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Implications of landscape changes for ecosystem services and biodiversity: A national assessment in Ecuador

Hongmi Koo[a,b,*], Janina Kleemann[a,b], Pablo Cuenca[c], Jin Kyoung Noh[c], Christine Fürst[a,b]

[a] Martin Luther University Halle-Wittenberg, Institute for Geosciences and Geography, Dept. Sustainable Landscape Development, Von-Seckendorff-Platz 4, 06120 Halle (Saale), Germany
[b] German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Puschstr. 4, 04103 Leipzig, Germany
[c] Tropical Ecosystems and Global Change Research Group, Universidad Regional Amaźonica Ikiam, Vía Muyuna, Km. 7, Tena, Ecuador

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ABSTRACT

Ecuadorian ecosystems experience high pressure due to anthropogenic activities and climate change. Despite the need of regular monitoring of biodiversity and ecosystem services (BES), attempts to assess the current and future interdependencies of BES and landscape changes are still lacking. This study suggests a spatial assessment of the capacity of ecosystems/land use types to provide BES as status quo and its future development under scenarios of deforestation and climate change. To address data scarcity and improve legitimacy, spatial modeling was combined with participatory approaches. Specifically, changes in landscape pattern were simulated using a modeling platform that combines Geographic Information System (GIS) and Cellular Automaton (CA) modules. Experts in ecosystem conservation and management participated through surveys and workshops. Food, drinking water, service water, soil erosion control, water flow regulation, pollination/seed dispersal, regulation of macro climate, and landscape aesthetic/amenity were identified as the most relevant ES. Among the forest ecosystems, Páramo-related ecosystems were regarded to provide multiple ES with high capacities. Compared to the current status, the deforestation scenario showed to decrease most BES by 20–25 %, while increasing food provision by 5 %, as a trade-off. Regarding the climate change scenarios, the “Representative Concentration Pathways” (RCP) by 2070 were simulated with an increase in temperature of 2 °C (RCP 2.6) and of 4 °C (RCP 6.0). RCP 6.0 showed more noticeable impact than RCP 2.6, which caused a decrease in most BES whereas an increase in food provision due to the possible expansion of arable land into higher altitudes. The results of the spatial assessment also indicated high and low potential areas for BES provision. Such information can support decision-making for BES management e.g., priority areas for actions. Furthermore, the applied spatially explicit assessment could be a starting point for a regular assessment of BES, which has not yet been implemented in Ecuador.

1. Introduction

Biodiversity and ecosystems in Ecuador are characterized by their equatorial location, the presence of mountains, different climatic zones, and the circulation of ocean currents (Cuesta et al, 2017; Rodríguez, 2018). Due to the variation in topography and environmental conditions, Ecuador offers a huge variety in habitats for species and ecosystems and it is considered as the top ten of the global megadiverse countries (WorldAtlas, 2023). According to a national investigation of biodiversity in 2012, 91 ecosystem types were identified in Ecuador (UN Biodiversity Lab, 2022). In relation to the status of biodiversity which supports ecosystem structures and functions, the Ecuadorian ecosystems provide different and relevant ecosystem services (ES) for human well-being. Specifically, 85 % of the surface water of Quito, the capital of Ecuador, particularly comes from the Páramo in the Andes (Buytaert et al., 2006). Recreational and aesthetic values from its unique landscape are especially important for tourism that is an essential income source (Montoya et al., 2020; Rivera, 2017). In addition, Ecuadoŕs gross domestic product is heavily dependent on natural resources. For example, crude oil exports accounted for 49 % of Ecuadoŕs export earnings and 21 % of public sector revenues in 2019 (EIA, 2021).

However, Ecuador’s dependency on natural resources is a blessing and a curse. Since large oil mining areas are located in sensitive ecosystems in the Amazon, extraction activities cause irreversible losses in

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* Corresponding author.
E-mail address: hongmi.koo@geo.uni-halle.de (H. Koo).

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biodiversity and ecosystem services (BES) due to pollution, degradation, and land conversion (Lessmann et al., 2016). The expansion of agriculture, settlements, and infrastructure also leads to noticeable landscape changes accompanied by deforestation across the country (Kleemann et al., 2022a; Buytaert et al., 2006; Fremout et al., 2020; Roy et al., 2018; Tapia-Armijos et al., 2015). According to the EU REDD Facility (n.d.), "Ecuador has the highest annual deforestation rate of any country in the Western Hemisphere" in relation to the size of the country. In specific areas, deforestation is even more dramatic. For example, the provinces Loja and Zamora Chinchipe in southern Ecuador have lost 46 % of its original forest between 1976 and 2008 (Tapia-Armijos et al. 2015). Consequently, Ecuador is on serious decline in many species and important ecosystems. Approx. 22 % of the Ecuadorian forest ecosystems are currently endangered (Noh et al. 2020).

In a portfolio of possible threats to BES, climate change can cause more pressure and brings in more uncertainty because of the long-term gradual alterations in BES (Cheng et al., 2013; Esquivel-Muelbert et al., 2019; Fadrique et al., 2018; Kleemann et al., 2022b; Lippi et al., 2019). Several studies have investigated the impact of climate change on Ecuadorian ecosystems, which is driven by an altitudinal shift due to an increase in temperature, especially in the Andean biome (Madriñán et al., 2013; Skarbø and VanderMolen, 2016; Sklenář et al., 2021). In addition to the elevational change, Esquivel-Muelbert et al. (2017) analyzed 106 plots of forests for long-term inventory in the Amazonian Biome; covering 30 years to identify a trend towards a drier climate. These studies have shown the possibility of a decrease in biodiversity due to missing adaptation to drier conditions, and the extinction of endemic species and ecosystems which could be trapped in isolated areas.

Considering the international relevance of Ecuadorian biodiversity and the anthropogenic pressure, as well as increasing climate risks, there is a need of assessing and monitoring the status of BES in Ecuador. Such heterogenity of ecosystems performs the pivotal role for sustaining ecosystem processes and functions generated by living organisms and their interactions, and that can seqentially influence the provision of ES (Bennett et al., 2015; Mace et al., 2012; Zhang et al. 2022). Thus, the importance of assessing ES together with biodiversity for sustainable landscape management has been emphasized with a conceptual and theoretical framework, e.g., the 'casecade model' (Haines-Young and Potschin, 2010). Since biodiversity is expected to affect directly and/or indirectly the provision of ES, and biodiversity is not always in positive correlation with ES, a framework for understanding the compatibility of biodiversity and ES has been developed for exploring potential win–win conditions for both aspects (Hermoso et al., 2018; Teixeira et al., 2019; Van der Biest et al., 2020). Furthermore, the focus on one ES could hamper the provision of other ES and biodiversity. For instance, agriculture for maximizing food provision can reduce landscape capacities for soil erosion control or carbon storage, and can destroy species habitats by land conversion, thereby threatening biodiversity (Ellis et al., 2019; Kragt and Robertson, 2014). Yet, the assessment of multiple ES and biodiversity, specifically considering future development in landscape is still lacking in Ecuador. In the regional report of Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) for "Americas" (IPBES, 2018), Ecuador is still addressed with minor relevance compared to Brazil and Mexico (Kleemann et al., 2022b). There have been attempts of a national identification and classification of BES (e.g. Cuesta et al., 2017; Lessmann et al., 2014; Noh et al., 2020; Sierra et al., 2002). However, some BES analyses related to human disturbance or climate change in the Ecuadorian context are limited by either focusing only on biodiversity (e.g., Bonilla-Bedoya et al., 2014; Cuenca and Echeverria, 2017), or on the ES status without including biodiversity (e.g., Dahik et al., 2018; Espinosa and Rivera, 2016; Portalanza et al., 2019; Treviño, 2022; Wilson et al., 2019).

Combining the integrative aspect of BES with scenario-based modeling can be a powerful approach to envision how landscapes might react to different trajectories of future development and policy interventions, and to determine priority options for BES conservation (Ramel et al., 2020; Rosa et al., 2020). The identification of potential trade-offs or synergies between BES induced by major changes in landscapes can be useful for elaborating effective landscape management or conservation practices at regional or national level (Bai et al., 2018; Karimi et al., 2020; Rodríguez-Echeverry et al., 2018; Teixeira et al., 2019). However, in the Ecuadorian context, scenario development was mostly used to predict deforestation patterns in the future without considering their potential impacts on ES or biodiversity (e.g., González-Jaramillo et al., 2016; Mena et al., 2017; López, 2022). Regarding climate change scenarios, existing studies focused only on the impact on biological diversity, which was limited to compare any potential trade-off with any other services and functions of ecosystems (e.g., Aguirre et al., 2017; Manchego et al., 2017).

This research contributes to close the knowledge gap concerning the identification of spatial relationships between BES capacity and landscape patterns. Specifically, we provided a national assessment of multiple ES and biodiversity taking deforestation and climate change scenarios as potential pathways. As a rapid assessment focusing on insights into future BES monitoring and management, the assessment was conducted at national level. In order to address the data scarcity issue, participatory approaches for collecting the knowledge of experts were combined with existing geophysical and spatial data using a spatially explicit modeling method. A research hypothesis tested in this study is that changes in landscape patterns due to deforestation and climate change lead to trade-offs or/and synergies between BES. Specifically, we focused on the research questions as follows:

1) Which ES are most relevant in the context of the Ecuadorian mainland?
2) Which ecosystems/land use types have the highest capacities to provide selected ES and biodiversity?
3) How are landscape patterns potentially influenced by deforestation and climate change in the future?
4) Which potential trade-offs or/and synergies could appear between BES according to the future scenarios at national level?

2. Data and methods

2.1. Study area

Ecuador is located in the equatorial zone of Latin America. The Ecuadorian mainland is delimited by the Pacific Ocean, Colombia, and Peru. The largest city in terms of population is Guayaquil with 3.1 Mio. inhabitants (2022). The capital, Quito, is located in 2,850 m a.s.l. In the year 2021, 64 % of the Ecuadorian population lived in urban areas (Statista, 2023).

The Ecuadorian mainland consists of the Coastal, the Andean and the Amazonian biomes (Fig. 1). The Coastal biome is characterized by coastal tropical rainforest and mangroves as primary natural ecosystems (Tomaselli, 2019). The Andean biome ("Sierra") covers two high mountain ridges that are connected by intermontane valleys and separated from the Coastal and Amazonian biomes by the western and eastern foothills. The intermontane valleys partially allow an exchange of flora species between the Coast and the Amazon due to their lower altitudes (sub-Andean forest, 1,000–2,300 m a.s.l) (Cabrera et al., 2019; González-Jaramillo et al., 2016; Homeier et al. 2010). The Ecuadorian highlands are up to 6,310 m a.s.l. with the Chimborazo volcano as the highest elevation. The Andean biome is characterized by montane broad-leaved forest (1,000–2,300 m a.s.l), upper montane forests (2,300-,500 m a.s.l) as well as grass-Páramo and shrub-Páramo (3,400–3,800 m a.s.l) (Cabrera et al., 2019; González-Jaramillo et al., 2016). The Amazon Basin is dominated by tropical lowland forest with its rich and unique rainforest biodiversity (Bass et al., 2010).

The anthropogenic landscape transitions in Ecuador are mainly based on three driving factors: population pressures, natural resource-

Fig. 1. Location of Ecuador in South America. The map shows the biomes as well as forest (2012) and agricultural areas (2018). .
Source: authors' elaboration in ArcGIS based on biome maps provided the Ministry of Environment, Water and Ecological Transition (MAATE)

based economy, and the agrarian reformation. Firstly, population in Ecuador has been nearly quadrupled between 1960 and 2022 (The World Bank, 2023), and especially the growth of urban population has been accelerated (Bonilla-Bedoya et al., 2020). In addition, due to the increasing demand for land use and the infrastructural expansion such as road systems, unexplored areas in the past are subject to economic development (Tapia-Armijos et al., 2015). Secondly, the main economic sector at national level is traditionally related to mining, farming, and fishing. Commercial crops are primarily banana, cocoa, and coffee while subsistence farmers grow mainly corn, potatoes, beans, and cassava (CropTrust, 2023). Apart from its huge economic dependency on petroleum, Ecuador was the largest global exporter of crustaceans and bananas as specialized products in 2021 (OEC, 2023). Forest plantations are the main sources for timber industry, which occupy approx. 180,000 ha, and largely planted with Eucalyptus, Pine, Teak, and Balsa (Tomaselli, 2019). As a major producer and exporter of raw materials, the country's biocapacity per capita has reduced by approx. 70 % since the 1960 s, while its ecological footprint has increased by approx. 35 % (Ilbay et al., 2021). Lastly, agricultural is an essential employment sector in Ecuador, and thus landscape changes due to agricultural activities have intensified (Thompson et al., 2021). The trend of agricultural expansion has been especially accelerated by the agrarian reform policies in the 1960 s and 70 s. The policies expropriated and redistributed marginal arable land to farmers, and stimulated clearing and converting forest to agriculture and cattle ranching (Balthazar et al., 2015; Ochoa-Cueva et al., 2015; Wilson et al., 2019). In the past, Amazon forests were also regarded as sterile land and settlers were encouraged to possess the land in a form of land tenure (Caballero-Serrano et al., 2017). As a result, more than 60 % of the land in the Coastal biome and more than 48 % of the land in the Andes are occupied today by agricultural area, and even the Amazon basin has become a hotspot of deforestation (Kleemann et al., 2022a).

2.2. *Data collection*

2.2.1. *Spatial data*

For the spatially explicit assessment, a land use and land cover (LULC) map which contains the spatial configuration of ecosystems and land use types was required. The currently available ecosystem map provided by the Ministry of Environment, Water and Ecological Transition (MAATE) only includes natural ecosystem types except agricultural area and other anthropogenic areas (e.g., infrastructure, populated areas) which occupy more than 50 % of the entire country. Considering the functions and pressure of agroecosystems on BES (Portalanza et al., 2019), the inclusion of such land use types is important to assess the status of BES at national level. In addition, only seven ecosystems already cover an area larger than 500,000 ha, and many ecosystem types occupy less than 0.05 % of the whole country (Cuesta et al, 2017), which could have only a marginal representation at national level. In this regard, a new map was generated by merging the ecosystem map 2012 and a land cover map 2018 provided by MAATE. The merged map was reclassified by involving experts who The merged map was reclassified by involving experts who worked directly and indirectly The merged map was reclassified by involving experts who have directly and indirectly worked on ecosystem mapping in Ecuador. They conducted the reclassifcation according to two criteria: 1) the possibility to merge ecosystem types in a higher class and 2) the representativeness / importance of ecosystem types at each biome level. For example, the Lower Montane Evergreen Forest of the Western Cordillera of the Andes, the Evergreen Montane Forest of the Western Cordillera of the Andes and the High Montane Evergreen Forest of the Western Cordillera of the Andes were merged as 'Evergreen Montane Forest of the Western Cordillera of the Andes'. As a result, the final LULC map included 44 ecosystem types (codes with E), water body, agricultural area, infrastructure, and populated area (codes with L) (Fig. A1). In addition, various spatial conditions and socio-economic status can affect the occurence of landscape changes, e.g., the influence of population density on deforestation. Thus, we collected national-level social and environmental data based on most reliable sources. A specific set of spatial data used for simulation was selected by a expert survey (see Section 2.2.2., 2.3.1., and Survey template III in Tab A1). They were a population density map 2018 obtained from the National Statistics and Census Institute, a National system of protected area (SNAP) map 2018, a water balance map 2019, maps of the Representative Concentration Pathway (RCP) (2019) from MAATE, and a Digital Elevation model (30 × 30 m, 2018) from the Military Geographical Institute (2018) (Fig. A2).

2.2.2. *Information and data from experts*

Participatory approaches provide a valuable opportunity to obtain place-based knowledge on BES (Pascua et al., 2017; Robson et al., 2019). Especially, expert elicitation is appropriate for integrative BES assessments in data-scarce environments which require regionally tailored information and the understanding of the biophysical and socio-economic conditions (Jacobs et al., 2015; Müller et al., 2020; von Thenen et al., 2020). Experts are assumed to have proficient knowledge on specific topics through their professional experiences and education, which is more reliable than in comparison to laymen's knowledge and increases the legitimacy of the results (Díaz-Reviriego et al., 2019; Jacobs et al., 2015; Pascua et al., 2017). In addition, expert-based approaches are useful for conservation and ecological studies which need to focus on intrinsic and intangible values of ecosystems (Höfer et al., 2020; Jacobs et al., 2015). Studies for assessing multifaceted BES values generally require an extensive amount of data. The application of expert knowledge is an effective alternative to complement data scarcity (Müller, et al., 2020). In this regard, this study collected and reflected the opinions and perspectives of experts throughout the assessment processes (Fig. 2). Experts who are currently working in the field of bioecology, natural conservation, forest science, and geography in Ecuador were contacted through the scientific networks of the authors, and in total, 26 experts composed of university professors (Loja National University, Central University, Regional College Amazon Ikiam) and researchers from the National Institute of Biodiversity (INABIO) and MAATE finally participated in this study. Four structured and semi-structured expert surveys were used for data collection (survey templates in Tab A1). Furthermore, experts' workshops took place two times between June 2020 and September 2021. Workshops and surveys were

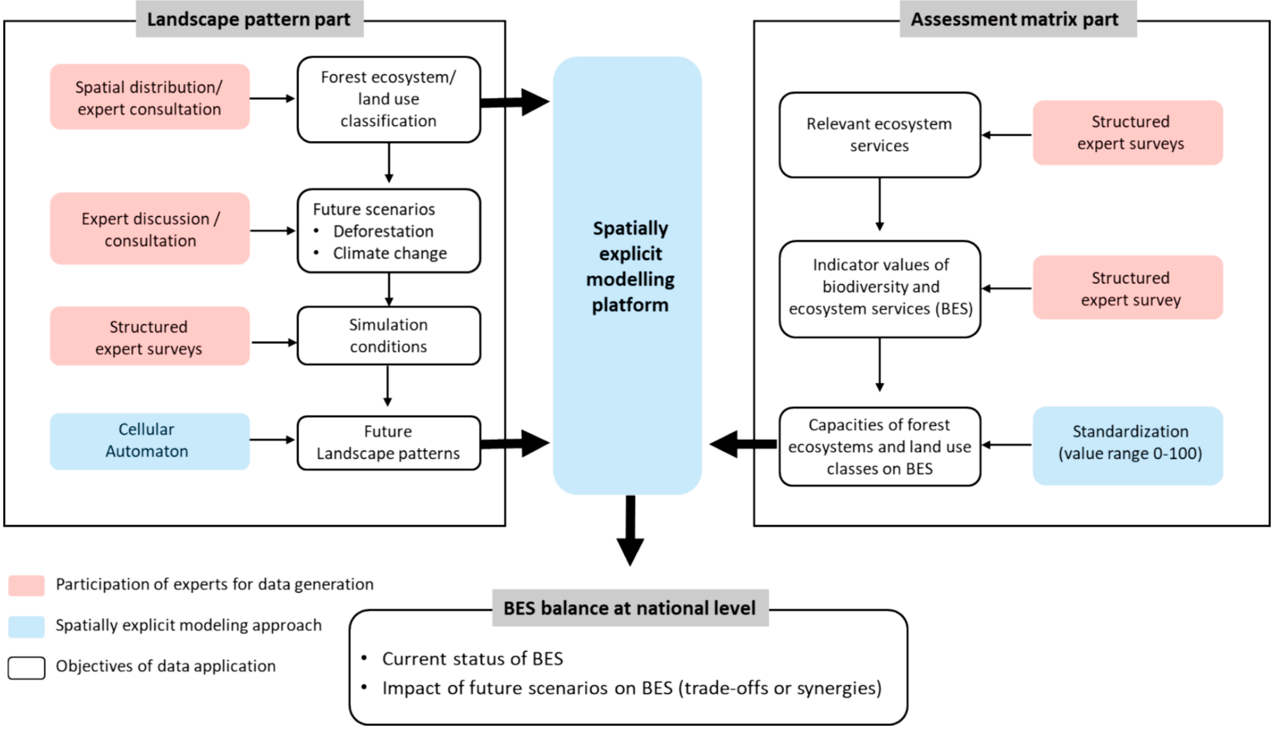


Fig. 2. Methodological framework for the impact assessment of future deforestation and climate change scenarios on biodiversity and ecosystem services (BES). Boxes in red and blue colors indicate specific methods for data generation and processing. Boxes with solid lines signify objectives of using the data. Source: authors' own elaboration (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conducted online due to the Covid situation. During the online workshops, we also offered spatial modeling training sessions to the experts in order to increase the understanding of the modeling process applied in this study. Considering the language barrier, all survey forms and workshops were written and spoken in both, English and Spanish.

2.3. Methodological approach for impact assessment of future scenarios

The status and changes of BES depending on future scenarios were assessed by a methodological framework which consists of a "landscape pattern part" and an "assessment matrix part" (Fig. 2). The landscape pattern part aimed to create future landscape patterns influenced by different scenarios. The assessment matrix part focused on identifying the relationship between ecosystems/land use types and the potential for the provision of BES. These two parts were integrated in the spatially explicit modeling platform GISCAME that is comprised of the Geographical Information System (GIS) module and the Cellular Automaton (CA) module (Fürst et al., 2011, 2012). This modeling platform allows to visualize the provision of various ecosystem functions and services in case study areas based on current and simulated landscape patterns. Positive or negative effects of simulated changes on BES can be observed in a spider chart and a balance table in comparison to the initial (current) landscape patterns (Koschke et al., 2012). Especially, numerically expressed BES values depending on scenarios allow to identify trade-offs or synergies between different ES as well as between ES and biodiversity ("output part" as BES balance at national level). The knowledge of experts was reflected in the selection of relevant ES in the Ecuadorian land use context, in the identification of BES indicators, and in the development of landscape change scenarios (red boxes in Fig. 2).

2.3.1. Landscape pattern part

Based on the newly generated LULC map (see Section 2.2.1) and expert consultation (see Section 2.2.2), future scenarios related to deforestation and climate change were developed and simulated. The deforestation scenario was defined as a decrease in forest cover which could possibly occur in next 50 years (2070) by anthropogenic pressures, especially the expansion of agricultural area. For the climate change scenarios, the "Representative Concentration Pathways" (RCP) from the Intergovernmental Panel on Climate Change (IPCC) were used. We chose two RCP scenarios: RCP 2.6 as a moderate climate change scenario with an increase in temperature between 0 °C and 2 °C expected by 2070 and RCP 6.0 as a worse scenario than the intermediate level of change with an increase in temperature between 0 °C and 4 °C projected by 2070 (IPCC, 2019). Changes in landscape patterns in areas where temperatures are likely to increase were elaborated as future scenarios.

Under the above definitions, the detailed future scenarios were developed together with the experts through workshops and structured surveys to suit the simulations using the GIS module and CA module of GISCAME. The GIS module integrates digital information on land use conditions and visualizes geographic spaces with overlapping various regional and local characteristics, e.g., soil conditions, slope conditions, accessibility to infrastructure, and population density (Fürst et al., 2013). For this study, the opinions of the experts were applied to specify affected ecosystems/land use types by deforestation and climate changes, and environmental conditions which could influence the landscape's potential to provide BES. Reflecting the information, the GIS module generated the Ecuadorian landscape map as strata of the various environmental data set. The CA module simulates cell-wise landscape changes by updating the state of individual cells depending on neighboring conditions and their own environmental status (Fürst et al., 2013). Specifically, CA was applied in this study for newly assigning ecosystems/land use types to all cells in the current landscape map according to transition rule-sets for deforestation and climate change scenarios (Fig. A3). They consist of initial (current) ecosystems/land use types, future ecosystems/land use types, transitional probability, neighboring ecosystems/land use types, and environmental attributes. The transition rule-sets were elaborated based on structured expert surveys (Survey templates III and IV in Tab A1) that were explained in Section 2.2.2. For instance, the experts were inquired if (with which probability, %) evergreen forest will be converted to agricultural area due to deforestation in the future under which specific neighborhood conditions (neighboring cell types, e.g., existing anthropogenic related land use types) and environmental conditions (e.g., slope conditions, existence of nature conservation programs, population density). Among various environmental factors that potentially influence landscape changes, three most relevant environmental conditions for each scenario were determined based on an expert survey: a) slope, b) water balance (water availability) and the c) National System of Protected Areas (SNAP) for the deforestation scenario, and a) elevation, b) population density, and c) water balance (water availability) for the climate change scenario.

2.3.2. Assessment matrix part

As an initial step to identify relevant ES in the Ecuadorian context, 21 potential ES were selected from the Common International Classification of Ecosystem Services (CICES, 2018) (https://cices.eu, version 5.1). Then, experts rated the relevance of the preselected ES with the Likert-scale from 0 (not relevant at all) to 5 (very relevant) (Survey template I in Tab A1). The mean and standard deviation of the collected relevance levels were used to determine the final set of ES for the impact assessment. Furthermore, in order to give high relevance to biodiversity as an underlying factor of ecosystem structures and functions to provide ES (IPBES, 2019; Potschin-Young et al., 2018), biodiversity was always considered in this impact assessment together with the selected ES.

The next step was the estimation of BES capacities that are potentially provided by each ecosystem/land use type. Expert-based estimation using a matrix model is one of the most popular assessment methods for BES capacities depending on different LULC classes (Campagne et al., 2017; Jacobs et al., 2015). The assessment matrix quickly provides comparable and comprehensive information under data scarce conditions, which can be transferred to BES mapping (Burkhard et al., 2012; Jacobs et al., 2015; Juanita et al., 2019). Apart from the uncertainty of the method regarding the exactness of measuring the complex relationship between humans and ecosystems, it is still a manageable instrument for exploring alternatives or comparing future scenarios (Müller et al., 2020; Sun et al., 2020). The indicator values for BES in this study were calculated based on the collected data through a structured expert survey (Survey template II in Tab A1). Specifically, the experts were asked for the potential of ecosystems/land use types to provide the selected ES with the Likert-scale from 0 (the minimum potential for ES provision) to 10 (the maximum potential for ES provision). The indicator values for biodiversity were identified as the perceived extent of variety of living species and their interactions potentially provided by individual ecosystem/land use types. Their values for the whole ecosystems/land use types were also collected with the Likert-scale from 0 (the minimum potential for biodiversity) to 10 (the maximum potential for biodiversity). All BES indicator values were standardized with value range between 0 (the minimum capacity) and 100 (the maximum capacity) in order to fit the GISCAME assessment to the matrix format.

2.3.3. Assessment of biodiversity and ecosystem service balance at national level

The newly generated landscape patterns according to the CA simulation for deforestation and climate change scenarios were integrated with the assessment matrix. Specifically, the BES values of the whole Ecuadorian mainland were calculated as the mean of BES values assigned to each ecosystem/land use type in the current and future landscape maps. Namely, the final assessment scores implied the mean capacity of the Ecuadorian mainland to provide BES. Through the comparison of the numerically presented BES status between the current landscape map and the future landscape maps, the potential impact of the scenarios was identified as trade-offs or synergies between the different ES and biodiversity. Capacity maps to visualize high capacity areas and low capacity areas regarding BES provisioning levels were also generated, which can be helpful to identify the locations of prioritized areas for actions.

3. Results

3.1. Relevant ecosystem services and indicator values

As the most relevant ES at national level, food, drinking water, service water (for irrigation, cooking, washing, etc.), soil erosion control, water flow regulation, pollination/seed dispersal, regulation of macro climate, and landscape aesthetic/amenity were identified. According to the BES assessment matrix (Table 1), land use types (L) induced by anthropogenic activities such as agricultural area, populated area and infrastructure (L2, L3, L4) showed lower capacity than ecosystem types (E) in delivering BES, except food provision by agricultural area. Specifically, Equatorial Mangrove (E2) that is only present in the Coastal biome showed the second highest value in food provision after agricultural area. Among ecosystem types, grassland- and shrub-related ecosystems (E9, E10) displayed relatively lower food provisioning capacity. The capacity of the Páramo ecosystem types (E9, E12) was highest in providing drinking water and service water. On the other hand, Equatorial Mangrove (E2) presented the lowest value in these two ES among all ecosystems. In terms of soil erosion control, Montane Evergreen Forest of the Western Cordillera of the Andes (E5) located in the Andes and the Coast, and Evergreen Piedmont Forest of the Eastern Cordillera of the Andes (E18) presented the highest capacity to provide this ES. Most ecosystem types showed high capacity for soil erosion control, while lowland grassland related ecosystem types (E24, E25, E31) had relatively lower values in this ES. The value of water flow regulation was higher in Páramo-related ecosystem types (E9, E12) than other ecosystem types. Most of the ecosystem types showed similarly high values for water flow regulation. Pollination was also at high capacity levels by most of the ecosystem types. Especially, evergreen forest located in the border between the Andes and the Coast such as Evergreen Piedmont Forest of the Western Cordillera of the Andes (E4) and Montane Evergreen Forest of the Western Cordillera of the Andes (E5) showed the highest capacities to provide pollination. The potential of water bodies (L1) and agricultural area (L2) to contribute to pollination was also captured. Regarding regulation of the macro climate, Evergreen Lowland Forest of the Equatorial Chocó (E3) mostly located in the Coastal biome presented the highest capacity, and most ecosystem types seemed to deliver this ES with high level. In addition, the contribution of water bodies (L1) to climate regulation was also perceived as high. The capacity to provide landscape aesthetic and amenity was shown mainly by ecosystem types located in the Cóndor-Kutukú mountain ranges of the Amazon (E30, E32, E34) and Equatorial Mangrove (E2). Lastly, the capacity to provide biodiversity was valued highest by the ecosystem types in the Amazon such as Lowland Evergreen Forests (E16) and Montane Evergreen Forest of the Cóndor-Kutukú Mountain ranges (E30, E32, E34). As for ES, most ecosystem types showed high capacities to provide biodiversity. Among the ecosystem types, Páramo related ecosystems (E9, E12) were regarded as most effective to deliver multiple services (6 different ES and for biodiversity) with capacity values above 90.

3.2. Scenario impact on biodiversity and ecosystem services

3.2.1. Impact of the deforestation scenario

The transition rule-sets to simulate deforestation are presented in Table 2. The expansion of agricultural area was the main cause of deforestation in the Ecuadorian mainland, e.g., shown as the conversion of evergreen forest to agricultural area with a 75 % of probability. When existing forest ecosystems are adjacent to anthropogenic land use types, i.e., agricultural area, populated area or infrastructure, the forest ecosystem types tend to change to agricultural area. Relevant environmental attributes that can push deforestation were a) slope conditions (defined as a threshold of the degree where deforestation occurred

Table 1

Indicator values of selected ecosystem services and biodiversity provided by ecosystems/land use types within a scale from 0 (the minimum provisioning capacity, in white) to 100 (the maximum provisioning capacity in dark green). Codes from E1 to E44 indicate “ecosystem types” and codes from L1 to L2 signify “land use types” especially related to anthropogenic activities.

Code	Ecosystem and land use types	Food	Drinking water	Service water	Soil erosion control	Water flow regulation	Pollination and seed dispersal	Regulation of macro climate	Landscape aesthetic and amenity	Biodiversity
E1	Flooded Forest of Alluvial and Intertidal Plain of the Equatorial Chocó	61	46	53	83	78	90	92	92	95
E2	Equatorial Mangrove	92	14	20	82	69	87	95	98	93
E3	Evergreen Lowland Forest of the Equatorial Chocó	74	64	59	94	88	96	100	92	96
E4	Evergreen Piedmont Forest of the Western Cordillera of the Andes	68	70	62	97	87	99	96	88	96
E5	Montane Evergreen Forest of the Western Cordillera of the Andes	65	74	72	100	94	99	97	90	96
E6	Seasonal Evergreen Piedmont Forest of Chocó Coastal Range	65	63	68	97	90	97	92	90	95
E7	Semideciduous and Deciduous Lowland Forest of Jama-Zapotillo	59	46	50	96	81	92	87	88	93
E8	Lower Montane Evergreen Forest of Chocó Coastal Range	70	58	59	96	91	100	95	93	96
E9	Rosetal Caulescente and Páramo Grassland (frailejones)	48	94	91	99	97	92	92	96	87
E10	Evergreen Shrub and Páramo Grassland	50	87	85	92	93	96	94	96	88
E11	Forest and Semideciduous Shrubland of the North of the Valleys	59	48	52	93	82	87	91	86	88
E12	Páramo Grassland	53	98	89	96	100	96	92	94	90
E13	Montane Evergreen Forest of the North of the Eastern Cordillera of the Andes	68	76	73	99	92	95	96	90	93
E14	Montane Evergreen Shrub in the Northern Andes	54	65	65	90	92	95	89	87	87
E15	Lower Montane Evergreen Forest of the North of the Eastern Cordillera of the Andes	61	70	68	97	95	92	96	93	90
E16	Lowland Evergreen Forests of the Amazon	79	70	73	97	94	96	95	94	100
E17	Flooded Forest of the Floodplain of the Amazon	65	51	64	92	89	96	96	95	95
E18	Evergreen Piedmont Forest of the Eastern Cordillera of the Andes	63	70	74	100	94	97	91	92	93
E19	Semideciduous and Deciduous Forest of the Equatorial Pacific Coastal Range	56	50	57	93	84	93	91	88	93
E20	Seasonal Evergreen Piedmont Forest of the Equatorial Pacific Coastal Range	62	55	59	93	87	95	91	92	93
E21	Low Montane Seasonal Evergreen Forest of the Equatorial Pacific Coastal Range	61	62	67	94	84	95	91	89	91
E22	Lowland Seasonal Evergreen Forest of Jama-Zapotillo	60	60	65	94	84	93	89	88	90
E23	Lake-riparian Flooded Grassland of the Amazon Floodplain	61	46	61	84	83	86	88	89	86
E24	Lowland Riparian Floodplain Grassland of Jama-Zapotillo	62	52	62	77	83	84	86	88	86
E25	Lowland Riparian Flooded-lake Grassland	63	51	63	73	79	82	86	86	86
E26	Evergreen Piedmont and Montane Forest of Galeras	64	63	66	97	86	97	95	94	91
E27	Seasonal Floodplain Evergreen Forest of Jama-Zapotillo Floodplain	59	58	63	96	87	95	95	90	90
E28	Riparian Evergreen Shrub of the Eastern Cordillera of the Andes	55	50	54	87	83	88	89	88	86
E29	Montane Evergreen Forest of the South of the Eastern Cordillera of the Andes	63	68	67	94	95	98	94	92	92
E30	Evergreen Piedmont Forest of the Cóndor-Kutukú Mountain ranges	65	66	73	99	97	97	95	99	98
E31	Low Montane Lake Grassland of the South of the Eastern Cordillera of the Andes	57	60	67	79	80	83	89	87	87
E32	Montane Evergreen Forest of the Cóndor-Kutukú Mountain ranges	59	64	70	96	91	94	96	98	99
E33	Evergreen Shrubland and Montane Grassland of the Cordillera del Cóndor	55	61	63	90	86	90	90	97	92
E34	Montane Evergreen Forest on Sandstone Plateaus of the Cóndor-Kutukú Mountain ranges	48	61	60	99	95	97	95	100	99
E35	Evergreen Piedmont Forest on Limestone Outcrops of the Amazonian Cordilleras	50	49	51	97	88	96	96	96	97
E36	Montane Evergreen Shrub of the Southern Andes	58	63	66	91	84	92	91	88	90
E37	Semideciduous Shrubland of the Southern Valles	58	60	68	90	85	89	89	85	86
E38	Evergreen Piedmont Forest of Catamayo-Alamor	61	66	73	95	93	92	94	86	92
E39	Lower Montane Seasonal Evergreen Forest of Catamayo-Alamor	59	65	73	97	89	96	89	86	90
E40	Montane Evergreen Forest of Catamayo-Alamo	58	65	68	98	94	97	95	87	92
E41	Semideciduous and Deciduous Forest of Catamayo-Alamor	54	55	62	93	91	92	95	89	93
E42	Lower Montane Semideciduous Forest of Catamayo-Alamor	57	55	61	94	91	90	95	86	92
E43	Lower Montane Deciduous Forest of Catamayo-Alamor	52	50	57	93	90	92	92	89	90
E44	Semideciduous Piedmont Forest of the South of the Eastern Cordillera of the Andes	59	53	59	95	91	96	95	88	90
L1	Water body	70	100	100	23	47	45	78	95	86
L2	Agricultural area	100	4	21	11	7	30	17	22	18
L3	Populated area	13	0	1	0	0	7	4	6	5
L4	Infrastructure	0	1	0	1	3	0	0	0	0

Source: authors’ own elaboration based on the experts’ surveys.

between 2014 and 2016) (MAATE, 2020), b) the water availability (water supply > water demand), and c) the areas outside the protection program SNAP.

The application of the transition rule-sets of deforestation showed the future landscape patterns (Fig. 3). Agricultural area expanded by the deforestation scenario across the country, especially in the Amazonian biome. Specifically, agricultural area would occupy in the deforestation scenario almost 50 % of the whole country (increased by 14.3 %) (Tab A2). In contrast, forest would decrease by 5 % the Lowland Evergreen Forests of the Amazon (E16), by 1.6 % the Evergreen Piedmont Forest of the Eastern Cordillera of the Andes (E18), and by 1 % the Evergreen Lowland Forest of the Equatorial Chocó (E3). Such changes in landscape patterns affected the provision of BES. The capacity maps in Fig. 3(a) visualize the spatial distribution of BES compared to the current status. The red areas – implying a low capacity to provide BES – expanded, which indicated a decline in the capacity of biodiversity and drinking water at national level. When it comes to the overall BES potential, most BES would decrease between 20 % and 25 % due to deforestation while food provision would increase approx. 5 % as a trade-off (Fig. 3(b)). This is obviously linked to a decrease in ecosystems by the replacement with agricultural area that has the highest potential to provide food.

3.2.2. *Impact of the climate change scenarios*

The identified transition rule-sets for simulating climate change scenarios are shown in Table 3. Páramo, Flood plain forest, and Piedmont evergreen forest were identified by the experts as vulnerable ecosystem types that would be particularly affected by an increase in temperature. Those ecosystems can be converted to Montane forest, Lowland evergreen forest and agricultural area respectively, due to changes in suitability and climate conditions. The probability of changes

Table 2
Simulation conditions of deforestation scenarios at national level.

Current ecosystem/land-use type	Future ecosystem/land-use type	Probability of change	Neighborhood type	Environmental attributes
Deciduous forest [a)]	Agricultural area	68 %	Agricultural area or populated area or infrastructure [e)]	• Slope ≤ 56 degree[1)] • Water supply > Water demand • Outside SNAP area
Evergreen forest [b)]	Agricultural area	75 %		
Lower montane semi-deciduous forest [c)]	Agricultural area	62 %		
Shrub land [d)]	Agricultural area	68 %		

a) E7, E19, E19, E41, E43 (codes in Table 1).
b) E3, E4, E5, E6, E8, E13, E15, E16, E18, E20, E21, E22, E26, E27, E29, E30, E32, E34, E35, E38, E39, E40.
c) E42.
d) E10, E14, E28, E33, E36, E37.
e) L2, L3, L4.
1) Slope condition: maximum degree (threshold) of areas that experienced deforestation in the period 2014–2016 (MAATE, 2020).
SNAP = National system of protected areas
Source: authors' own elaboration based on experts' surveys.

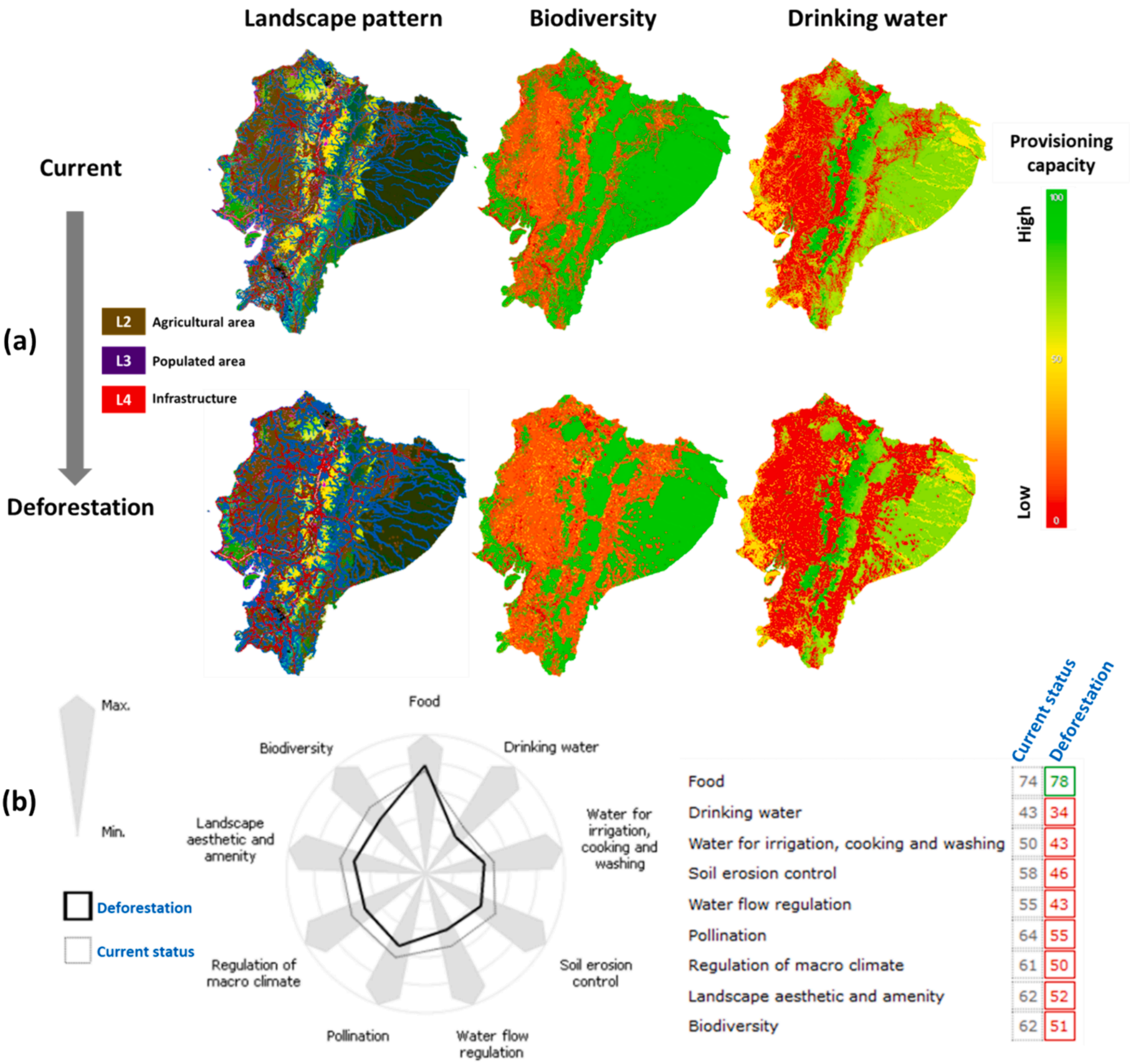


Fig. 3. Schematic representation of the deforestation scenario impacts on landscape patterns and the status of biodiversity and ecosystem services (BES). Capacity maps of ecosystems/land use types to provide BES are presented according to the current status and future deforestation scenario (a). The spider charts and the balance tables show changes in the values of BES compared to the current status as reference. Values are presented in a standardized value range between 0 (the minimum capacity to provide BES) and 100 (the maximum capacity to provide BES). Increased values are in green boxes and decreased values are in red boxes (b). Source: authors' own elaboration based on captured images from the GISCAME platform. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Simulation conditions of climate change scenarios at national level.

Current ecosystem/land-use type	Future ecosystem/land-use type	Probability of change	Neighborhood type	Environmental attributes
RCP 2.6: An increase in temperature by 2 °C				
Páramo a)	Montane forest d)	35 %	Páramo a)	• Elevation: ≤ 5,228 m 1) • High population density 2) • Water supply > Water demand
Flood plain forest b)	Lowland evergreen forest e)	35 %	Agricultural area f) or Lowland evergreen forest e)	
Piedmont evergreen forest c)	Agricultural area f)	62 %	Agricultural area f) or Lowland evergreen forest e)	
RCP 6.0: An increase in temperature by 4 °C				
Páramo a)	Montane forest d)	48 %	Páramo a)	• Elevation: ≤ 5,328 m 1) • High population density 2) • Water supply > Water demand
Flood plain forest b)	Lowland evergreen forest e)	45 %	Agricultural area f) or Lowland evergreen forest e)	
Piedmont evergreen forest c)	Agricultural area f)	68 %	Agricultural area f) or Lowland evergreen forest e)	

a) E9, E10, E12 (codes in Table 1).
b) E1, E17.
c) E4, E6, E18, E20, E26, E30, E35, E38.
d) E5, E8, E13, E15, E21, E29, E32, E34, E39, E40, E42, E43.
e) E3, E16, E22.
f) L2.
1) Elevation condition: maximum elevation (threshold) of that will be affected by the increase of temperature by 2070 (generated by overlapping an elevation map 2018 and the RCP maps 2019).
2) Population density condition: ≥ 70 people /Km^2 (the first 1/3 quantile of the population density in 2018).
Source: authors' own elaboration based on experts' surveys.

was rated by the experts as being higher in the RCP 6.0 scenario compared to the RCP 2.6 scenario. The following environmental attributes which can affect the landscape changes were identified by the experts: a) elevation conditions (altitudinal shift of habitat), b) population density, and c) the status of water balance (water availability).

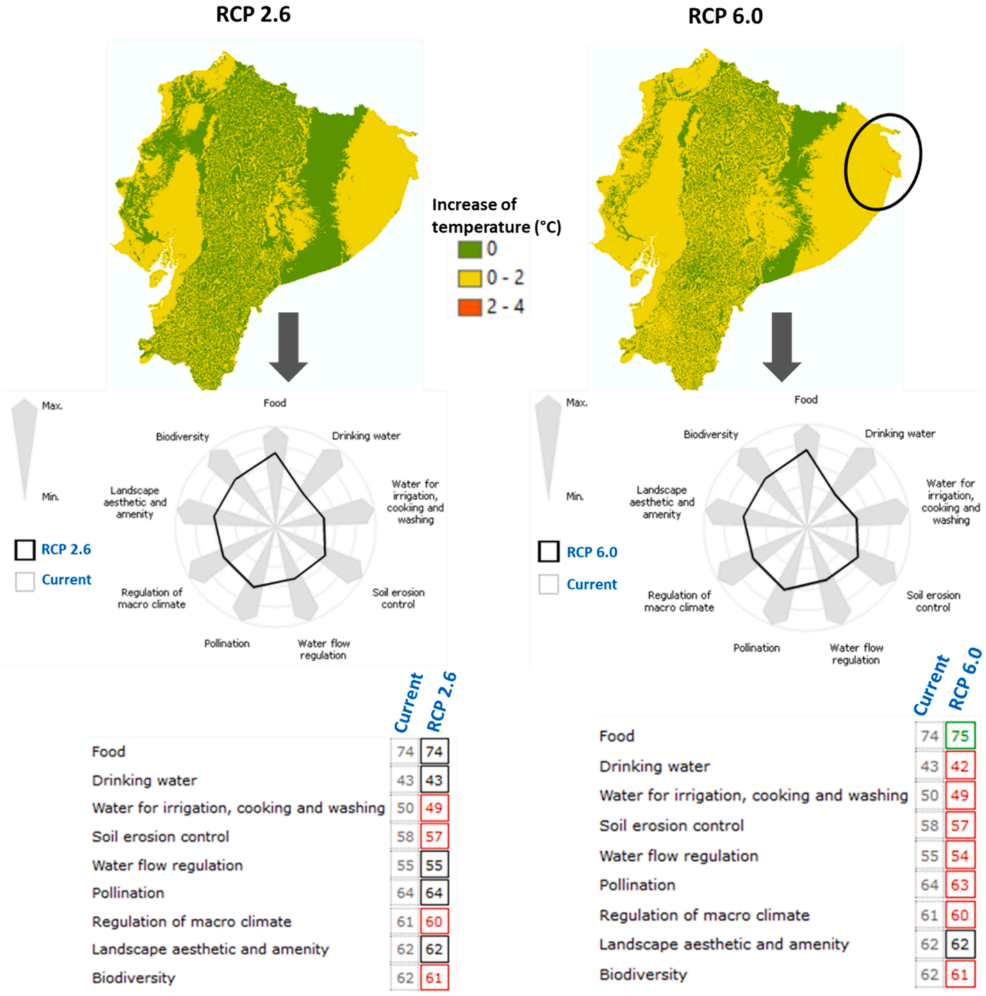
The application of the transition rule-sets led to the changes in the capacity to provide BES at national level (Fig. 4). If temperature would increase by 2 °C, according to the RCP 2.6 scenario, service water, soil erosion control, regulation of macro climate and biodiversity could slightly decrease. The climate change impact was more visible in the RCP 6.0 scenario (an increase in temperature by 4 °C). However, only a limited area in the east side of Amazonian lowland would experience an increase in temperature above 2 °C. Most capacities of BES, except landscape aesthetic, would decrease, while the food provisioning capacity would increase as a trade-off. This can be linked, according to the expert's knowledge, to the possible elevational expansion of arable land into higher altitudes, e.g., the conversion of Piedmont Evergreen Forest to agricultural area. In addition, forest ecosystems could be disturbed due to climate change. For example, the Flooded Forest of the Floodplain of the Amazon (E17) could decrease by 2.6 %. In contrast, Lowland Evergreen Forests of the Amazon (E16) could increase by 2.4 % in RCP 6.0 (Tab A2). Unlike the deforestation scenarios, noticeable changes of more than 3 % in BES provision were not induced by the climate change scenarios.

4. Discussion

4.1. The characteristics of the impact of the scenarios

As one of the most unique ecosystem types, mangroves are only located in the Coastal biome and are considered to be highly productive habitats which provide various socio-economic and environmental services, including forestry products, estuary and littoral fishing, ecotourism, and carbon sequestration (Latorres, 2012; Rodríguez, 2018). Especially, the marine environment established around mangroves is suitable for aquaculture such as shrimp farming (Mestanza-Ramón et al., 2019), and this was reflected in this study by the high capacity of Equatorial Mangrove (E2) in food provision. Due to the relatively small size of their habitat (0.6 % of the whole country), such positive impact of mangroves was not well captured in this national level assessment. Páramo-associated ecosystem types are mainly located above the montane tree line in the Andean biome (Peyre et al., 2019). As one of the most humid ecosystems due to its ability to absorb and store water (Balthazar et al., 2015; Espinosa and Rivera, 2016; Ross et al., 2017), Páramo ecosystems provide a wide range of ES particularly related to water provision and water regulation (Table 1). Most of the cities in the northern Andes benefit from, e.g., domestic and industrial water supply, water for irrigation, and hydroelectric power generation (Dahik et al., 2018). In addition, the tropical Andean Páramo in high elevation is regarded as a "hotspot within a hotspot" in terms of plant diversity and endemism (Madriñán et al., 2013; Ross et al., 2017), as well as regarding soil carbon storage (Thompson et al., 2021). Regional perspectives based on the experts' knowledge in this study were also similar to literature, as Páramo-related ecosystems (E9, E12) were rated with high capacity values for multiple ES and biodiversity. Lowland Evergreen Forests of the Amazon (E16), occupying the majority of the Amazonian biome, were identified as the ecosystem type with the highest capacity for biodiversity provision. This is in line with the fact that the habitat in the Lowland Evergreen Forests has no temperature limitation (no seasonality) on the growth of plants, as well as the development of different niche species, which results in high biodiversity (Buscardo et al., 2018).

Deforestation scenarios were simulated considering the proximity to existing anthropogenic land use types – reflected in the neighboring cell conditions (Table 2). This indicates that human pressure is an important driver of landscape patterns, such as the distance to high population densities and infrastructure (Fernandez et al., 2015; Van Der Hoek, 2017) and agricultural areas (Kleemann et al., 2022a; Lippe et al., 2022). As agricultural activities were identified as the main driver of the deforestation in this study, slight or no slopes (e.g., Kleemann et al., 2022a; Tapia-Armijos et al., 2015) and water balance indicating water availability (e.g., Fries et al., 2020; Salmoral et al., 2018) were reflected as the simulation conditions. The designation of SNAP areas was applied as the restriction of deforestation. However, some studies have doubted the effectiveness and usefulness of such protected areas because the deforestation trend in the areas of SNAP was not weaker compared to the areas with lower protection status due to insufficient control (Kleemann et al., 2022a; Lippe et al., 2022).



	Current	RCP 2.6
Food	74	74
Drinking water	43	43
Water for irrigation, cooking and washing	50	49
Soil erosion control	58	57
Water flow regulation	55	55
Pollination	64	64
Regulation of macro climate	61	60
Landscape aesthetic and amenity	62	62
Biodiversity	62	61

	Current	RCP 6.0
Food	74	75
Drinking water	43	42
Water for irrigation, cooking and washing	50	49
Soil erosion control	58	57
Water flow regulation	55	54
Pollination	64	63
Regulation of macro climate	61	60
Landscape aesthetic and amenity	62	62
Biodiversity	62	61

Fig. 4. Potential impact of climate change scenarios (RCP 2.6 with a temperature increase up to 2 °C and RCP 6.0 with a temperature increase up to 4 °C) on the provision of biodiversity and ecosystem services (BES). The area influenced by the increase of temperature above 2 °C is only located in the east side of Amazonian lowland (in the circle). The spider charts and the balance tables show changes in the values of BES compared to the current status as reference. Values in the balance tables are presented in a standardized value range between 0 (the minimum capacity) and 100 (the maximum capacity to provide BES). Increased values are in green boxes and decreased values are in red boxes. No change is shown in black boxes. Source: authors' own elaboration based on captured images from the GISCAME platform. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Climate change scenarios were elaborated as the impact of an increase in temperature on landscape patterns, which were the decline of specialized cold-adapted plant species, the expansion of lowland forests, and the expansion of agricultural area (Table 3). Unlike deforestation scenarios that converted ecosystems into anthropogenic areas, climate change scenarios mostly simulated changes from one ecosystem to another with similar capacities to provide BES. Thus, the impact of climate change was not as visible as in the deforestation scenarios. However, the changes in temperature are closely linked to the altitudinal shift of ecothermal belts (Bendix et al., 2010). This indicates that some endemic species can be threatened by ecosystem disturbance and loss. Although climate change-affected areas are more widely distributed in the Amazon than in the Andes (Fig. 4), endemic species highly adapted to cold climate in the Andes could experience more losses if the temperature increases equally across the country. Specifically, as presented in the simulation condition, high altitude restricted ecosystems like Páramo would be subject to changes, since only limited species are possible to migrate, thereby progressively reducing their habitats under an increase in temperature (Madriñán et al., 2013; Sklenář et al., 2021). Skarbø and VanderMolen (2016) identified the upward expansion of maize cultivation during last two decades in Ecuador as a climate change adaptation strategy, which allows to maintain or increase food production similar to the result of this study.

4.2. Implications for landscape management

The BES assessment linked with different landscape patterns can further explore future recommendations to enhance positive effects or handle adverse effects (Bagstad et al., 2014; Lawler et al., 2014). Based on the simulation and assessment results, measures and actions can be contemplated for better landscape management. For instance, conservation measures should focus on Páramo-related ecosystems that are vulnerable to climate change impacts and the expansion of agricultural areas, while providing a variety of ES and biodiversity most effectively. The degradation of the ecosystems is mainly caused by burning coupled with overuse in agriculture, plantations and livestock grazing (Bremer et al., 2019; Dahik et al., 2019). For the alteration of such traditional land use activities, the Ecuadorian government started the SocioPáramo program to provide conservation incentives for land owners to protect the Páramo instead of burning them (Farley and Bremer, 2017). The sustainability of conservation activities via payments, however, is being often questioned due to the instability and uncertainty of subsequent funding (Hayes et al., 2022). Thus, alternative options to support livelihood with less pressure on the ecosystems, e.g., ecotourism, as well as environmental education to increase an awareness of BES values should be suggested for behavioral changes.

The Amazonian biome which showed prominent changes in landscape patterns by deforestation and the increase of the temperature needs intensive and proactive protection strategies. Conservation activities have been emphasized and activated due to the vital role of the Amazon for producing various ecological functions and services from local to global scales. At the same time, the conflicts between ecosystem conservation and socio-economic developments have continued (Bonilla-Bedoya et al., 2018). Beyond the regeneration of degraded forest ecosystems and the expansion of protected areas, the incorporation of conservation strategies into mid-term and long-term landscape planning should be taken into account. Considering that most BES studies conducted in the Ecuadorian context over the past 20 years have focused on either micro (local, field level) or meso (regional, watershed level) scales (Kleemann et al., 2022a), the results of this study as a rapid assessment at national level could be a starting point to establish a regular BES monitoring and assessment system for future landscape planning. Furthermore, the applied framework presented as a stepwise process can be tested in similar regions. For instance, Peru is one of the worlds' top ten megadiverse countries like Ecuador, but ecosystem related studies in the Peruvian context have been so far biased to specific regions, taxa and topics (Sotomayor et al., 2024). This study could inspire future landscape research in Peru, especially related to addressing data scarcity and incorporating different methods for comprehensive BES assessment.

4.3. Methodological discussion

Participatory approaches in combination with land use mapping and modeling, as applied in this study, have advantages and disadvantages (Koo et al., 2020; Mallampalli et al., 2016). Using experts' knowledge tailored to the case study context is a suitable method under data scarcity and uncertainty (Jacobs et al., 2015; Müller, et al., 2020). Specifically, cultural ES that are considered as important but hard to be measured using any quantified indicators due to the lack of national data, e.g., landscape aesthetic and amenity, can be evaluated based on the knowledge of experts. The involvement of relevant experts from the initial stage of data collection to the development of simulation conditions for future scenarios can also increase the credibility, legitimacy, and acceptance of the findings (Sarkki et al., 2014). Furthermore, discussion among experts can guide future questions and developments in landscape and conservation management by understanding the impact of BES maintenance and protection (Dietl et al., 2023; Kusi et al., 2020; Urgenson et al., 2013). Landscape management experts at national level from various research institutes, universities, and ministries in Ecuador had the opportunity to interact each other and to coproduce knowledge about potential trade-offs, decision options, and assessment criteria. Specifically, the collaboration between scientists and environmental experts in ministries and public institutions allows to cross the science-policy border (Sarkki et al., 2014; Young et al., 2014). Furthermore, the involvement of representatives from public institutions (MAATE, INABIO) have increased the relevance of this study due to their political mandate. However, the most prominent contra argument towards participatory approaches is the subjectivity in data and that the results are dependent on the knowledge and expertise of participants. Although we chose the experts according to their long-lasting experience in biodiversity and ecosystems at national level in Ecuador, it should be considered that the perspectives and opinions of the experts could be altered depending on the changing environmental conditions, land use policies, and their duties and interests in the future.

A spatially explicit simulation using GISCAME was applied for the quantification and mapping of BES values. As GISCAME can perform with simplified environmental data, it is straightforward to test various future alternatives and translate the simulated results into decision-making, e.g., priority areas for conservation actions (Koo et al., 2020). Visualized and quantified simulation results can improve the understanding of future pathways for BES provisioning and facilitate the communication between different experts (scientific experts and policy-makers) for establishing shared visions (Verburg et al., 2016). In order to increase model transparency which is a crucial process in participatory modeling (Mendoza and Prabhu, 2005; Saarikoski et al., 2018), we provided the GISCAME training to the experts. Similar to the experience by Price et al. (2012), it was worthy to train the experts and explain the technical modeling process to ensure that the experts understood all assessment steps and the aim of data elicitation. Understanding why and how landscapes are changing requires more than just the creation of a map. The input on causal landscape processes and conditional values provided by experts allows a better and deeper understanding of interdependencies between BES (Price et al. 2012). On the other hand, as modeling approaches focus on addressing the abstract of complex environments, dynamics of interactions between landscape patterns and the status of BES should be inevitably simplified. Especially, even within the same forest ecosystem types, the level of biodiversity can vary depending on their environmental conditions (e.g., soil conditions, humidity, size of patches), and they can be measured by Essential Biodiversity Variables (EBVs) (Pereira et al., 2013). In addition, some ES are indirectly and directly connected with EBVs, e.g., regulation of macro climate with net primary productivity, and pollination with habitat structure (O'Connor et al., 2020). Although their linkages were not included in this study due to the lack of national level data to calculate EBVs, this aspect should be considered with attempts to combine remote sensing data, field data, and benefit transfer methods.

Lastly, we faced some challenges with spatial and temporal resolution. For instance, despite the uniqueness and importance of the Galapagos Island in a BES assessment, the archipelago could not be included due to its small size in relation to the national scale (data resolution-related problems). It would require an additional and separate data elicitation process at finer spatial resolution to properly assess the Galapagos Islands biome that was not possible in the short duration of the research. Spatial data applied in this study were only partially available at different temporal scales, e.g., the ecosystem map 2012 and the land use map 2018 for generating new LULC map. As these two maps were not fully overlapping due to the time difference, there is the limitation to track potentially missing forest ecosystems between 2012 and 2018. Related to the temporal issue, the time scale inside the modeling platform is basically dimensionless. Although scenarios were simulated for 2070 according to the definition agreed with the experts, the assessment results should be understood as one of the potential pathways in the near future.

5. Conclusion

An assessment of potential impacts of future scenarios on BES was conducted at national level for Ecuador by integrating expert knowledge with a spatially explicit modeling approach. Scenarios were developed as the impact of deforestation and climate change on current landscape patterns. Deforestation scenarios were simulated considering the proximity to the existing anthropogenic areas, slope conditions, and water availability, as well as the status of protection program (SNAP). The deforestation scenario showed the increase of agricultural area by approx. 14.3 %. In contrast, some forest ecosystems declined, e.g., 5 % decrease in the Lowland Evergreen Forest of the Amazon, and 1.6 % decrease in the Evergreen Piedmont forest of the Eastern Cordillera of the Andes. Such changes would influence the BES capacities. Most BES would decrease between 20 % and 25 % while food provision would be enhanced by approx. 5 % as a trade-off. This change is highly related to the replacement of forest ecosystems with agricultural area which has the highest potential to provide food. Climate change scenarios were simulated as potential landscape changes due to an increase in temperature. RCP 2.6 which indicates an increase in temperature up to 2 °C by 2070 and RCP 6.0 which presents an increase of temperature up to 4 °C by 2070 were chosen. Future scenarios related to RCPs were elaborated as the replacement of cold-adapted ecosystems (e.g., Páramo) to other ecosystems or agricultural area. RCP 6.0 showed more visible changes in BES than RCP 2.6, which would decrease most BES, except landscape aesthetic, while food provision would increase as a trade-off. The approach and results of this study, e.g., visualized synergies or trade-offs between BES, and changes in BES capacity maps can provide useful information for establishing a national monitoring system to assess the progress in maintaining and improving BES. Considering the distinct characteristics of biomes in Ecuador, there should be further research on BES assessment at biome level. Especially, the development of biome-specific landscape change scenario (e.g., degradation scenarios vs. conservation scenarios) and the assessment of their impacts on BES can be useful to provide recommendations tailored to each biome.

CRediT authorship contribution statement

Hongmi Koo: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Janina Kleemann:** Writing – review & editing, Project administration, Funding acquisition, Data curation. **Pablo Cuenca:** Writing – review & editing, Resources, Funding acquisition, Data curation. **Jin Kyoung Noh:** Writing – review & editing, Project administration, Investigation, Data curation. **Christine Fürst:** Supervision, Software.

Declaration of competing 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

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2024.101652.

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