frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 12 July 2022
doi: 10.3389/fenvs.2022.941887

Spatiotemporal Changes in Land Use and Ecosystem Service Values Under the Influence of Glacier Retreat in a High-Andean Environment

Santiago Madrigal-Martínez[1]*†, Rodrigo J. Puga-Calderón[1]†, Victor Bustínza Urviola[2] and Óscar Vilca Gómez[2]

[1]Dirección de Información y Gestión Del Conocimiento, Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña, Huaraz, Perú, [2]Oficina Desconcentrada Macro Región Sur, Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña, Cusco, Perú

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***Correspondence:**
Santiago Madrigal-Martínez
smadrigal@inaigem.gob.pe

†These authors have contributed equally to this work and share first authorship

Specialty section:
This article was submitted to
Land Use Dynamics,
a section of the journal
Frontiers in Environmental Science

Received: 11 May 2022
Accepted: 07 June 2022
Published: 12 July 2022

Citation:
Madrigal-Martínez S, Puga-Calderón RJ, Bustínza Urviola V and Vilca Gómez Ó (2022) Spatiotemporal Changes in Land Use and Ecosystem Service Values Under the Influence of Glacier Retreat in a High-Andean Environment. Front. Environ. Sci. 10:941887. doi: 10.3389/fenvs.2022.941887

Glaciers supply multiple ecosystem services that are threatened by climate change. The retreat and disappearance of tropical glaciers is an important dynamic that affects ecosystems and local communities. The knowledge of the impacts of this land-change dynamics on the supply of ecosystem services is lacking. In that sense, the assessment developed can provide evidence about the costs and benefits of promoting conservation and human well-being at the same time. Then, the main objective of this research is to determine the spatial–temporal changes and their effects on the economic value of ecosystem services in a glacial retreat environment. We selected the Marangani district as a study area. It comprises the La Raya Mountain range in the Andes. The assessments were carried out across two scales of observation: the municipality and the watershed level. Here, we process spectral information from Landsat Sensor using the Random Forest algorithm in the Google Earth Engine platform to classify 10 biomes. It was carried out over more than 30 years (from 1986 to 2019). After that, ecosystem services provided by the biomes were valued using the transfer method. This research shows that at the municipality level, almost all the LULCs faced variations over time, and the glaciers had the highest change, accumulating a ratio of –85.51%, whereas at the watershed level, a higher tendency of land changes is observed in the areas without glaciers, and those with glacier areas count on permanent larger bofedales. At the municipality level, the economic value of ecosystems shows that bofedales and water surfaces are the LULCs that supply the highest ecosystem services (~33,000 USD ha^{-1} yr^{-1} each). In addition, without the inflation adjustment, the total ESV is on a trajectory of losing ESV (–\$9.67 × 10^6). In the watersheds with glacier retreat, significant quantity of bofedales and natural grasslands controls the fluctuations of ESV. These high-mountain watersheds play an essential role in providing benefits and value to local communities. In general, the municipality level indicates the trajectory of changes in the district, whereas the watershed scale shows the urgency for implementing spatial conservation actions.

Keywords: glacier retreat, ecosystem service (ES) values, tropical mountain, high-Andean, land-use and land cover change, spatial scale, bofedal

1 INTRODUCTION

Glaciers are retreating and disappearing worldwide (Marzeion et al., 2014; Zemp et al., 2015), and these processes have been accelerated globally in the early 21st century (Hugonnet et al., 2021). The causes are attributed to a combination of several factors related to anthropogenic and biophysical dynamics (Marzeion et al., 2014; Veettil and Kamp, 2019). Concretely, in the case of mountain glaciers, albedo reduction, increasing temperatures, and changing precipitation are drivers that may have a significant relation to glacier retreat and mass balance changes (Crossman et al., 2013; Tang et al., 2013; Zhang et al., 2021). However, the glacier recession pattern is more complex at higher elevations of the Andes because it is likely to be related to other components of the energy balance as net radiation and ground heat fluxes (Juřicová and Fratianni, 2018). These causes may have produced a fast retreating of Andean glaciers (Dussaillant et al., 2019; Hock et al., 2019). The mountain range of La Raya (the study area), situated northwest of the Peruvian high plateau, shows an ice area decrease from 11.27 km^2 estimated from aerial photos of 1962 (Hidrandina, 1989) to 1.90 km^2 assessed from Sentinel images of 2016 (INAIGEM, 2018).

Glaciers supply multiple ecosystem services (ESS), mostly related to the provision, regulation, and maintenance of water (Cook et al., 2021). Then, the disappearance of glaciers will alter hydrological regimes in downstream systems (Milner et al., 2017), which will have consequences on water management, food and energy security, and environmental management (Rasul and Molden, 2019). However, rapid melting of glaciers has a temporary rise in streamflow (Mark and Mckenzie, 2007; Mark et al., 2009), which added to the increase in precipitation can hide the impact downstream. Moreover, concerning biodiversity, responses of ecosystems are diverse and depend on internal species attributes, local environment, and external drivers of change (Cauvy-Fraunié and Dangles, 2019). In that sense, glaciers in the high-Andean mountain ranges can be associated with sensitive ecosystems such as bofedales (peat bogs and wetlands). The studies of the effects of glacier retreats on bofedales indicate a positive relation (Dangles et al., 2017; Polk et al., 2017), but the knowledge of impacts on the ESS is limited. Then, the prolonged disappearance of glaciers is a land-cover change that already has uncertain costs for ecosystem function and services to human well-being.

Land cover and land use (LULC) change has gained prominence as the main cause of degradation and change in ecosystems worldwide (Brandt and Townsend, 2006; Yin et al., 2011; Ektvedt et al., 2012; Kuemmerle et al., 2016; Quintero-Gallego et al., 2018; Madrigal-Martínez and Miralles i García, 2019b). LULC changes are the results of a combination of socio-economic, environmental, and political factors (Lambin et al., 2003). In the mountain environments, these changes are often caused by biophysical factors, land abandonment, deforestation, agricultural expansion, and urbanization to a lesser extent (Madrigal-Martínez and Miralles i García, 2019a; Msofe et al., 2019; Jiménez-Olivencia et al., 2021). Then, mapping the spatiotemporal transitions of LULC is fundamental to identifying landscape patterns for planning sustainable ESS (Luck et al., 2012; Chaudhary et al., 2017; Egarter Vigl et al., 2017; Madrigal-Martínez and Miralles i García, 2019a).

Mapping the spatiotemporal changes of LULC has been undertaken in several studies using different methodological approaches, but with the growing use of remote sensing and geographic information system (GIS) tools (Lu et al., 2004). In the same way, different types of multisource satellite images and classification methods have been used, but among all, Random Forest (RF) is a supervised classifier algorithm broadly used that performs well (Gislason et al., 2006). These change detection techniques provide a flexible environment for rapidly developing image classification and analyzing for changes, maintaining a satisfactory level of accuracy over the area being classified. In this context, LULC maps can provide a high capacity for identifying and explaining the supply of individual ecosystem services (Burkhard et al., 2009; Koschke et al., 2012).

Knowing the value of ESS is recognized as an essential pathway to sustainability (Abson et al., 2014). Per se, a suitable assessment is needed to improve policy and decision-making linked to management of the territory (Ling et al., 2018; Dang et al., 2021; Selivanov and Hlaváčková, 2021). Thus, such assessments can provide evidence about the costs and benefits of promoting conservation and human well-being at the same time (de Groot et al., 2010). The monetary value of ecosystem services (ESV) from a global to local scale is being established to accomplish this goal (Costanza et al., 1997; Groot et al., 2010; Costanza et al., 2014; de Groot et al., 2020; Foundation for Sustainable Development, 2021). The benefit transfer method has the highest worldwide usage frequency for determining the ESV (Schägner et al., 2013). Its main improvement is that it offers a relatively quick and low-cost estimation. However, to our knowledge, studies on spatiotemporal changes of ESV related to tropical glacier retreat environments have not been conducted.

Therefore, our study maps and evaluates the LULC change and associated ESV across the Marangani district for more than 3 decades (1987–2019). We performed the assessments across two scales of observation: the municipality and the watershed level, considering at least two spatial scales which should assure robustness (Scholes et al., 2013; Felipe-Lucia et al., 2014; Madrigal-Martínez and García, 2020). Based on spectral information from Landsat Sensor using the RF algorithm, we select this district of the higher elevations of the Andes because it is part of the mountain range of La Raya–an environment where glaciers are shrinking rapidly (INAIGEM, 2018). The results of this study provide answers to the following questions: 1) which spatiotemporal changes on LULC in a territory are under the influence of glacier retreat? 2) which spatiotemporal changes and relationships between glaciers and bofedales are at the watershed level? 3) how do these changes affect the monetary value of ecosystem services? Then, we discuss the reasons for the main spatiotemporal and ESV changes and their implications for the socio-ecosystem.

2 MATERIALS AND METHODS

2.1 Study Area

The selected area is the district of Marangani (Canchis, Cusco), comprised within the Raya Mountain range (**Figure 1**). It is the third most populated district of Canchis, and the population at the end of 2017 was 10,554 (National Institute of Statistics and

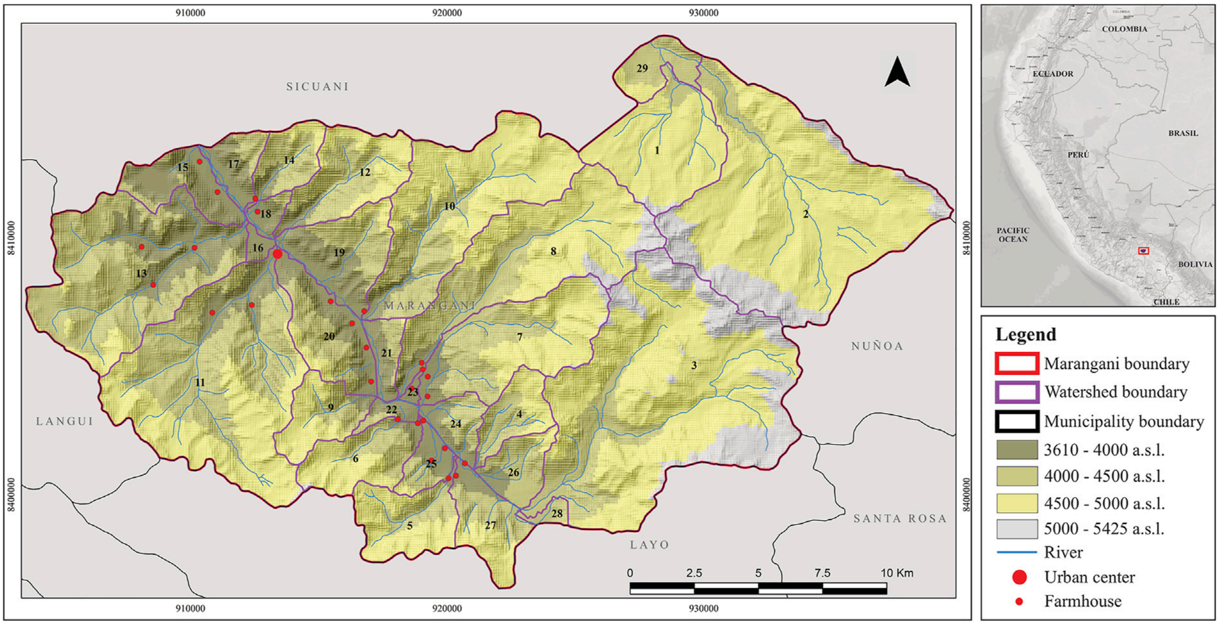

FIGURE 1 | Study area with elevation and watershed distribution (left), Peru with ESRI′ Standard map (top right). Watersheds: 1. Tañihua stream; 2. Aucara river; 3. Cantacanta river; 4. Chuabamba stream; 5. Tadiohuayco stream; 6. Llallahui stream; 7. Quiscamayo stream; 8. Quecjra river; 9. Lorocachi stream; 10. Cuyo stream; 11. Casuira river; 12. Cayco stream; 13. Comayacu stream; 14. Ccatunhuasi stream; 15. Intercuenca 1; 16. Inter-watershed 2; 17. Inter-watershed 3; 18. Inter-watershed 4; 19. Inter-watershed 5; 20. Inter-watershed 6; 21. Inter-watershed 7; 22. Inter-watershed 8; 23. Inter-watershed 9; 24. Inter-watershed 10; 25. Inter-watershed 11; 26. Inter-watershed 12; 27. Inter-watershed 13; 28. Inter-watershed 14; 29. Inter-watershed 15.

TABLE 1 | Landsat series Surface Reflectance data in each year.

Data	Acquisition year	Band	Resolution (meter)
Landsat 5 (TM)	1986	Multispectral	30
Landsat 5 (TM)	1995	Multispectral	30
Landsat 5 (TM)	2007	Multispectral	30
Landsat 8 (OLI/TIRS)	2019	Multispectral	30

Informatics, 2022). It covers an area of 440.32 km^2, comprising 29 watersheds that range from 70 to 0.5 km^2 with an average of 15 km^2. This landscape is dominated by an expansion of livestock breeding in the upper lands and farming in the fertile lowlands. It is typical of many mountain agroecosystems across the world. In that sense, Marangani has natural grasslands, sparsely vegetated areas, glaciers upstream, bofedales in the mid-stream, and agricultural land in the downstream reaches. The most important river is Vilcanota. The district has a semi-frigid rainy season with a dry winter climate (58%). Almost 47.63% of the population mainly works in the agricultural sector (National Institute of Statistics and Informatics, 2022), characterized by annual crops such as alfalfa, bean, potato, and wheat (National Institute of Statistics and Informatics, 2012). The natural pastures present in the territory make an optimal fodder for camelids, sheep, and cattle.

2.2 Spatiotemporal Analysis

2.2.1 Data Sources

This research used two types of data and information (primary and secondary information). The primary datasets are free and available on the Google Earth Engine (GEE) platform. The data acquisition was conducted during the dry season (July and August). It allowed cloud-free images. The selected years of the study were based on the period that evidenced the reduction of glaciers in Cordillera La Raya, around a decade, and in low-rainfall months. Four specific images from two Landsat Series were used (**Table 1**).

We used sort filtering functions about cloud cover for the select years in GEE. This function allows acquiring smooth continuous coverage of the scene without clouds. In our study case, the software gets the first (least cloudy) scene during the month in the dry season and nearby dates.

The primary dataset used was the atmospherically corrected Tier 1 TOA reflectance Landsat imagery. Landsat 5 was used for the first 3 years, while Landsat 8 in 2019. Operating at a spatial resolution of 30 m from both, we used 11 bands (six bands referring to the satellite, three bands made from the indices, and two topographic information bands).

The secondary data for this research were gathered from the Peru official flora cover map from 2013 (Ministry of Environment, 2015a) and its report (Ministry of Environment, 2015b). This map was used and referred together in training and testing samples with the primary data. The shape files of the study area were obtained publicly from the online server of the Ministry of Environment.

2.2.2 Land Use/Land Cover Classification

LULC units were delimited using the RF classifier within the GEE platform. We used 100 trees in the ensemble to improve the accuracy of the pixel-based supervised classification. For generating reference data (based on GEE, and Peru official

TABLE 2 | Description of LULC classes used in the study.

LULC Class	Description
Continuous urban fabric	Urban area
Agricultural areas	Andean agriculture with mainly seasonal crops
Forest plantation	Mainly *Eucalyptus* species
Natural grassland	Herbaceous vegetation consisting mainly of grasses, scrublands, and some scattered shrubby associations
Shrublands	Woody and shrubby vegetation of variable composition and structure
Sparsely vegetated areas	Low and dispersed vegetation
Glaciers	Ice masses that accumulate in the highest floors of the mountain ranges
Peat bogs and high-Andean wetlands	Hydrophilic herbaceous vegetation, permanently flooded or saturated with running water. Also known with the Spanish term bofedal
Water courses	River
Water bodies	Lagoons and lakes

flora cover map), a sampling of training and testing points—between 7 and 76—were selected of the composite images to identify the ten LULC classes (**Table 2**) for 1986, 1995, 2007, and 2019 as feature collection using the geometry tools and import. To obtain acceptable visual and statistical results, the script was repeatedly run. Also, the input images were divided into ten homogenous regions or segments (10 km × 10 km) and then classified using them. Ten GEE Code Editor scripts were used for each image to avoid confusion and assist in processing time (the links to access the script are presented in **Supplementary Table S1**). This methodology allows improving the calculation of RF in each grid and facilitates the analysis of the coverage generated. However, some biases may exist since the selection was completed manually based on the available references. The typology of the LULC classes was adopted from the Peruvian standardized nomenclature of the Corine Land Cover (CLC).

Different spectral indices were derived and added as the input parameters for training. The Normalized Difference Vegetation Index (NDVI) was used as an indicator of vegetation greenness. Then, the Modified Normalized Difference Water Index (MNDWI), a modified version of the Normalized Difference Water Index, facilitated the recognition of open water bodies by removing various noises of built-up areas, soil, and vegetation. The third index, the Normalized Difference Built-up Index (NDBI), was used to detect built-up areas.

Topographic information such as slope and elevation, derived from the SRTM (Farr et al., 2007), was also used in the classification.

Confusion matrices were used for accuracy assessment. The producer accuracy (PA), user accuracy (UA), overall accuracy (OA), and Kappa statistics (Kappa) were calculated using the previously collected samples that were scripted to be randomly segregated by 70:30 percent for training and testing, respectively. The four indexes were obtained from the confusion matrix (**Supplementary Table S2**). The UA showed the highest accuracy (100%) for glaciers during the 4 years, whereas the lowest values (50% in some grids) were for the urban class between 1986 and 1995. Forest plantations and river courses showed low accuracy (50 and 56%, respectively) in 2007 and 2019 in some grids. Similarly, PA revealed 96% for the glacier class, and 20% and 43% (in some grids) for built-up areas. Also, a similar performance can be seen in the forest plantations and the river courses classes for the years 2007 and 2019, respectively. It is due to the small area of these classes that results in rarer training and testing samples. On the contrary, the three larger extent classes (natural grasslands, sparsely vegetated areas, and wetlands) obtained values of UA and PA that averaged above 80% over the 4 years. The Kappa coefficients (0.87–0.89) were considered almost in perfect agreement. The OA indicated that 89–91% of data were correctly classified.

2.2.3 Land Use/Land Cover Change

Land-use change analyses were conducted at the municipality and watershed levels. We used the Watershed tool to delimitate watershed boundaries (Arc Map, 2022). The study calculated the LULC changes over 33 years (1986–2019) through a transition matrix obtained after using ArcGIS 10.5 (ESRI, 2019). The matrices were established for three-time periods (including 1986–1995, 1995–2007, and 2007–2019). Each transition matrix gathered the quantity of land converted from each LULC unit to any other in the study periods. Land-use changes of interest for this research were related to bofedales and glaciers as fragile ecosystems. These variations were further calculated, obtaining the intensity as the proportion of area increased and decreased at the watershed level. This index gave a relative measure of the land-use change. It was ranked in five equal intervals representing the intensity of expansion/contraction of each chosen class at the watershed level. Complementarily, the land of bofedales and glaciers remaining in each period was classified with Jenks's natural breaks. Furthermore, we performed Pearson's correlation (r) to assess the pairwise relations (land decreasing, increasing, and remaining) among the two classes for the three periods, using R (R Development Core Team, 2016).

2.3 Assessment of the Economic Value of Ecosystem Services

To estimate the ESV, we used the benefit transfer method, transferring available data from previous studies in various

TABLE 3 | Different LULC types and ESV coefficient (USD ha^{-1} yr^{-1}) adjusted by using the CPI in the Marangani district.

LULC Class	Equivalent biome	1986	1995	2007	2019
Continuous urban fabric	Urban	6,441	6,245	6,503	6,672
Agricultural areas	Cultivated areas	3,093	2,992	3,124	3,204
Forest plantations	Forest	4,928	4,778	4,976	5,105
Natural grasslands	Grass/Rangelands	6,186	5,944	6,248	6,383
Shrublands	Woodland and shrubland	5,202	4,855	5,302	5,412
Sparsely vegetated areas	Inland Un- or Sparsely Vegetated	321	307	325	333
Glaciers	Ice/Rock	4,972	4,565	5,087	5,182
Peat bogs and high-Andean wetlands	Wetlands	38,856	37,670	39,229	40,247
Water courses	Lakes/Rivers	29,688	28,624	30,015	30,770
Water bodies	Lakes/Rivers	38,112	36,358	38,632	39,548

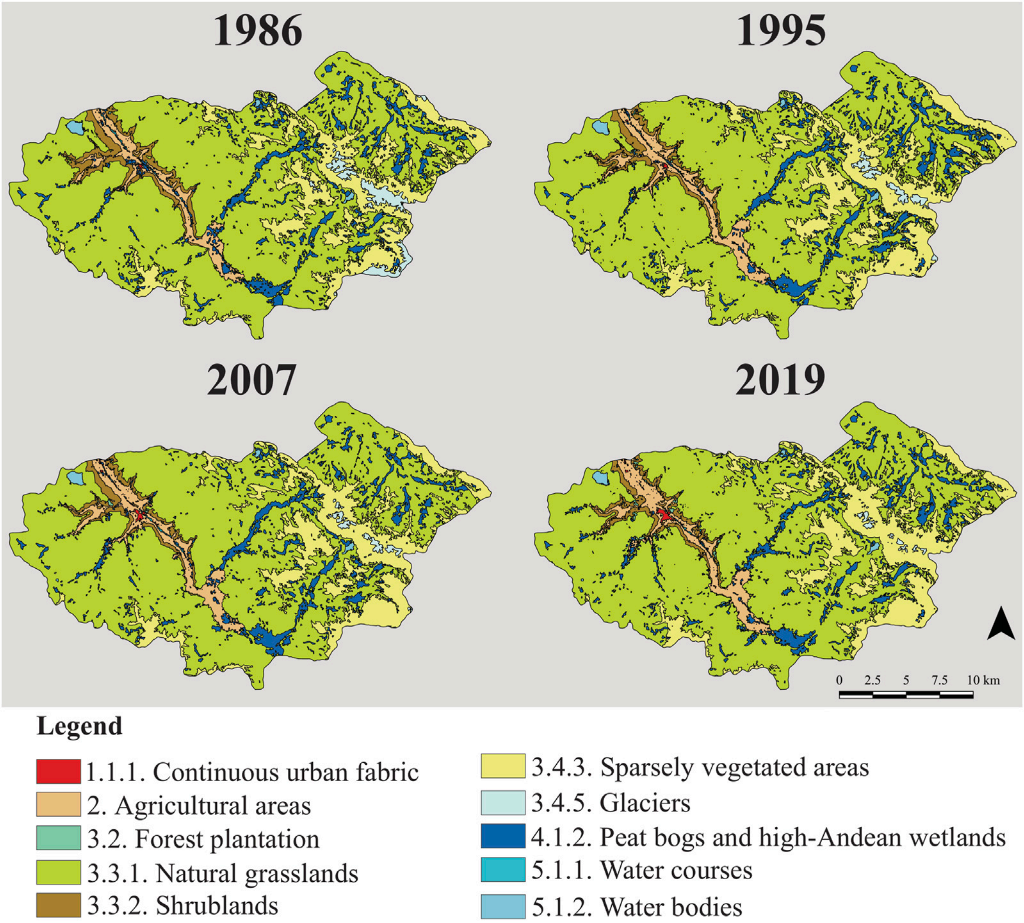

FIGURE 2 | Maps of the spatial distribution of LULC for Marangani municipality over the 4 years.

locations and from different ecosystems globally that have similitudes with the biomes of the study area. The search was carried out on the ESV database (Foundation for Sustainable Development, 2021) and published research (Costanza et al., 2014; Xie et al., 2017; de Groot et al., 2020) for 38 ecosystem services and ten biomes. After the search, only values for 23 ecosystem services were found. According to Costanza et al., (1997), the ESV coefficient (unit values in USD ha^{-1} yr^{-1}) of a given LULC was counted as all the ESV for that LULC. To achieve the total ecosystem service value of each LULC at the municipality and the watershed level, we multiply the area of each LULC type at the corresponding level by the ESV coefficient. Finally, the ESV coefficients were adjusted using the Consumer Price Index (CPI) obtained from the website of the World Bank (2022) and applying the inflation rate formula (**Table 3**).

TABLE 4 | Area of the different LULC classes for the 4 years.

	1986		1995		2007		2019	
LULC class	ha	%	ha	%	ha	%	ha	%
Continuous urban fabric	21	0.05	24	0.1	49	0.1	71	0.2
Agricultural areas	1,481	3.4	1772	4.0	1860	4.2	1851	4.2
Forest plantation	6	0.01	28	0.1	36	0.1	164	0.4
Natural grassland	29,872	67.8	29,352	66.7	30,054	68.3	30,152	68.5
Shrublands	1,402	3.2	1,145	2.6	1,013	2.3	1,069	2.4
Sparsely vegetated areas	6,691	15.2	7,451	16.9	7,033	16.0	7,155	16.2
Glaciers	897	2.0	353	0.8	246	0.6	130	0.3
Peat bogs and high-Andean wetlands	3,419	7.8	3,656	8.3	3,521	8.0	3,242	7.4
Water courses	87	0.2	72	0.2	65	0.1	41	0.1
Water bodies	157	0.4	179	0.4	154	0.3	157	0.4

3 RESULTS

3.1 Quantification of Land Cover and Land Use Changes Over Time

The spatiotemporal distribution of LULC of the Marangani district among the study years revealed some variations (**Figure 2**). The precise area of each LULC is shown in **Table 4**. Natural grasslands coincided with being the most abundant class each year, spatially dispersed covering more than 65% of the landscape. Sparsely vegetated areas delimited more than 15% of the landscape over time. This LULC is spatially associated with glaciers in the highland. The third LULC type was peat bogs and high-Andean wetlands (bofedales) with an average of 8%, mainly located in the upland depressions. Agricultural areas (>4%) were evident in the lowland valley around the main river (Vilcanota river) related to the urban center, the farmhouses, and even topography. However, shrublands mainly drew a transitional zone in the lowland that separated agriculture from the natural grassland. Last, built-up areas, forest plantations, and water surfaces enclosed less than 1% of the territory.

The details of LULC changes for 1986–1995, 1995–2007, and 2007–2019 are presented in the transition matrices (**Supplementary Tables S3–S5**). In terms of the total area, 4,217 ha (9.6%), 3,999 ha (9.1%), and 3,914 ha (9%) were transformed in each period, respectively. Two transitions (>2,900 ha) involved the deterioration and the recovery of natural grasslands and bofedales during each period. A third important transition was related to glacier retreat, being more intense during the first period (543 ha). Another significant land-use change over time (strongest during the first period, >300 ha) refers to agricultural expansion, which implicated the conversion of natural grasslands, bofedales, and shrublands. Last, the farming land abandonment represented an increase in shrublands, mainly shown during the third period (>200 ha).

3.1.1 Landscape Analysis of the Overall Trajectories of Changes

The LULC changes over time (**Table 4**) demonstrated some trajectories at the municipality level. Two classes (natural grasslands and water bodies) show low variability that indicates almost no disturbances, whereas water courses display no clear variations. Four LULC uncovers consistent patterns of increase influenced by humans at works dynamics (agriculture, urbanization, and afforestation) and glacier retreat (sparsely vegetated areas). In contrast, three classes (among them the fragile ecosystems like the bofedal and the glacier) have decreased due to the conversion into grazing and farming lands (for shrublands and bofedales) and the effects of climate change (for glaciers).

3.1.2 Watershed-Level Analysis of Changes in the Fragile Land Cover and Land Use

The intensity of glacier retreat at the watershed level is evidenced in each period (**Figure 3A**). No glacier advances are observable. During the first period, a high average decrease intensity is registered (60.65%), whereas it is moderate (average of 12.43%) for the others.

Figure 3B illustrates the intensity of land increase and decrease for bofedales in each period. The spatial distribution shows a higher tendency of land changes at the watersheds without glaciers. It may be possible because the glaciers provide a water flow that stabilizes the fluctuations (appearance balance) of the bofedales. In that sense, the watersheds with glacier areas count on permanent larger bofedales (**Supplementary Figure S1**).

At the watershed level, the relationships among the two fragile LULC changed over time (**Supplementary Table S6**). In terms of both the type of relationship and its strength, glaciers' decrease over time is negatively related to bofedales decreasing, whereas bofedal increase showed a positive correlation (for the first period) and negative during the other periods, but nonsignificant for all the relationships. Bofedal increase showed a consistent and significant negative relationship with bofedal decrease in the first period but varied from a significant positive correlation coefficient of 0.51 in the second period to a nonsignificant coefficient of 0.21 in the final period. The relationship among the areas of both classes remaining over time is significant and positive.

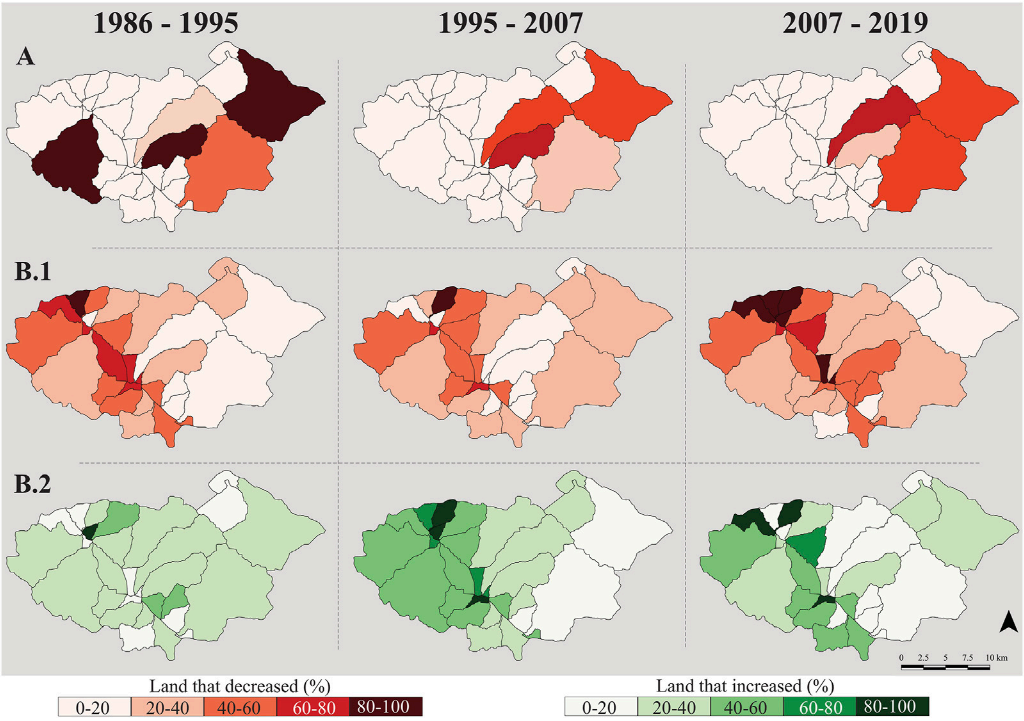

FIGURE 3 | Land decrease intensity of the glaciers **(A)** and the land decrease/increase intensity of the bofedales **(B.1,B.2)** at the watershed level in the Marangani district over the three periods.

3.2 Valuation of Ecosystem Services of the Marangani District

The search of 38 ecosystem service values for the ten study area biomes resulted in 23 ESVs found (**Supplementary Table S7**). The values (**Supplementary Table S8**) focused on provisioning (5), regulating (12), and cultural services (6) that are classified in the MEA (Millennium Ecosystem Assessment, 2005). This last group of services provides the highest total economic value (74,260.98 USD ha^{-1} yr^{-1}), mainly due to the value of recreation (57,248.23 USD ha^{-1} yr^{-1}), while regulating and provisioning afford lower values (35,356.34 and 33,124.41 USD ha^{-1} yr^{-1}), being the value of regulation of extreme events and the provision of habitat for wildlife species (9,634.75 and 18,444.80 USD ha^{-1} yr^{-1}) those who contribute most in each category. Bofedales and water surfaces are the LULCs that supply the highest ESV (~33,000 USD ha^{-1} yr^{-1} each), mainly because of the value of the habitat for wildlife species, erosion prevention, regulation of extreme events, and recreation. However, human-related areas retain values that range between 3,211.69 and 6,687.02 USD ha^{-1} yr^{-1} due to the provision of food production, recreation, and air quality regulation.

3.2.1 Ecosystem Service Values at the Municipality Level

The total ESV at the municipality level shifted from \$344.85 × 10^{6} in 1986 to \$346.51 × 10^{6} in 2019 (**Table 5**). Practically, there is a slightly positive change (+\$1.66 × 10^{6}), but it is observed that without the inflation adjustment, the district is on a trajectory of losing ESV (−\$9.67 × 10^{6}). It is mainly due to the decrease in the area of glaciers and bofedales. The bofedal is one of the main classes supplying ESV (from \$132.85 × 10^{6} in 1986 to \$125.97 × 10^{6} in 2019), although the value of glaciers is lower (\$4.46 × 10^{6} in 1986), and its conversion to bared areas signifies a substantial decrease of \$3.67 × 10^{6} in 2019. However, the highest supply of ESV corresponds to natural grasslands (attributed to its high extension), although its value is rather constant, resulting only in an increase of 1% (+\$1.73 × 10^{6}) during the study period. Furthermore, agricultural areas and forest plantations increased the ESV from 4.58 × 10^{6} to 5.72 × 10^{6} and 0.03 × 10^{6} to 0.81 × 10^{6}, respectively. These escalations are not enough to achieve a positive overall rate at the municipality level.

3.2.2 Ecosystem Service Values at the Watershed Level

The supply of ESV changed (decreased and increased) during the study period at the watershed level (**Figure 4**). The extreme changes in the economic value of the ecosystem services of the watersheds in the study area are mainly caused by considerable increase or decrease of the bofedales. For example, between 1986 and 1995, a severe ESV reduction in watersheds 16, 23, and 28 was observed. It is mainly due to the conversion of bofedales into agricultural areas. Similarly, it occurs in the comparison of the period 2007–2019. On the contrary, land abandonment facilitates the increase of bofedales between 1995 and 2007, showing better valuation. The watersheds with glaciers (numbers 2, 3, 7, and 8) did not experience a severe

TABLE 5 | ESV of each LULC at the municipality level between 1986 and 2019 and the overall trajectory of change. The values in parentheses represent the adjustment by the inflation. Top arrow for the increase and down arrow for decrease. NC = no change. Trajectories in parentheses include values from inflation adjustment.

LULC Class	ESV (10^6\$)							Trajectory of change
	1986	1995		2007		2019		
Continuous Urban Fabric	0.14	0.15	(0.15)	0.32	(0.32)	0.46	(0.47)	↑ (↑)
Agricultural areas	4.58	5.48	(5.30)	5.75	(5.81)	5.72	(5.93)	↑ (↑)
Forest plantations	0.03	0.14	(0.13)	0.18	(0.18)	0.81	(0.84)	↑ (↑)
Natural grasslands	184.79	181.57	(174.46)	185.92	(187.79)	186.52	(192.48)	NC (↑)
Shrublands	7.29	5.96	(5.56)	5.27	(5.37)	5.56	(5.79)	↓ (NC)
Sparsely vegetated areas	2.15	2.39	(2.29)	2.25	(2.28)	2.29	(2.38)	NC (NC)
Glaciers	4.46	1.76	(1.61)	1.22	(1.25)	0.65	(0.67)	↓ (↓)
Peat bogs and high-Andean wetlands	132.85	142.06	(137.72)	136.81	(138.12)	125.97	(130.48)	↓ (↓)
Water courses	2.58	2.14	(2.06)	1.93	(1.95)	1.22	(1.26)	↓ (↓)
Water bodies	5.98	6.82	(6.51)	5.87	(5.95)	5.98	(6.21)	NC (NC)
Total	344.85	348.46	(335.80)	345.52	(349.03)	335.18	(346.51)	↓ (NC)

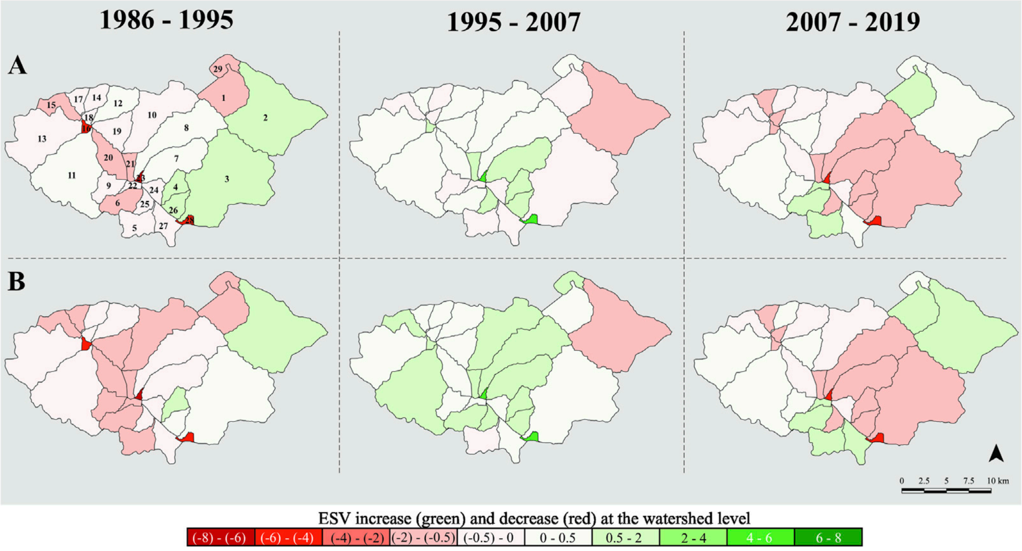

FIGURE 4 | Spatial distribution of ESV increase and decrease **(A)** and adjusted by the inflation **(B)** at the watershed level in the Marangani district over the three periods (ESV units in 10^3\$).

change in ESV. Although the glacial retreat is probed, the loss of ESV is neutralized by the considerable proportions of bofedales and high Andean grasslands. The slight variation of these biophysical structures produces a low ESV variability through the years.

4 DISCUSSION

4.1 Land Cover and Land Use Changes During More Than Three Decades has Diverse Implications on the Landscape

At the municipality level, almost all the LULCs faced variations over the study period of 33 years (**Table 4**). It should be noted that glaciers—as fragile ecosystems perturbed by climate change—had the highest change (accumulated ratio of −85.51%), which agreed with studies in the Himalayas (e.g., −23.8% and −35%, Rai et al., 2018; Shrestha et al., 2019). However, Andean glaciers seem to be under critical conditions that accelerate their disappearance (Juřicová and Fratianni, 2018; Vicente-Serrano et al., 2018). In the Marangani district, this situation reached its peak between the first period (1986–1995, ratio of −60.65%). It can be explained by the very strong ENSO warm events between 1987 and 1992 (Gergis and Fowler, 2009), which are related to the annual glacier mass balance (Wagnon et al., 2001). Consequently, the current ice loss in the study area signifies a variability of water availability on downstream socio-ecosystems that may impact agricultural irrigation of permanent crops and human-domestic use. In that sense, the cropland and the bofedales have shown a moderate increasing trend over the first period that may be driven by the increase of the population (National Institute of Statistics and Informatics) and the water supply from glaciers, respectively, while for the second and third periods, agricultural frontier expansion showed a deceleration influenced by a decrease in the population. This decline overlaps with the displacement by domestic terrorism in the second period (Transfer Commission, 2014) and internal migration by work opportunities in the third (Bergmann et al., 2021). However, existing farmland abandonment is very low, but if this land-change dynamic continues, it can lead to risks associated with land degradation (Narendra Raj and Teiji, 2006). Furthermore, during the last two periods, the bofedales faced a reduction coexisting with a decline of the melting of glaciers, causing augmentation of natural grassland, sparsely vegetated areas, and the conversion by humans at work activities as agricultural land and forest plantation.

At the watershed level, the study observes a higher tendency of land changes in the territory without glaciers, and those with glacier areas count on permanent larger bofedales. Then, glaciers provide a water flow that stabilizes the fluctuations (appearance balance) of the bofedales. This biome is considered sensitive to changes in extreme rainfall and glacial meltwater supply (Dangles et al., 2017). The main reason is that perennial bofedales are connected to the hydrological cycle through runoff generated by melting glaciers, while temporal wetlands depend directly on precipitation (Otto et al., 2011). It suggests that the total disappearance of the glaciers in the study area would cause the main water supply contribution by snow melting and rainfall. In this case, the mountain depositional landforms—glacial rocks immersed in the biome of the sparsely vegetated area—will constitute effective water distribution and storage. This function has an operation in the short and intermediate-term (Reato et al., 2021). It may cause a predominance of temporal bofedales. This condition could have a possible variation in the benefits provided by ecosystem services in the same biome for the different compositions of species. In general, temporal bofedales (mainly species of the Poaceae family) provide food for raising animals and wildlife during the flood season, whereas perennial bofedales (mainly cushion-forming species) accumulate organic soil, forage, and water storage also in the dry season (Cooper et al., 2010; Ruthsatz, 2012). In this last service, the hydrological importance enables change in the water flow paths and discharge velocity (Otto et al., 2011). In addition, perennial wetlands provide vital habitats for wildlife and extensive grazing of camelids (Loza Herrera et al., 2015; Dangles et al., 2017).

4.2 The Economic Value of Ecosystem Services in an Environment of Glaciers Retreat Is in Decline

For the first time, the results presented here (**Table 5**) calculated the spatiotemporal changes of ESV in an environment of tropical glacier retreat. Concretely, the territory is on a trajectory of losing ESV appreciated in the scenario without inflation adjustment. This degradation is mainly due to reduction of provisioning and regulating services provided by the bofedales and the glaciers. The disappearance of these services not only has implications for a direct economic loss but also, in the case of the reduction of the flood protection provided by the glaciers, can pose the risk of dangerous glacial outburst floods on downstream communities that may lead to catastrophic economic damages (Chen et al., 2022). At the same time, the disappearance of bofedales endangers the regulation of extreme events that can increase these impacts. Likewise, the augmentation of water erosion, induced by the decline of bofedales, may affect negatively food security and natural resource management practices, principally in the poorest societies (Sartori et al., 2019), such as the study area. In the same way, the drop in water supply amplified by the reduction of both fragile ecosystems may affect livestock production, irrigated agriculture, availability and quality of water for human consumption, and generation of hydroelectricity (Carey et al., 2016), increasing the economic losses in the territory. Biophysical processes and human activities are the highest threats and causes of this situation. The ESV supplied by the human-related classes is in a crescendo, whereas the natural and semi-natural classes are losing their capital. This may result in a critical situation since the growth of provisioning services provided by agricultural development is at the expense of regulating services like water flow regulation and erosion prevention. This trajectory of ecosystem services is characteristic in mountain environments (Locatelli et al., 2017; Madrigal-Martínez and Miralles i García, 2019a).

At the watershed level, the variation of ESV is mainly influenced by the changes of bofedales into farming and grasslands. These changes harm the value of regulation services. However, the value of provisioning services like habitat for wildlife species, genetic libraries, livestock production, and raw materials increased due to expansion of pastures. In general, the economic value of these provisioning services could be underestimated by the global sources researched by Costanza et al. (2014) because the principal cattle in the study area are llamas, alpacas, and vicuñas (National Institute of Statistics and Informatics, 2012). These two last species are considered of great interest for their finest fibers worldwide and are used for luxury costumes (Vilá and Arzamendia, 2020; Zarrin et al., 2020). In the same way, the production of meat from llamas and alpacas has interesting value for their use as a principal protein source for Andean rural communities (Pérez et al., 2000); and their healthy characteristics (low in fat and cholesterol) make them attractive for local and international markets, signifying an important income for small- and medium-scale local producers (Mamani-Linares and Gallo, 2014). Moreover, llamas have smaller and simpler nanobodies beneficial for human immunology and therapeutic applications (Wesolowski et al., 2009). Furthermore, although the density of alpacas in the study area is high (123 alpacas km^{-2}), according to the levels established in other locations (Muñoz et al., 2015), biodiversity conservation is guaranteed with appropriate management practices (Alkemade et al., 2013).

In the watersheds with glacier retreat, the significant quantity of bofedales and natural grasslands controls the fluctuations of ESV. It is a consequence of the extension of grasslands that varies between 48 and 72.2% and the bofedales between 5.5 and 12%. Then, these watersheds still have an advantage from the water flow of glaciers and supply multiple provisioning and regulating services such as water yield, habitat for wildlife species, food production, carbon sequestration, erosion control, soil fertility, and regulation of extreme events. Therefore, these high-mountain watersheds play an essential role as hotspots of ecosystem services, giving benefits and value to local communities. The identification of ES hotspots guides the prioritization of areas for conservation (Li et al., 2017). In that sense, ES hotspot maps have potential benefits that can be transmitted to stakeholders to improve management planning (Hauck et al., 2013). Also, the implication of knowing this information provides a scientific basis for making relevant decisions in a territory (Li et al., 2022). Consequently, these ES hotspot watersheds should get the priority of being strategically managed for maintaining their essential ecosystems. So, understanding the relationship between nature and people in mountain socio-ecological systems is significant for planning sustainable development strategies (Madrigal-Martínez and Miralles i García, 2019b; Payne et al., 2020), including conservation strategies at different spatial levels, such as prioritizing the small wetlands of these watersheds, according to Otto and Gibbons (2017).

4.3 Methodological Limitations of the Study

In this study, the analyses presented should be understood as using the best existing data of acceptable quality to admit robust evidence. Even so, the procedures used in processing satellite images may have a situation of some biome coverage. It is mainly related to four factors: 1) the definition of biome classes, 2) reliability of Landsat images with their limitations of the sensor used, 3) auxiliary variables in the classification, and 4) validated data and no clarity of training (Calderón-Loor et al., 2021). The selection of the training points was based on the national vegetation coverage map (Ministry of Environment, 2015b). Also, to best interpret the satellite image, the authors made an expert judgment. In that sense, subjectivity at the decision point regarding the pixel classification could cause statistical noise in the training and validation data. However, this noise in the final categorization could have a low effect on the final product (Zhu et al., 2016). In addition, the research applied the transfer method of benefits for valuation ecosystem services. Despite the benefits, it has several limitations that imply transfer errors from generalization (Schmidt et al., 2016). However, it has been taken into account that the extrapolation of the valuation is in similar geographies.

5 CONCLUSION

This research develops for the first time a study about the land-use changes and their implications on the economic value of ecosystem services under the influence of glacier retreat in a tropical mountain environment. Also, our research has provided a procedure using satellite images that obtains a robust classification as a base for the estimation of ESV, which can be applied to other areas and contexts. The research utilizes two scales of observation, the municipality and the watershed level, for 33 years. In that sense, the analysis uncovered consistent differences that define the results depending on the scale. In general, the municipality level indicates the trajectory of changes in the district, while the watershed scale shows the urgency for implementing 1) measures to moderate the severe impacts on the landscape or 2) management actions for improving the spatial conservation of ecosystems. At the municipality level, the territory suffers trade-offs mainly in the supply of regulating services, declining the total monetary value. At the watershed level, the trade-offs are more evident in the areas without glaciers, and an economic balance over time is maintained in the landscapes with glaciers.

Bofedales and glaciers are fragile ecosystems that play an essential role in supplying regulating and provisioning services benefiting the socio-ecosystem. However, these ecosystems are being impacted over time, gathering a loss of ESV. Biophysical dynamics are diminishing glaciers and, in a lesser measurement, the bofedales, while for the latter, the increase of human activity is also a threat, mostly causing the trade-off between provisioning services and regulating services such as water flow regulation and erosion prevention. It is worth noting that during the study period, the glaciers were continuously shrinking, and their spatial–temporal changes had direct implications on the increase of bare land. However, they still have positive effects on downstream ecosystems such as bofedales but negative on the total economic value due to the reduction of their capability to supply water-related services. In addition, future studies should focus on a much more exhaustive LULC classification to improve the results reached in this research. It means including perennial and temporary bofedales and open and close natural grasslands. Likewise, knowing how spatiotemporal changes affect the quality and amount of ESS in this type of environment is an important issue. Last, the relationship between the trajectories of glaciers, bofedales, and ESV needs to be researched deeply, incorporating similar scenarios to find more robust spatial–temporal patterns.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, SM-M and RP-C; methodology, SM-M and RP-C; software, RP-C; validation, SM-M, VB and OV; formal analysis, SM-M; investigation, SM-M; resources, SM-M; data curation, SM-M; writing—original draft preparation, SM-M and RP-C; writing—review and editing, SM-M and RP-C; visualization, SM-M; supervision, SM-M, VB; funding acquisition, VB and OV. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research was funded by Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña (INAIGEM).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.941887/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.