Research Article

Unlocking Natural Capital in the Megadiverse Colombian Pacific Basin: Navigating Challenges and Governance Gaps

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The Pacific region is considered a biodiversity hotspot and presents high species endemic levels. The Colombian Pacific basin occupies an area of approximately eight million hectares, located in the country's west. The literature about the economic valuation of ecosystem services (ES) and the spatial information on natural resources in the Colombian Pacific basin was revised through various information sources to document the earliest approximation to the state, spatial distribution, and economic value of the natural capital at the scale of biomes, specific ecosystems, and political-administrative units. Our assessment estimated a natural capital loss of 40 billion Int.$2020/year (15% of Colombian GDP in 2020) and a remnant natural capital worth 139 billion Int.$2020/year (51% of Colombia's GDP in 2020) for 15 ecosystem services. This research establishes that a potential expansion in livestock production systems will generate an additional loss of natural capital between six and eight billion Int.$2020/year. Additionally, we include an analysis based on the GLOBIO4 initiative models, identifying future natural capital losses between 7.5 and 7.6 billion Int.$2020/year. Lastly, the policy challenges and gaps in research and management concerning this remaining natural capital in the Colombian Pacific basin are pointed out.

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1. Introduction

Natural capital refers to the living and non-living components of ecosystems (ecosystem assets) that provide a continuous flow of goods and services (Guerry et al., 2015; van den Belt & Blake, 2015). Through this approach, it is possible to understand that stocks of renewable and non-renewable natural assets promote direct and indirect benefits to people in the form of ecosystem services that sustain society (Hinson et al., 2022). Natural capital is fundamental to enabling critical and irreplaceable functions (Ekins, 2003); however, natural capital and the ecosystem services derived from it are often undervalued by Governments, businesses and the public (Daily et al., 2009). Therefore, natural capital accounts are an important additional tool to inform sustainable development (Guerry et al., 2015). In this regard, valuation plays an important role (Costanza et al., 2014; Daily et al., 2009).

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According to Duque and collaborators (2017), the very wet forests of the Colombian Pacific Basin are unique in their plant diversity. The region extends across 8 million hectares, with high extensions of rainforest (Escobar, 2010). The Pacific Basin is considered a hotspot, presents high levels of endemic species (Myers et al., 2000), high cultural diversity, and the highest poverty levels in the country (PNUD, 2014; Lozada-Ordóñez et al., 2018). More than 50% of the territory exhibits low levels of government presence (Escobar, 2010). In addition, the territory is typified by the occurrence of illegal armed groups and drug traffickers (Oslender, 2008; Defensoria, 2016; Rincón-Ruiz & Kallis, 2013). Any attempt to approximate the value of the Colombian Pacific Basin's remnant natural capital (Mora, 2019) constitutes a significant contribution to the informed conservation and management of such a significant ecoregion.

Therefore, the literature about the economic valuation of ecosystem services (ES) and the spatial information about remnant natural resources after human transformation in the Colombian Pacific Basin was revised using various sources of information. The objectives of this research were: 1) - To provide an account of the current state of knowledge about ecosystem services (ES) economic valuation in the Colombian Pacific Basin. 2) - To develop the first approximation of the state, spatial distribution, and economic value (Int.$2020/year) of the current and future remnant natural capital of this basin with regard to biomes, specific ecosystems, and political-administrative units.

2. Methods

2.1. Study area

Colombia is in the northwest of the South American continent and has a land area of 1'141,748 km2, a marine area covering 928,660 km2, a population of 48'258,494 (DANE, 2021) and is the fourth most populous country in the American continent. Most of its population inhabits the central (Andean) and north (Caribbean) regions. The country is divided into 32 geographic regions (departments) and a capital district (Bogotá) of 8,879,000 inhabitants. In addition, according to the National Biodiversity Index (NBI) provided by the Convention on Biological Diversity in the Global Biodiversity Outlook 1 (https://www.cbd.int/gbo1/annex.shtml), Colombia is an outstanding megadiverse country (NBI= 0.93/1).

The Colombian Pacific basin (Figure 1) holds an area of approximately eight million hectares and is located in the country's west. According to the Colombian hydrographic zoning map (IDEAM 2013), this comprises nine (9) Colombian departments: Chocó, Valle del Cauca, Cauca, and Nariño (in mayor extension); and Antioquia, Risaralda, Caldas Huila and Putumayo (in minor extension). Its territory shares similar characteristics: jungle vegetation and hydrographic basins over wide, and sometimes flooded, valleys, where the Serranía de Baudó stands out in the department of Chocó and the Andes Mountain range in the departments of Cauca and Nariño (Romero, 2009).

Figure 1. Study area. The Colombian Pacific basin

The Pacific basin experimented with rapid changes in many ecosystems, driven by economic development (Romero, 2009; Lozada-Ordóñez et al., 2018). The most important anthropogenic disturbances in the Colombian Pacific basin are mainly due to historical deforestation (Leal & Restrepo, 2003; Velez et al., 2020; Gonzalez-Gonzalez et al., 2021), continental or/and alluvial illegal mining (Romero, 2009; Rodríguez-Zapata & Ruiz-Agudelo, 2021), arms conflict and violence (Restrepo & Rojas, 2004; Hougaard, 2022), illegal crops (Romero, 2009; Lobo & Vélez, 2022), overfishing (Castellanos-Galindo et al., 2018; Selvaraj et al., 2022), and expansion of the agricultural and livestock frontier (Romero, 2009; Velez et al., 2020). Additionally, the persistence of poverty in this region of the country is another threat to biodiversity and ecosystem services (Lozada-Ordóñez et al., 2018).

2.2. Methodological process

For the estimation of the Remnant Natural Capital (RNC) in the Colombian Pacific Basin, three phases were proposed (Figure 2), according to Ruiz-Agudelo and collaborators (2022a).

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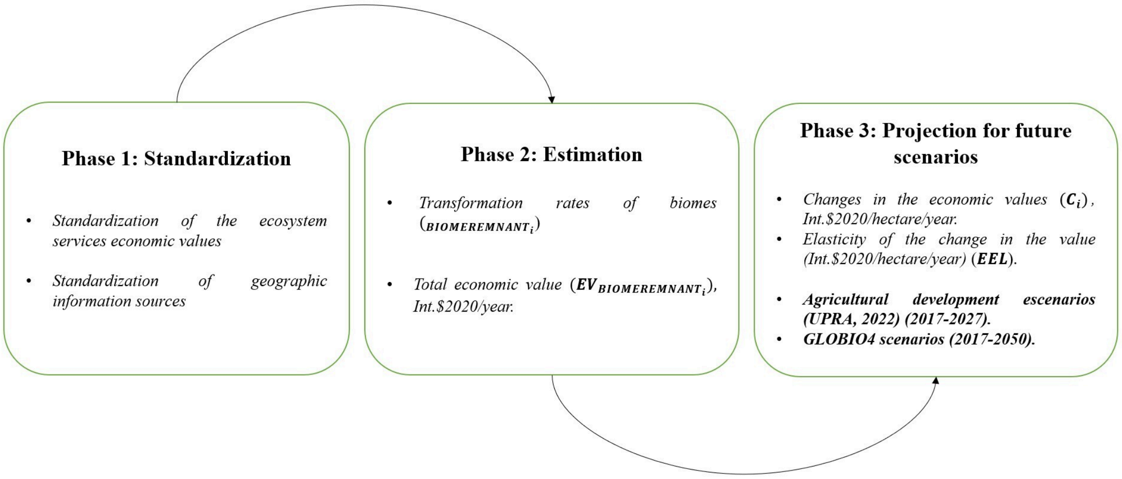

Figure 2. Proposed phases to estimate the RNC in the Colombian Pacific Basin

2.2.1. Phase 1: Data standardization and values aggregation

Review, standardization and aggregation of ecosystem service's economic values. Several sources of information were examined to collect information on the Colombian Pacific Basin ecosystem services economic valuation:

1. A systematic literature search was conducted using journals whose papers contained the following search terms (in English and Spanish): Ecosystem services, economic valuation, valuation, Colombian ecosystems, biodiversity, ecosystem services valuation, ecosystem valuation, human wellbeing valuation, Pacific region, Colombian Pacific basin. Each search term was combined with the Colombian municipality's and department's official names. Papers were sourced from the following science databases: Science Direct, SCOPUS, SCIELO, ISI Web of Knowledge, Web of Science, DIALNET, EBSCO, REDALYC, and Google Scholar.
2. Document databases of the following Colombian Government institutions were reviewed: Ministry of Environment and Sustainable Development (MADS. https://www.minambiente.gov.co/), Regional Environmental Authorities (Regional Autonomous Corporations. https://www.asocars.org/), National natural parks of Colombia (https://www.parquesnacionales.gov.co/portal/es/), Biological Resources Research, Institute Alexander von Humboldt (IAvH Institute. http://www.humboldt.org.co/es), and Institute of environmental studies (IDEAM. http://www.ideam.gov.co/).
3. The web and several university (domestic or foreign) collections of books, theses, and working papers, in both Spanish and English.

4. Databases of Ecosystem services valuation. EVRI (Environmental Valuation Reference Inventory, https://www.evri.ca/en). EVRI is a searchable online database of studies on the economic valuation of environmental assets. Other valuation literature databases that were consulted included ESValues (https://esvalues.org/) and the Ecosystem Services Valuation. Database (ESVD. https://www.es-partnership.org/esvd/) (De Groot et al., 2020. The last version of December 2020).

As for the choice of studies concerning the economic valuation of the Colombian Pacific Basin ecosystem services, we defined a series of selection criteria based on the works of Ruiz-Agudelo et al. (2011), Ruiz-Agudelo & Bello (2014), Ruiz-Agudelo et al. (2022a; 2022b), and the UK's Value Transfer Guidelines (http://www.eftec.co.uk/). Our selection criteria included: (a) must have been conducted in the Colombian Pacific Basin; (b) be a case study; (c) provide information about the valuation method employed; (d) provide a monetary value for any given ecosystem service and (e) provide a detailed location of the case study. Additionally, for Benefits Transfer to be reliable, we reviewed the Brouwer (2000), Muthke & Holm-Mueller (2004) and Eftec (2009) conditions that include: 1. The environmental good (or service) in both sites, including any proposed change in provision levels, should have approximately the same characteristics. 2. The population in both areas should have similar characteristics, including income, education level, and culture. 3. The values estimated for the study site should not be dated, as preferences could change over time. 4. The availability and price of substitutes should be the same. 5. The relative prices of other goods and services should be the same. 6. The technical quality of the study site, including adequate data, sound economical methods, and appropriate analytical techniques, needs to be determined. 7. The constructed or hypothetical markets for estimating the value of environmental resources, including the distribution of property rights, should be similar at both the study site and policy site.

This research identified 31 case studies (70 economic valuations of environmental goods or services – EVESs - **Supplementary material 1)** dealing with the Colombian Pacific Basin. Values are reported in the literature in a wide variety of currencies, price levels per year, spatial units, temporal units, and beneficiary units. Following de Groot et al. (2020), the standard unit we used was Int.$2020 (USD adjusted for differences in purchasing power across countries), per hectare, and per year for the total number of beneficiaries. We applied a five-step standardization process: price level, currency, spatial unit, temporal unit, and the beneficiary unit, as suggested by De Groot et al. (2020), allowing advancing the adjusted unit values transfer. Finally, essential information was recorded from each study, including publication descriptors and geographic information (**Supplementary material 1)**. Now, it's important to clarify that, in this research, the unit value is expressed as $ per unit of the type of benefit or good (e.g., $ per hectare, $ per ton of emissions, etc.); therefore, aggregation over the affected population is not necessary (Eftec, 2006; 2009; Ready et al., 2004).

The Pacific Basin ecosystems/biomes were identified following the Colombian continental, coastal, and marine ecosystems map (IDEAM, 2017). Ecosystem names were homologated, according to the IUCN Global Ecosystem Typology 2.0 (Keith et al., 2020). This research applied the CICES V5.1 ecosystem services classification (Young &

Potschin, 2018). The specific economic valuation method employed was documented for each unit value transferred, following the categorization of economic valuation methods built by Brander et al. (2018) and De Groot et al. (2020).

Review and standardization of geographic information sources. The following sources of cartographic information were employed to estimate and map lost and remnant natural capital in the Colombian Pacific Basin:

1. To define the official limits of the Colombian Pacific Basin, we resorted to the Colombian Hydrographic Zoning map (IDEAM, 2013) on a scale of 1:100000.
2. To define and map the biomes, original, transformed and natural (remnants) of the Colombian Pacific Basin, we turned to the information from the 2017 Colombian continental, coastal, and marine ecosystems map (V.2.1) (IDEAM, 2017) at 1:100000 scale.
3. To identify future threats to the remnant natural capital (RNC) of the Colombian Pacific Basin, we referred to two specific sources:
    1. SIPRA (Information System for Rural Agricultural Planning of Colombia) (UPRA, 2022a). Spatial information on the zoning of suitability was used at a scale of 1:100000 specifically for the following production systems: Beef production (UPRA, 2022b), rice crop (UPRA, 2022c), bulb onion crops (UPRA, 2022d), potato crops (UPRA, 2022e), bovine milk production systems (UPRA, 2022f), *Angleton* grass production systems (UPRA, 2022g), *Brachiaria* grass production systems (UPRA, 2022h), *Ginnea* grass production systems (UPRA, 2022i) and *Kikuyo* grass production systems (UPRA, 2022j), considering that these productive systems entail the biggest threats to the ecosystems and biomes of the Colombian Pacific Basin.
    2. GLOBIO4 Scenario data (https://www.globio.info/what-is-globio). The GLOBIO4 model (Schipper et al., 2020) produces spatial datasets with scenario outcomes for land use/cover. Here, we evaluated the changes in Colombian Pacific Basin terrestrial biodiversity, expressed by the mean species abundance (MSA) metric, resulting from three of the shared socioeconomic pathways (SSPs) combined with different levels of climate change (according to representative concentration pathways [RCPs]): a future oriented towards sustainability (SSP1xRCP2.6), a future determined by a politically divided world (SSP3xRCP6.0) and a future with continued global dependency on fossil fuels (SSP5xRCP8.5). All global model output datasets are in GeoTif raster format and use the WGS84 coordinate system on a 10-arcsecond spatial resolution; this roughly equals 300 x 300 meters at the equator (Schipper et al., 2020).

2.2.2. Phase 2: Estimation of the current RNC

Mapping the economic values of ecosystem services and first estimation of loss and remnant natural capital. According to the information sources detailed in the preceding sections, 80 specific biomes are reported (and 65 general ecosystems. **Supplementary material 2**) for the Colombian Pacific Basin. The following spatial analysis was applied to identify the transformation rates of biomes (Ruiz-Agudelo et al., 2022a).

$$BIOMEREMNANT_i = BIOMEORIGINAL_i - BIOMETRANS_{(i(2017))} \qquad \text{(Equation 1)}$$

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Where:

$BIOMEREMNANT_i$, is the extension in hectares of remnant biome i. Vector spatial information layer.

$BIOMEORIGINAL_i$, is the projection of the original area in hectares of the Biome i, according to IDEAM (2017). This is a vector information layer.

$BIOMETRANS_{(i(2017))}$, is the current transformed area (in hectares) of biome i, according to the information from the IDEAM (2017). This is a vector information layer.

i is correspondent with each of the 80 biomes reported in the Colombian Pacific Basin.

The economic values of the lost and RNC in the Colombian Pacific Basin (Int.$2020/hectare/year) were obtained through the revision, standardization, and aggregation values process. The first approach to total economic value ($EV_{(BIOMEREMNANT_i)}$) of each $BIOMEREMNANT_i$ was estimated according to equation two (2):

$$EV_{(BIOMEREMNANT_i)} = TEVES_{(BIOMEREMNANT_i)} * BIOMEREMNANT_i \qquad \text{(Equation 2)}$$

Where:

$EV_{(BIOMEREMNANT_i)}$ is the total economic value (Int.$2020/year) of $BIOMEREMNANT_i$.

$TEVES_{(BIOMEREMNANT_i)}$ are the total economic values (Int.$2020/hectare/year) of all ecosystem service documented for $BIOMEREMNANT_i$.

$BIOMEREMNANT_i$, is the extension in hectares of remnant biome i. Vector spatial information layer.

The total economic values (Int.$2020/hectare/year) of ecosystem services for $BIOMEREMNANT_i$ was estimated as:

$$TEVES_{(BIOMEREMNANT_i)} = \sum_{i=1}^{n} ESV_i \qquad \text{(Equation 3)}$$

Where:

$TEVES_{(BIOMEREMNANT_i)}$ are the total economic values (Int.$2020/hectare/year) of all ecosystem service documented for $BIOMEREMNANT_i$.

ESV_i is the economic value (Int.$2020/hectare/year) of each ecosystem service (ES) recorded for each $BIOMEREMNANT_i$.

The economic value of each ecosystem service (ESV_i) was estimated using equation four (4), derived from the model proposed by Costanza et al. (1997) and modified by Zhao and He (2018).

$$ESV_i = \sum A_k * V_k \qquad \text{(Equation 4)}$$

Where:

$ESV_i$is the economic value (Int.$2020/hectare/year) of each ecosystem service (ESi), recorded on each $BIOMEREMNANT_i$.

A_k refers to the area (in hectares) of land use k within the $BIOMEREMNANT_i$.

V_k refers to the economic value of SEi for each type of land use k within $BIOMEREMNANT_i$.

Based on the above estimates, a database was built with the economic values of the remnant and lost natural capital of the 80 biomes of the Colombian Pacific Basin (**Supplementary material 3**). It is important to clarify that in several cases, it was not possible to identify economic values for some ecosystem services for Colombian Pacific Basin biomes or ecosystems. These information gaps are recorded as "No registered values" (**Supplementary material 6**), which do not represent zero or the absence of the service offer; instead, this response is due to an information gap, or ignorance of values for these biomes or ecosystems. Finally, those economic values were mapped at the 1:100000 scale in the MAGNA-SIRGAS / Colombia Bogotá - Zone coordinate system. All spatial analyses were completed under the Spatial Analysis function of the R program (Development Core Team, 2019), and all the maps were edited in QGIS (Version 3.16.15).

2.2.3. Phase 3: Projection for future scenarios

Economic valuation of RNC in future agricultural development scenarios. For this analysis, Government spatial information on the projection of new areas with potential for agricultural growth was used (UPRA, 2022). These maps represent future scenarios for the expansion of crops and pastures for livestock. The purpose of this spatial analysis was to identify potential losses or gains of natural capital under these scenarios of conventional agricultural expansion, simulating that such changes would be materialized in the period 2017 to 2027 (ten years).

Changes in the areas of each of the remnant biomes of the Colombian Pacific Basin were estimated under this future scenario of agricultural development. The changes in the economic values (Int.$2020/hectare/year) of each ES ($\boldsymbol{ESVi}$) for each remnant biome were calculated using equation five (5) according to Song and Deng (2017) and Ruiz-Agudelo et al. (2022a).

$$C_i = \frac{E_{\text{end}} - E_{\text{start}}}{E_{\text{start}}} \; x \; \mathbf{100}\% \qquad \text{(Equation 5)}$$

Where:

C_i is the change in the value (Int.$2020/hectare/year) of each ES ($ESVi$), for the $BIOMEREMNANT_i$.

$\boldsymbol{Estart}$ is the economic value (Int.$2020/hectare/year) of each ES in 2017.

$\boldsymbol{Eend}$ is the economic value (Int.$2020/hectare/year) of each ES in 2027 when the agricultural growth projections are materialized.

Following the elasticity concept of economics, which refers to the measurement of a variable's sensitivity to a change in another variable, elasticity $ESVi$ is due to the percentage change in land use (by projected agricultural expansion) for each $BIOMEREMNANT_i$. The elasticity formula of Song and Deng (2017) was applied as follows:

$$EEL = \left[\frac{(E_{\text{end}} - E_{\text{start}}) / E_{\text{start}} \times 100\%}{LCP} \right] \qquad \text{(Equation 6)}$$

Where:

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$\boldsymbol{EEL}$ is the elasticity of the change in the value (Int.$2020/hectare/year) of each ES, for $BIOMEREMNANT_i$. regarding changes in land use projected for agricultural expansion.

$\boldsymbol{Estart}$ is the economic value (Int.$2020/hectare/year) of each ES in 2017.

$\boldsymbol{Eend}$ is the economic value (Int.$2020/hectare/year) of each ES in 2027 when the agricultural growth projections are materialized.

LCP is the percentage of land conversion from a remnant biome (2017) to an area for conventional agricultural production (2027).

The LCP is estimated as follows:

$$LCP = \frac{\sum_{i=0}^{n} LUT_i}{\sum_{i=0}^{n} \Delta LUT_i} x \frac{1}{T} \times 100\% \qquad \text{(Equation 7)}$$

Where:

LCP is the percentage of land conversion from a remnant biome (2017) to an area of conventional agricultural production (2027).

$\boldsymbol{LUTi}$ is the area in hectares of type i land use for a $\boldsymbol{BIOMEREMNANTi}$ in 2017.

$\Delta\boldsymbol{LUTi}$ is the area converted from type i land use (for a $\boldsymbol{BIOMEREMNANTi}$ in 2017) to new lands for conventional agricultural (in 2027).

T is the time interval (in years) of the period of change (in this case, ten years).

Economic valuation of RNC in future global change scenarios. We use the maps derived from the GLOBIO4 model (Schipper et al., 2020) downscaling to the Colombian Pacific Basin. The models used were: 1. A future-oriented toward sustainability (SSP1xRCP2.6). 2. A future determined by a politically divided world (SSP3xRCP6.0). 3. A future with continued global dependency on fossil fuels (SSP5xRCP8.5). The models are expressed by the mean species abundance (MSA) metric and result from three shared socioeconomic pathways (SSPs) combined with different levels of climate change for the 2050 year. The changes in the economic values (Int.$2020/hectare/year) of each ES for each remnant biome were calculated using equations five (5), six (6), and seven (7). We define that $\boldsymbol{Estart}$ = 2017 and $\boldsymbol{E}$**end** = 2050. Additionally, we suppose that the land cover change to non-natural cover in 2050.

3. Results

3.1. General overview of the Colombian Pacific Basin Biomes and General Ecosystems

According to this research, 80 biomes and 65 general ecosystems exist in the Colombian Pacific Basin, which adds up to 8 million hectares. Three million hectares have been transformed (for multiple anthropic activities), preserving around five million hectares in their natural state. **Figure 3** shows that four biomes have been 100% transformed (*Helobioma Estribaciones Pacífico sur, Zonobioma Humedo Tropical Estribaciones Pacífico norte, Orobioma Azonal Subandino*

Estribaciones Pacífico norte, Orobioma Azonal Andino Cordillera central; 3,275 hectares), and 28 biomes have been transformed between 51% and 99% (1.3 million hectares). On the other hand, 16 biomes display no human intervention **(Figure 3A, Supplementary material 4).** At an ecosystem scale (**Figure 3B, Supplementary material 5**), the Mosaic agroecosystem of crops, pastures and natural spaces (619,349 hectares), Transitional transformed (360,883 hectares), Crop and Pasture Mosaic Agroecosystem (306,239 ha), and Secondary vegetation (292,816 ha) are the most extensive in the Colombian Pacific Basin.

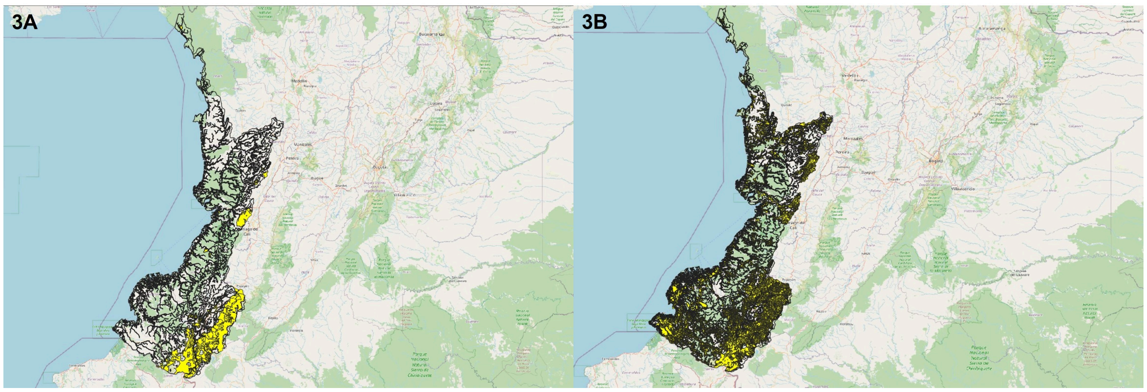

Figure 3. 3A. Location of biomes with a human transformation between 51% and 100%. 3B. Location of transformed ecosystems.

3.2. Economic values of the ecosystem services (EVES) identified in the Colombian Pacific Basin

Based on the review and standardization of the EVES, monetary values were identified for fifteen (15) ecosystem services (**Figure 4A, 4B and 4C, Supplementary material 6**).

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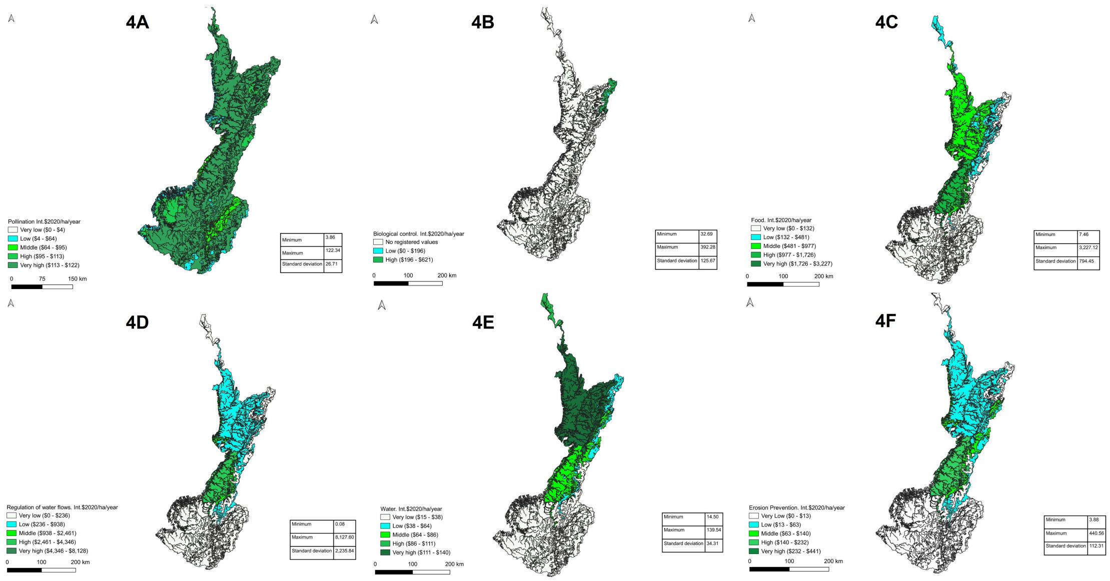

Figure 4A. Maps of the monetary value of ecosystem services (Int.$2020/ha/year). 4A. Pollination. 4B. Biological Control. 4C. Food. 4D. Regulation of water flows. 4E. Water. 4F. Erosion prevention.

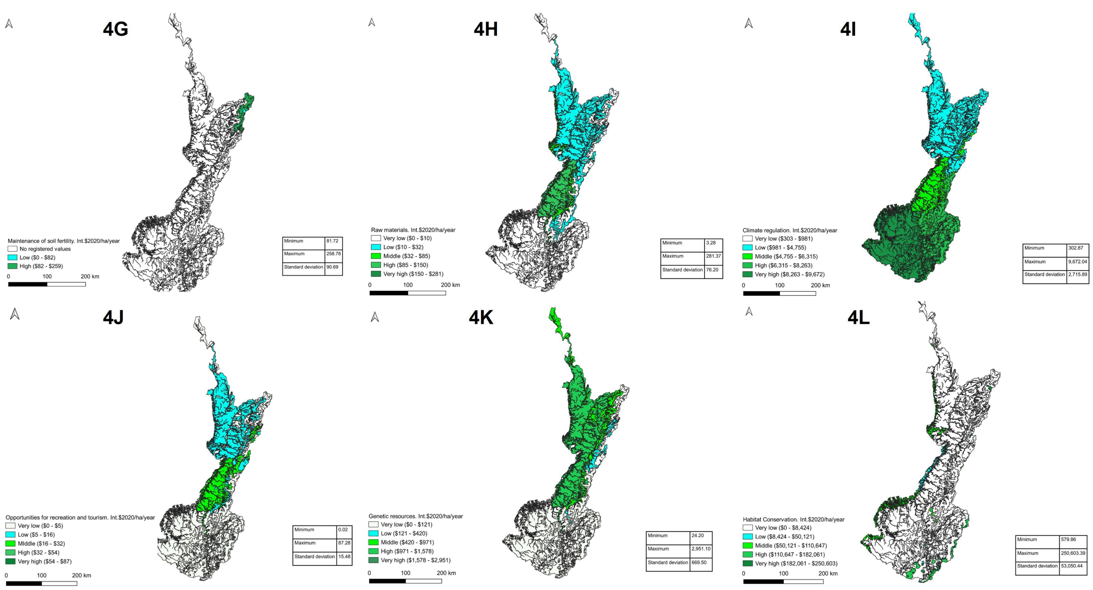

Figure 4B. 4G. Maintenance of soil fertility. 4H. Raw materials. 4I. Climate Regulation. 4J. Opportunities for recreation and tourism. 4K. Genetic Resources. 4L. Habitat Conservation.

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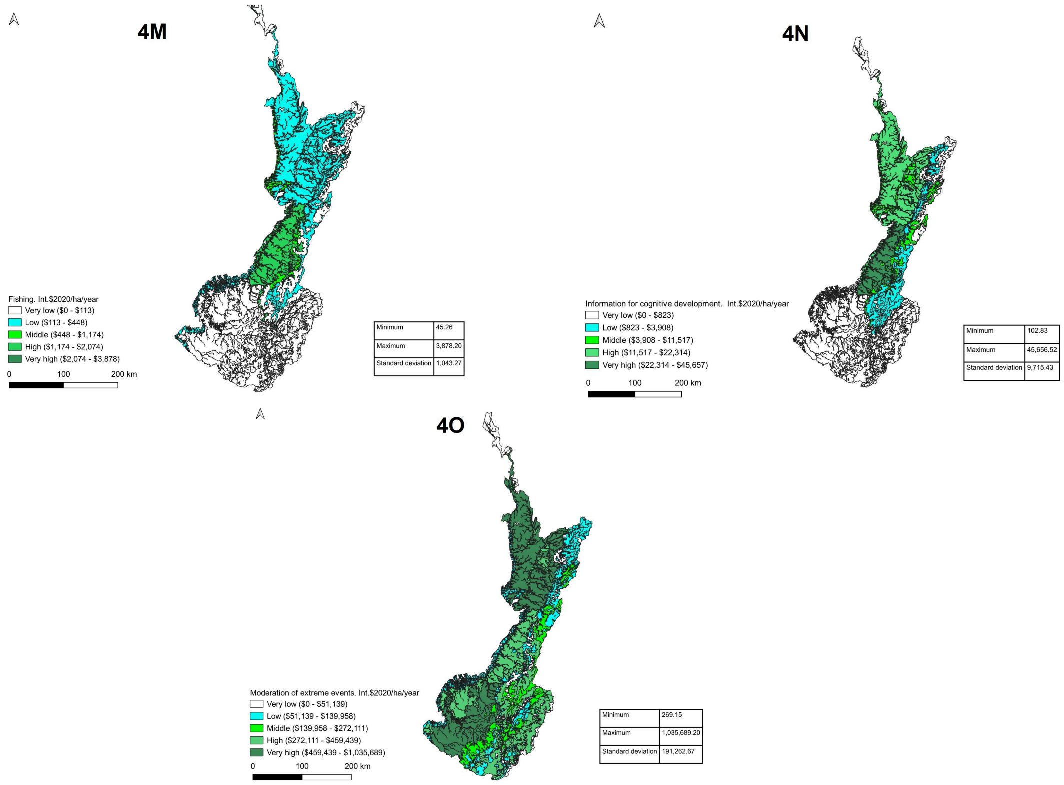

Figure 4C. 4M. Fishing. 4N. Information for cognitive development. 4O. Moderation of extreme events.

3.3. The first approach to the Natural Capital of the Colombian Pacific Basin's original biomes

The natural capital of the Colombian Pacific Basin's original biomes amounted to 179 billion Int.$2020/year (**Table 1S - Supplementary material 7).** It is crucial to stress that the information about the economic values of ecosystem services is quite asymmetric for the Pacific Basin. Twelve biomes reported economic values for Three and five ecosystem services, and 40 biomes (of 80) have data values for six or more ecosystem services (**Table 2S - Supplementary material 7**). In **Figure 5A**, the monetary values vary between 1,100 and 251,510 Int.$2020/ha/year (with a standard deviation of 50,614). The lowest values appear in the original biomes: *Hidrobioma Darién –Tacarcuna, Hidrobioma Estribaciones Pacífico norte, Hidrobioma Truandó,* and *Hidrobioma Vertiente Pacífico-Chocó*. On the other hand, the highest values (Int.$2020/ha/year) occur in the original biomes: *Orobioma de Paramo Cauca medio, Orobioma de Paramo Estribaciones Pacífico norte, Orobioma de Paramo Cordillera central, Orobioma de Paramo Patía, Orobioma de Paramo Nudo de los pastos* and *Orobioma de Paramo Estribaciones Pacífico sur*. The original Pacific Basin biomes with the highest total economic values worth of natural capital (**Figure 5B, Table 1S - Supplementary material 7)** are the *Halobioma Pacífico nariñense-Tumaco* (23 billion Int.$2020/year), followed by the *Zonobioma Humedo Tropical San Juan* (18 billion Int.$2020/year) and the *Orobioma de Paramo Cordillera central* (17 billion Int.$2020/year).

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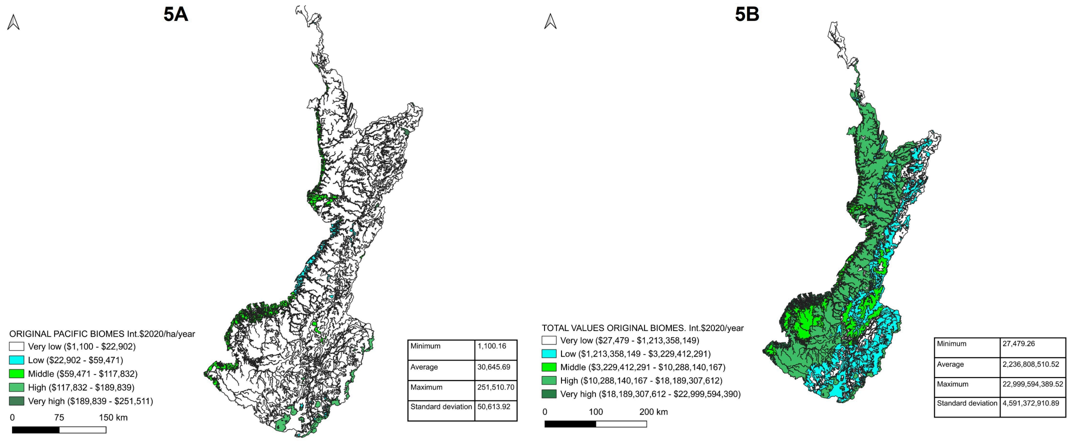

Figure 5. Monetary value maps of original Colombian Pacific Basin biomes. 5A. Average Int.$2020/ha/year. 5B. Int.$2020/year.

3.4. The first approach to Natural Capital loss in the Colombian Pacific Basin biomes

There is a 40 billion Int.$2020/year loss of natural capital in 66 biomes (22% of the original Natural Capital) (**Table 1S - Supplementary material 8)** and 20 general ecosystems (**Table 2S - Supplementary material 7**). Natural capital losses, in Int.$2020/ha/year, vary between zero (*Orobioma de Paramo Cauca medio, Orobioma Andino Vertiente Pacífico-Cauca, Oceanico/marino, Hidrobioma Vertiente Pacífico-Chocó, Hidrobioma Vertiente Pacífico-Cauca, Hidrobioma Truandó, Hidrobioma San Juan, Hidrobioma Patía, Hidrobioma Pacífico nariñense-Tumaco, Hidrobioma Nudo de los pastos, Hidrobioma Estribaciones Pacífico sur, Hidrobioma Estribaciones Pacífico norte, Hidrobioma Darién –Tacarcuna* and *Helobioma Vertiente Pacífico-Cauca*) and 42,502 (*Hidrobioma Micay*), with a standard deviation of 6,737.57 (**Figure 6A**). The biomes with the most relevant total losses of natural capital (due to anthropic transformation) are the *Zonobioma Humedo Tropical Pacífico nariñense-Tumaco* (6.6 billion Int.$2020/year), followed by *Zonobioma Humedo Tropical San Juan* (3.7 billion Int.$2020/year), *Orobioma Andino Nudo de los pastos* (2.7 billion), *Zonobioma Humedo Tropical Micay* (2.5 billion), and *Helobioma Pacífico nariñense-Tumaco* (2.5 billion) (**Figure 6B, Table 1S - Supplementary material 8**). At the scale of political-administrative divisions, Nariño (20 billion Int.$2020/year), Cauca (8 billion), Valle del Cauca (7 billion), and Chocó (4.4 billion) are the Pacific Basin departments with the most significant total losses of natural capital (**Figure 6C**).

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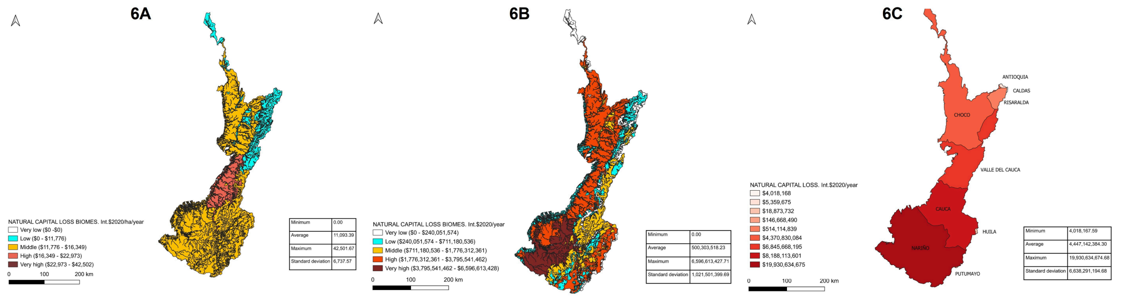

Figure 6. Maps of monetary values of natural capital loss. 6A. Natural capital loss in Pacific Basin biomes (Int.$2020/ha/year). 6B. Pacific Basin biomes' total natural capital loss (Int.$2020/year). 6C. Pacific Basin departments' total natural capital loss (Int.$2020/year).

On the other hand, natural capital loss values vary between zero and 27,979 Int.$2020/ha/year at the ecosystems level. The ecosystems with the highest total loss of natural capital (Int.$2020/year) in the Colombian Pacific Basin are Mosaic agroecosystem of crops, pastures and natural spaces (8.3 billion), Transitional transformed (4.8 billion), Crop and Pasture Mosaic Agroecosystem (4.2 billion), Secondary vegetation (4 billion), Fragmented Forest with secondary vegetation (3.7 billion) and Livestock agroecosystem (3.5 billion) (**Table 2S. - Supplementary material 8**).

3.5. The first approach to the remnant natural capital of Colombian Pacific Basin biomes

The Colombian Pacific Basin remnant natural capital amounts to 139 billion Int.$2020/year. The values of the remnant natural capital in Int.$2020/ha/year range between 0.00 and 260,451 with a standard deviation of 67,694 (**Figure 7A, Table 1S - Supplementary material 9**). The total values of remnant natural capital in Int.$2020/year vary between zero (*Helobioma Estribaciones Pacífico sur, Orobioma Azonal Andino Cordillera central, Orobioma Azonal Subandino Estribaciones Pacífico norte, Zonobioma Humedo Tropical Estribaciones Pacífico norte)* and 22.3 billion (*Halobioma Pacífico nariñense-Tumaco*) (**Figure 7B, Table 1S -Supplementary material 9**). The Pacific Basin departments with the highest total values of remnant natural capital (Int.$2020/year) are Nariño (59.6 billion; 43% of the total Colombian Pacific basin remnant natural capital), Valle del Cauca (29 billion), and Chocó (25.5 billion) (**Figure 7C).**

At a General Ecosystems level, remnant natural capital values (Int.$2020/ha/year) vary between zero and 260,419 (**Table 2S-Supplementary material 9).** The ecosystems with the highest total remnant natural capital (Int.$2020/year) in the Colombian Pacific Basin are Paramo (39.1 billion), Moist basal forest (37.3 billion), Mixohaline water mangrove (36 billion), and Humid sub-andean forest (12 billion) (**Table 2S-Supplementary material 9**).

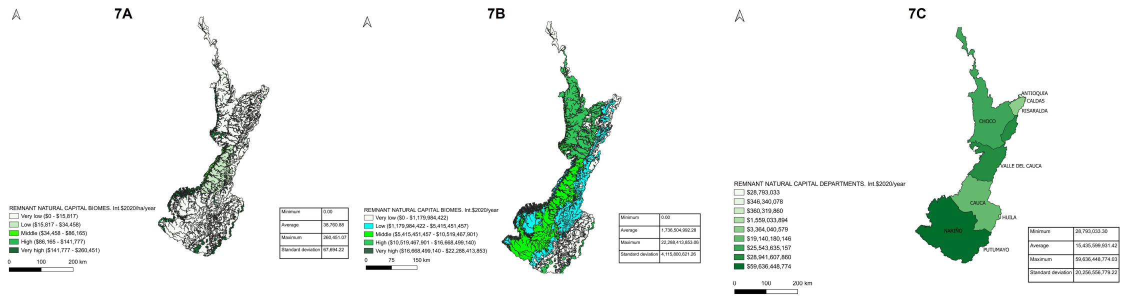

Figure 7. Maps of remnant natural capital monetary value. 7A. Remnant natural capital of Pacific Basin biomes (Int.$2020/ha/year). 7B. Remnant natural capital of Pacific Basin biomes (Int.$2020/year). 7C. Total remnant natural capital of Pacific Basin departments (Int.$2020/year).

In the Colombian Pacific Basin, we identified 115 protected areas (756,031 hectares), which contain approximately 33 billion Int.$2020/year (27% of total Remnant Natural Capital). We also registered 159 indigenous reservations, which contain 13.4 billion Int.$2020/year (10% of total Remnant Natural Capital). Finally, we report the presence of 140 community lands of Afro-descendant people (around five million hectares) with approximately 104.2 billion Int.$2020/year (75% of total Remnant Natural Capital).

3.6. Probable loss of remnant natural capital during future socioeconomic development scenarios

RNC losses in future agricultural development scenarios. Our results suggest that if beef production systems were allowed to expand (in a 10-year scenario 2017-2027), about 8.3 billion Int.$2020/year would be lost (**Table 1S - Supplementary material 10**). The biomes most affected in their remnant natural capital would be *Orobioma Andino Nudo de los pastos* (1.5 billion Int.$2020/year), *Halobioma Pacífico nariñense-Tumaco* (1.3 billion), and *Zonobioma Humedo Tropical Pacífico nariñense-Tumaco* (1.1 billion). In the case of bovine milk production systems being allowed to expand (in a 10-year scenario 2017-2027), around 8.3 billion Int.$2020/year would be lost mainly in the *Orobioma Andino Nudo de los pastos* (1.5 billion) and the *Halobioma Pacífico nariñense-Tumaco* (1.2 billion) (**Table 5S - Supplementary material 10**). Now, if an expansion in bulb onion crops is encouraged, losses of 10.2 billion Int.$2020/year of remnant natural capital are expected, mainly in the *Orobioma Andino Nudo de los pastos* (2 billion) and the *Orobioma Subandino Patía* (1.3 billion) (**Tables 3S - Supplementary material 10**).

Finally, with the expansion of rice crop production systems, additional natural capital losses of close to 3 billion Int.$2020/year are estimated (**Table 2S - Supplementary material 10**). The expansion of other pasture types would generate losses between four and six billion Int.$2020/year (**Supplementary material 10**).

RNC losses in future global change scenarios. Our results on the downscaling of the GLOBIO4 models to the Colombian Pacific basin indicate that under a scenario of continued global dependency on fossil fuels (SSP5xRCP8.5), they wait for additional losses of the remnant natural capital of 10. 3 billion Int.$2020/year, by 2050 **(Figure 8A)**. Under the scenario of a future determined by a politically divided world (SSP3xRCP6.0), additional losses of 9.6 billion Int.$2020/year are

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estimated (**Figure 8B**). Finally, the scene where they estimate the major losses (by 2050) is a future oriented toward sustainability (SSP1xRCP2.6), with a value of 22.1 billion Int.$2020/year (**Figure 8C).**

Figure 8. 8A. Global dependency on fossil fuels (SSP5xRCP8.5). 8B. Future determined by a politically divided world (SSP3xRCP6.0). 8C. future-oriented toward sustainability (SSP1xRCP2.6).

4. Discussion

4.1. Economic values of Colombian Pacific basin ecosystem services, restrictions, and gaps in available information

According to our assessment, there is no research oriented towards identifying the Natural Capital of the Pacific Basin. However, there are multiple contributions to the economic valuation of specific ecosystem services oriented to tourism, climate regulation and fishing, focused mainly on ecosystems such as mangroves (more than 32% of the economic values identified in this research).

Despite the above, the contribution of Lozada-Ordoñez and collaborators (2018), who identify a significant loss of ES due to changes in land use, is notable. According to this research, crops, cultural, community activities, and traditional production systems have been lost, with negative consequences for agrobiodiversity and community life. On the other hand, Palacios-Peñaranda et al. (2019) highlight that underground biomass and sediments represented the major carbon reserves in the mangrove forest. Additionally, shows that carbon stocks in Colombian Pacific mangroves were similar compared to other tropical mangrove areas.

This research shows that estimates per ecosystem service vary significantly; for this reason, these results should be interpreted as a first approximation that can be complemented by further efforts. Considering that, according to our research, there are no reports of transferable values for some ecosystem services in many Colombian Pacific Basin biomes ("No registered values" in the Supplementary material 6), future research on some ESs is necessary, such as waste treatment, pollination, moderation of extreme events, medicinal resources, soil fertility, raw materials, cultural, spiritual, and maintenance of genetic diversity, which have been poorly studied and value in the Colombian Pacific Basin.

On the other hand, it's evident the efforts concentrate on the valuation of opportunities for recreation and tourism, fishing, and Climate regulation in mangrove ecosystems. Some ecosystem services, such as those coming from biodiversity, are challenging to assess economically, and such assessments tend to rely on revealed or stated preference techniques (Laurila-Pant et al., 2015). Other services, such as cultural, spiritual, and aesthetic benefits, involve a variety of value perceptions (Small et al., 2017). Therefore, there are no economic value estimates attached to some ecosystem services, leading to an underrepresentation of the total values of the Colombian Pacific basin. For example, 12 of the 80 biomes present economic values for less than five ES.

4.2. The present and future of the Colombian Pacific Basin RNC. Implications of this first approximation

4.2.1. Natural capital losses in the Colombian Pacific Basin

As humanity's requirement for resources continues to rise and productive arable lands become increasingly scarce, many of Earth's remaining intact regions are at heightened risk of destruction from agricultural development (Williams et al., 2020), which can aggravate the tension over limited natural resources (He et al., 2014) and may also damage the ability to sustain the supply of ecosystem services (Foley et al., 2005). This situation is also underway in the Colombian Pacific Basin, where the Natural Capital loss has been estimated at 40 billion Int.$2020/year (29% of the Remnant Natural Capital).

According to Romero (2009), geographical conditions are important for the economy in the Pacific basin. The relationship between geography and economy is complex, and as it is the cause or effect of a wide variety of phenomena (market failures, geographic determinism, or geographic predisposition), it has led to heterogeneous concepts, questions, and problem definitions. Five major economic activities (legal or illegal) likely to influence the future of the region include:

1. The extraction (legal or illegal) of wood has been in force in different regions of the Pacific basin since the beginning of the 19th century, generating deforestation and degradation of the different types of forests (Contraloría General de la República, 1943; Leal & Restrepo, 2003; Vélez et al., 2020).
2. The Colombian Pacific Basin is an agricultural and recently livestock region. As an economic activity that generates added value, the sector has a share of more than 25% (Pérez, 2008). However, it is noteworthy that these activities lack adequate planning and technology to make them compatible with the region's environmental conditions.
3. A third element of the Pacific Basin economy is mining persistence. This activity has existed since before the conquest. Despite its artisanal condition, it is an exploitation mode rooted in Colombian Pacific culture. West (1957) estimated that artisanal exploitation in Colombia represented 45% of platinum extraction and between 20 and 25% of gold. The figures show that in the Pacific economy, mining represents more than 11% of its added value (Bonet, 2008). The emerging problem is that in the last 20 years, there has been a migration from artisanal

mining to illegal mining, affecting large natural areas, mainly in the Chocó department (Rodríguez-Zapata & Ruiz-Agudelo, 2021).

4. The economic activities of the communities' inhabitants around the swamps and mangroves revolve around fishing, agriculture, and livestock. Putting pressure on these wetlands' ecosystems due to overexploitation, deforestation, and degradation by biodiversity decrease. (Aguilera-Díaz, 2011).
5. Finally, armed violence, social displacement, the absence of an effective government presence (Restrepo, 2004; Diaz et al., 2021), and the growth of illicit crops (Lobo & Vélez, 2022) generate severe socio-environmental pressures on the remnant natural capital.

The repercussions of the losses in natural capital in the Colombian Pacific Basin can be analyzed from two approaches:

1. According to Duque and collaborators (2017), the very wet forests of the Colombian Pacific Basin are unique in their plant diversity. This basin includes ecosystems such as tropical forests, coral reefs, and mangroves, with high biological productivity and great importance to local economies. Alterations in the natural biomes, ecosystems, and hydrology cycles will reduce the ecosystems' productivity, biomass, biogeochemical cycles, and the supply of ecosystem services.
2. The gross domestic product (GDP) expressed in current international dollars, translated through the purchasing power parity (PPP) conversion factor of Colombia for 2020, was 270.3 billion (World Bank, 2022). This implies that the natural capital lost in the Pacific basin is equivalent to 15% of the Colombian 2020 GDP, a significant percentage when considering that the contribution of the Pacific departments to the Colombian GDP (for 2020) amounts to approximately 3.5% (DANE, 2022).

4.2.2. The current RNC in the Colombian Pacific Basin

Other studies have advanced global and national estimates of ecosystem services' economic value. At a global assessment level, de Groot and collaborators (2012) estimated the value of one hectare of tropical forest at 5,264 (Int.$/ha/year, 2007), while Costanza et al. (2014) estimated the same value at 5,382 (2007$/ha/year), these evaluations involve 20 ESs and are much smaller than our estimates in the Colombian Pacific Basin biomes and ecosystems which are, on average, 38,761 (Int.$2020/ha/year). Now, at a national assessment level, the contributions of Kubiszewski et al. (2017) and Hernández-Blanco et al. (2020) become relevant as they estimated the total value of ecosystem services in Colombia (under different scenarios) at 717 billion USD/year in 2011. More recently, Jiang et al. (2021), in their mapping of the global value of terrestrial ecosystem services by country, estimated the value of seven ES (by calculating the Gross Ecosystem Product- GEP) for Colombia at 2.2 trillion dollars.

The estimated value of the remnant natural capital in the Colombian Pacific Basin is equivalent to 51% of Colombia's GDP in 2020, a very significant percentage that welcomes rethinking the ecoregion's importance. It also invites new management strategies to enhance the multiple socioeconomic benefits of sustainably using the remnant natural capital of this diverse region. According to Fedele and collaborators (2021), the proportion of people highly dependent on nature in the Pacific Basin ranges between 60% and 70%. This high dependency represents a new challenge for remnant natural capital management, which must ensure a sustainable flow of vital benefits (natural housing materials, food, fishing, energy from biomass, and water from natural sources, among others) for a growing human population and highly dependent on these.

According to our analyses, 75% of the Colombian Pacific Basin's remnant natural capital is present in community lands of Afro-descendant and 10% in the Indigenous reservations. These indigenous peoples face today are ecological degradation, occupation of their territories by non-Indigenous people, lack of lands to sustain the Indigenous population, and cultural clashes caused by the incursion of industries and foreigners into their lands (Sanchez, 2007; Finer et al., 2008). On the other hand, according to Garzón-Rodríguez & Moreno-Calderón (2018), since the implementation of Law 70 of 1993, the black communities in Colombia have not made significant progress in terms of the economic, social, and political aspects; this can be explained by the low governmental administrative level, the violence, illegal mining, illegal crops, wood traffic, and the massive presence of illegal groups in the Afro-descendant territories.

According to Hougaard (2022), ethnic recognition and collective titling have, since the second half of the 20th century, been promoted as ways of compensating for historical injustices and countering the destructive effects of capitalist development. Despite this, the appropriation of community lands of Afro-descendants by other stakeholders continues to increase, creating a permanent governance conflict in the Colombian Pacific basin (Quintero-Angel et al., 2021) that affects the permanence of remnant natural capital. Thus, the post-conflict scenario constitutes a challenge for the public administration since it is called upon to formulate and manage public policies to guarantee peace, development in the territories, and the sustainable management of its immense natural capital. Finally, we estimate that 27% of the Colombian Pacific Basin natural capital is in 115 protected areas; it's important to mention that the presence of protected areas is not a guarantee of effective conservation (Golden et al., 2019) given the obvious shortcomings in their management by the Colombian government. Considering that a little more than 85% of the Colombian Pacific Basin natural capital is in these territorial management figures, their strengthening represents an urgent task for the Colombian government.

4.2.3. The future of Colombian Pacific Basin remnant natural capital

This contribution focused on the possible losses of remnant natural capital due to the expansion of nine agricultural production systems, under the assumption that these productive systems represent important threats to the remnant biomes of the Colombian Pacific Basin. Unfortunately, the lack of official information on the oil palm did not allow the evaluation of this production system (Castiblanco et al., 2013). Our results show that an expansion of beef production systems has the most negative impact and would generate 8.3 billion Int.$2020/year of new losses of natural capital. Additionally, if the bulb onion crops were expanded, the losses would amount to 10 billion.

Cattle ranching accounts for the most significant emergent land use in the Pacific basin. Those poorly managed pasture systems typically entail soil compaction, acidification, losses of organic matter, and soil erosion, leading to soil

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health impairments and ecosystem services losses. Livestock production in the tropics has been widely questioned because of the adopted production system, which involves establishing grass monocultures with fewer animals per hectare (stocking rate) after cutting and burning the native vegetation (Tapasco et al., 2019). Those activities destroy biodiversity (Murgueitio et al., 2008), affect precipitation and evapotranspiration (Vergopolan & Fisher, 2016), and increase greenhouse gas emissions (Navarrete et al., 2016; Hubau et al., 2020). The possibility of expanding livestock production activities poses an unmistakable threat to the conservation and sustainable use of the remnant natural capital in the short- and medium-term. This future loss of remnant natural capital could be mitigated if practices such as silvopastoral systems were implemented (Carriazo et al., 2020). The massive implementation of these silvopastoral systems and more precise environmental zoning of these economic activities constitute another challenge for Colombian Pacific Basin management.

On the other hand, Schipper and collaborators (2020) found considerable variation in projected biodiversity change among different world regions for the GLOBIO4 scenarios. For the Colombian Pacific Basin case, the minor losses of RNC are in the future determined by a politically divided world (SSP3xRCP6.0) scenario. According to this contribution, effective measures to halt or reverse the decline of terrestrial biodiversity and natural capital should not only reduce land demand (e.g., by increasing agricultural productivity and dietary changes) but also focus on reducing or mitigating the impacts of other pressures (e.g., illegal mining and the climate change impacts). Our results show that the RNC will decrease in all future scenarios. In this way, the policy challenge is to identify the scenario that configures the smallest losses and that allows for maintaining the Pacific ecoregion resilience.

4.3. Limitations and caveats

According to Sumarga et al. (2015), regarding the spatial analysis of ES values, a key issue in mapping ecosystem values is the generalization error when a benefit transfer approach is used (Plummer, 2009; Liu et al., 2010). This first approximation shows how three aspects of our mapping approaches can reduce generalization error. Firstly, by only using empirical data from specific cases within the Colombian Pacific Basin (Sumarga & Hein, 2014), the potential error from transferring values can be minimized. Secondly, by presenting the spatial variation of ecosystem services inside a land cover type by applying interpolation. Thirdly, by detailing the mapping units by breaking down cover types in the Colombian Pacific Basin. In synthesis, our results build on a far more refined approach to ecosystem services valuation than those adopted by most studies.

This spatially explicit first approach to some critical natural capital components significantly enhances our ability to plan land use where protection or sustainable use in different natural regions must be prioritized. Decision-makers need to remain prudent about two aspects of our work: First, our maps represent values for different groups at different levels of society, for deforestation may incur economic losses to individual production activities or miss opportunities to capture societal benefits; second, our maps do not provide sufficient guidance where value components that may contradict each other overlap. For instance, regions with high timber values may overlap with highly biodiverse areas, which benefit different social groups.

In this research, we attempt to make comprehensive estimates of the total economic value (TEV) of the Colombian Pacific basin by using all national available values rather than valuing subsets of particular ecosystem services relevant to particular biomes. Valuations of individual ecosystem services such as soil retention can be useful for justifying investments in specific restoration programs but may not be sufficient to provide overall ecosystem service valuation (Anderson et al. 2017). Additionally, we recognize that these numbers are likely conservative underestimates for many reasons including spatial resolution, valuation methods, and the generalization of land cover classifications. This method poses a hugely controversial issue, some academics may argue that we are merely underestimating the infinite value of ecosystem services based primarily on the "economy in society in nature" argument (Fisher et al. 2008; Bateman et al. 2011; Sutton and Anderson, 2016; Nijnik and Miller 2017). Nonetheless, according to Anderson et al. (2017), ecosystem services have historically been valued at something closer to zero than infinity and our numbers provide an estimate of value that can be usefully compared to GDP.

Despite the above, this research recognizes that the focus on valuing total natural capital stocks is controversial. According to O'Gorman and Bann (2008), future valuation work should focus on the development of marginal assessment of changes in services that can be provided by an ecosystem. Marginal valuation is relevant as a measure of changes in ecosystem services, and marginal changes in values are important.

Future research should focus, in greater detail, on the potential future impacts of the expansion of other economic activities such as legal and illegal mining (Rodríguez-Zapata & Ruiz-Agudelo, 2021), oil and gas exploitation (Codato et al., 2019), palm oil (Ocampo-Peñuela et al., 2018), and the expansion of other types of agricultural systems (Rodríguez et al., 2021). In addition, to estimate the tradeoffs between conservation and agricultural sustainable practices implementation.

5. Conclusions

Our research estimated a natural capital loss worth 40 billion Int.$2020/year (equivalent to 15% of Colombian GDP in 2020) and a remnant natural capital for 15 ecosystem services worth 139 billion Int.$2020/year (51% of Colombia's GDP in 2020). Multiple challenges arise from this first approximation. First, a broader assessment and valuation of the multiple ecosystem services of the Colombian Pacific is necessary; this is an urgent endeavor to measure with more certainty its remnant natural capital and the social benefits derived from this. Second, these results invite new management strategies to enhance the multiple socioeconomic benefits derived from sustainably using the remnant natural capital of the Colombian Pacific (e.g., promote the use of economic instruments such as Payments for Ecosystems Services focusing on the most valuable areas). Third, given that 85% of the remnant natural capital is located in Community lands of Afro-descendant, Indigenous Reservations, and Protected Areas, it's urgent to strengthen these land management systems; this last challenge directly involves the Colombian government. Finally, future planning and zoning for productive activities in the Colombian Pacific Basin must be more careful to avoid further loss of natural capital.

Statements and Declarations

Author contributions

Cesar Augusto Ruiz-Agudelo: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing - original draft; Writing - review & editing. **Francisco de Paula Gutierrez-Bonilla**: Writing - original draft; Writing - review & editing.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

All data and information presented in this contribution are fully available in supplementary materials.

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