherie et al., 2022).

Table 2. Minimum, maximum, and mean values as well as of water ecosystem service provisioning by inland regions of Ecuador. Standard deviation is also included.

Ecosystem Service	Region	Minimum	Maximum	Mean	Standard Deviation
N retention (kg of N)	*National*	0.00	2.00	0.23	0.16
	Amazonian	0.00	2.01	0.34	0.12
	Highland	0.00	1.08	0.17	0.11
	Coastal	0.00	1.33	0.07	0.07
Flood-risk mitigation (m3 of water)	*National*	2.26	208.52	85.63	26.50
	Amazonian	2.78	208.52	92.37	19.15
	Highland	2.78	208.52	80.84	28.56
	Coastal	2.78	208.51	78.40	32.09
Stormwater retention (m3 of water)	*National*	0.82	718.20	208.41	153.49
	Amazonian	9.36	718.20	339.80	102.59
	Highland	0.82	498.60	124.48	70.86
	Coastal	1.29	540.00	58.17	69.50

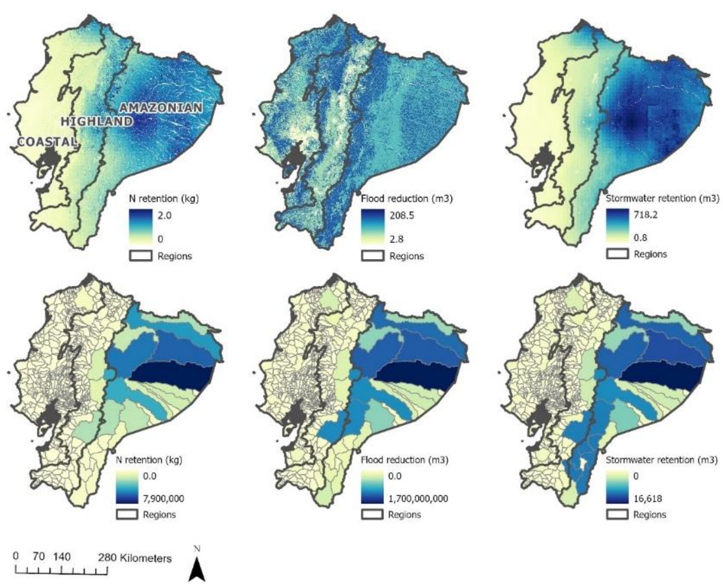

Figure 2. Water ecosystem services in Ecuador. Outputs from InVEST modeling for nitrogen retention, flood-risk mitigation, and stormwater management are shown as raster maps (top row) and aggregated into level-5 watershed polygons (bottom row). Results are visualized for the 3 subregions of inland Ecuador.

In terms of all water ecosystem services, the pattern of high provisioning for most of the Amazonian region is followed by adjoining areas of the highland region (Table 2, Figure 2). However, the highland regions as a whole, mountainous and extending north to south along the Andes Mountains, is characterized by its rugged terrain, high-altitude valleys, snow-capped peaks, and diverse ecosystems. Although it homes Ecuador's capital (urbanization index of 65%, which is lower than that of other Latin American cities – see Obaco & Díaz Sánchez, 2018), these biophysical characteristics are behind the varying provisioning ranges of water ecosystem services in the highland landscape (as it has been behind other ecological observations with pronounced variations – e.g., Jacobsen & Encalada, 1998).

Studies have documented high numbers of people impacted by historical floods in the coastal region of Ecuador (Bucherie et al., 2022), and the vegetation composition (refer to Figure 1) among other characteristics accounted for in the InVEST models demonstrate how the biophysical conditions of the region restrict provisioning of water ecosystem services (as shown in Table 2 and Figure 2). However, the flood-risk mitigation model best captured deviations from this pattern (Figure 2) and is consistent with the impact severity studies performed for the country (Bucherie et al., 2022). This could mean that the InVEST Flood Risk Mitigation model could be a viable pathway to testing different land management strategies through future scenarios (e.g., Guerry et al., 2012; Tallis & Polasky, 2009).

Conclusions

Three ecosystem services provided by terrestrial ecosystem processing of hydrologic systems were mapped for the Republic of Ecuador. Findings allowed providing management recommendations for stakeholders managing Ecuador's natural resources. For example, the congruence of the patterns observed in this study with documented floodings could imply a potential use for the InVEST software when building future scenarios to inform land management, especially if aiming to secure the wellbeing of local communities.

Author contributions

MIRG wrote the initial draft of the manuscript, while KGTG edited it. MIRG ran the InVEST models, while KGTG summarized and aggregated the data.

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Conflict of interest

The authors declare no conflict of interest.

Abbreviations

InVEST – Integrated Valuation of Ecosystem Services and Tradeoffs

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