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Land Use and Land Cover Changes in the Diversity and Life Zone for Uncontacted Indigenous People: Deforestation Hotspots in the Yasuní Biosphere Reserve, Ecuadorian Amazon

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Citation: Heredia-R, M.; Torres, B.; Cabrera-Torres, F.; Torres, E.; Díaz-Ambrona, C.G.H.; Pappalardo, S.E. Land Use and Land Cover Changes in the Diversity and Life Zone for Uncontacted Indigenous People: Deforestation Hotspots in the Yasuní Biosphere Reserve, Ecuadorian Amazon. *Forests* **2021**, *12*, 1539. <https://doi.org/10.3390/f12111539>

Academic Editors: Gabriel de Oliveira, Liming He, Guilherme A. V. Mataveli, Carlos Antonio Costa dos Santos and Yosio Edemir Shimabukuro

Received: 27 September 2021

Accepted: 2 November 2021

Published: 8 November 2021

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Abstract: Land use and land cover change (LULC) is an essential component for the monitoring environmental change and managing natural resources in areas of high natural and cultural biodiversity, such as the Amazon biome. This study was conducted in the northern Amazon of Ecuador, specifically in the Diversity and Life Zone (DLZ) of the Yasuní Biosphere Reserve (YBR). The general aim was to investigate the territorial dynamics of land use/land cover changes to support policies for environmental and sociocultural protection in the DLZ. Specific objectives included (i) mapping LULC spatial and temporal dynamics in the DLZ in the period from 1999 to 2018, (ii) identifying sensitive LULC hotspots within the DLZ, and (iii) defining the possible policy implications for sustainable land use in the DLZ. Multitemporal satellite imagery from the Landsat series was used to map changes in LULC, which were divided into three-time stages (1999–2009, 2009–2018, 1999–2018). We adopted open-access Landsat images downloaded from the United States Geological Survey (USGS). The processes for assessing LULC in the DLZ included (1) data collection and analysis, (2) data processing for remote sensing, (3) thematic land cover, and (4) homogenization and vectorization of images. The results showed that in the period 1999–2018, most of the uses and land cover were transformed into pastures in the DLZ. Therefore, it is important to improve territorial planning, to avoid conflicts between indigenous populations, migrant settlers, and uncontacted indigenous populations that live in the DLZ, within the YBR.

Keywords: forest; indigenous peoples; traditional productive systems; migrant settlers

1. Introduction

Land use and land cover change (LULC) has become a fundamental and essential component in current strategies that concern monitoring environmental change and managing natural resources [1,2]. Increasing anthropogenic activities around the biosphere are causing large-scale alterations to the Earth's land surface, affecting the efficiency of global systems [3]. LULC and its resources have been used for humans' social, material, cultural, and spiritual needs, leading to significant changes [4,5]. Rapid changes in LULC, particularly in developing countries [6–8], have resulted in the depletion of vital resources,

including water, soil, and vegetation [9,10]. However, due to their speed, extent, and intensity, they have numerous critical global implications [11,12], particularly on natural resources [12] and on greenhouse gas emissions from land use change [13–15]. The increasing change is alarming and may have a significant impact on the local [16], regional [17], national [18], and global environment [3,19].

Within the United Nations Sustainable Development Goals (SDGs), goal number 15 focuses on “promoting sustainable life on land” [20] and its sub-indicator 15.3.1 concerns the proportion of land that is degraded over the total land area. Researchers, policy makers, and planners use LULC information to determine changes in natural resources, including assessing growth patterns [21], to achieve the SDG 15’s Target 3: “By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world”. A better understanding of land dynamics requires the detection of LULC changes [22]. Empirical studies by researchers from various disciplines have shown that changes in LULC are key to various applications, such as hydrology, agriculture, forestry, the environment, geology, and ecology [1,2,23,24]. Many researchers argue that LULC change could result in an ecosystem imbalance and impacts on the environment caused by humans and their role in climate change [25–28].

In developing countries, resource bases, such as land, forests, and water, are declining significantly [29]. However, information on the rate of decline is often lacking [30]. Accurate information on LULC changes is needed to understand the root causes and environmental costs of such changes. Furthermore, analyzing the driving forces causing LULC change is essential to understand current changes and forecast future alterations [17].

The Northern Ecuadorian Amazon (NEA) is an area where various dynamics and complex interactions take place between the different local, national, and international actors identified, namely migrant settlers, emerging communities and market centers, indigenous peoples, oil and mining companies, and government and non-governmental agencies [17].

The following dynamics were identified: migrant settlers have migrated from different parts of Ecuador, especially the highlands, characterized by rural areas with high poverty rates, extremely concentrated land tenure, and smallholdings [31,32]; some migrant settlers are considered environmental refugees [33]. Emerging communities and market centers are expanding services, providing a source of off-farm employment for settlers, and affecting land use and land cover (LULC) in a direct and indirect manner [17]. Indigenous peoples, in response to declining per capita land tenure attributable to population growth [34], migrated north from the NEA, leaving their historic lands in the southern Ecuadorian Amazon [35,36]. These groups include the Waorani and Kichwa, who continue with their often-unsustainable traditional production systems [37,38] and coexist with the ecosystem services of the forest but are increasingly involved in market agriculture [39], wage employment [40,41], and other external agents, thereby transitioning to a market-oriented economy. It also comprises other indigenous people in voluntary isolation (Tagaeri and Taromenane), who live off shifting agriculture and services from the forest land [42,43]. Oil companies built the roads to lay pipelines and continue to find and extract more oil [44] in colonial and indigenous areas [45,46] and even in national parks [47], generating several oil spills in the process [48]. Government agencies, such as the Ministry of Environment (now the Ecuadorian Ministry of Environment, Water and Ecological Transition—MAATE, acronym in Spanish), are encouraged by certain Ecuadorian and international NGOs to set aside and monitor large areas of the Amazon for the conservation and protection of the region’s extraordinarily rich ecological and cultural diversity [49]. The relationships between these five actors are complex, partly due to feedback between spatial patterns and rates of LULC change in the NEA. Overall, LULC change associated with tropical deforestation is complex: population–environment linkages and feedback create dynamics with emergent properties, especially with the advance of the agricultural and development frontier [17].

The Yasuní Biosphere Reserve (YBR) has experienced different invasive territorial dynamics, such as oil activities, openings of road network, colonization processes and their consequences in deforestation, land use changes and impacts on fauna and flora, expansion of the agricultural frontier, logging, indiscriminate hunting and fishing, water pollution, and contamination by crop fertilizers [50–53]. These dynamics have caused (a) territorial conflicts and the mobility of the uncontacted indigenous peoples (Tagaeri and Taromenane), which have generated several incidents of aggression against migrant settlers, mestizo wage earners, and sedentary indigenous people in the area [54]; and (b) the intensification and extensification of colonization and agricultural processes on the main road (called Via Auca) and its offshoot roads [55,56]. In this context, in 2015, under the leadership of the Ministry of Agriculture and Livestock (MAG) in coordination with other government institutions, the creation of the Diversity and Life Zone (DLZ) was legalized, whose objective was special territorial management for the protection of migrant settlers, indigenous nationalities, and uncontacted indigenous peoples who live in the Yasuní National Park (YNP), Intangible Zone, or Zona Intangible Tagaeri Taromenane (ZITT) [57,58] and even outside these areas [59].

Given this background, the general aim of this research was to investigate the territorial dynamics of land use/land cover changes to support policies for environmental and sociocultural protection in the area Diversity and Life Zone (DLZ). Specific objectives included (i) mapping LULC spatial and temporal dynamics in the DLZ in the period from 1999 to 2018, (ii) identifying sensitive LULC hotspots within the DLZ, and (iii) defining the possible policy implications for sustainable land use.

This research is organized as follows: Section 2 describes the study area, the data, and the methodological process. The results with the historical changes and hotspots of LULC are described in Section 3, which includes the discussion and the policy implications for sustainable land use are described. Finally, the main conclusions of the research are described in Section 4.

2. Materials and Methods

2.1. Study Area

This study was conducted in the DLZ. It is located within the transition, buffer, and core areas of the Yasuní Biosphere Reserve in the northeast sector of the Ecuadorian Amazon Region. The zone is 116 km long and approximately four kilometers wide, parallel to the boundaries of the existing communities in the DLZ, and has a total area of 38,857.5 ha. The extension is distributed between the parishes of Taracoa (area: 787 ha; perimeter 27.26 km), Dayuma (area: 19,900 ha; perimeter 139 km), and Inés Arango (area: 17,354 ha; perimeter 125.72 km), all in the canton of Francisco de Orellana in the province of Orellana. The geographical limits of the DLZ are the Indiyama river to the north, the Tiwino river to the south, and both the limits of the Yasuní National Park (YNP) (982,300 ha) and the Waorani Ethnic Reserve (WER) (809,339 ha) to the east. The DLZ is overlapped by seven oil blocks and is located next to the ZITT and its buffer area (Figure 1).

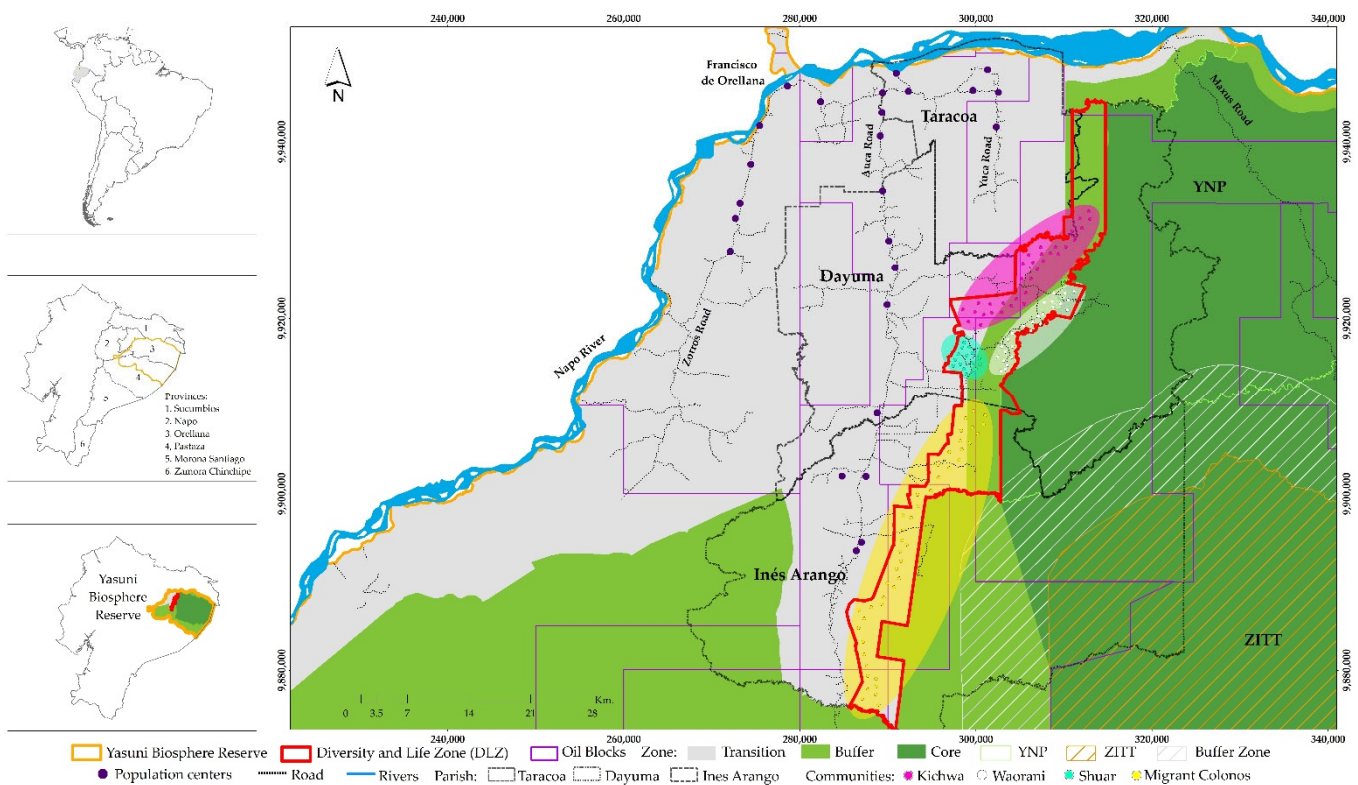


Figure 1. Diversity and Life Zone located in the parishes of Tarao, Dayuma, and Inés Arango, Yasuni Biosphere Reserve of the Ecuadorian Amazon Region.

2.2. Classification and Detection of Changes in the DLZ

For the classification and detection of changes in the DLZ, its surface area was divided into two zones: north and south, based on two criteria: (1) proximity to the most populated settlement (Coca City), and (2) the political and administrative division between the parishes (Tarao, Dayuma, and Inés Arango) that overlap with the DLZ. Hereunder, the processes for assessing LULC in the DLZ are detailed: (1) data collection and analysis (Table 1, Figure 2), (2) data processing for remote sensing, (3) thematic land cover (Table 2, Figure 3), and (4) homogenization and vectorization of images (Figure 4).

Table 1. Satellite images used in the LULC spatial analysis of the Life and Diversity Zone, Yasuni Biosphere Reserve of the Ecuadorian Amazon Region.

Mission	Sensor	Bands	Path/Row	Date	Cloud Cover (%)	Training Samples Number
Landsat 5	ETM+	1, 2, 3, 4, 5, 7	9/60 & 61	10 July 1999	10.00 & 7.00	2003
Landsat 7	ETM+	1, 2, 3, 4, 5, 7	9/60 & 61	26 May 2009	15.00 & 9.00	2314
Landsat 8	OLI	2, 3, 4, 5, 6, 7	9/60 & 61	18 October 2018	16.77 & 7.42	1876

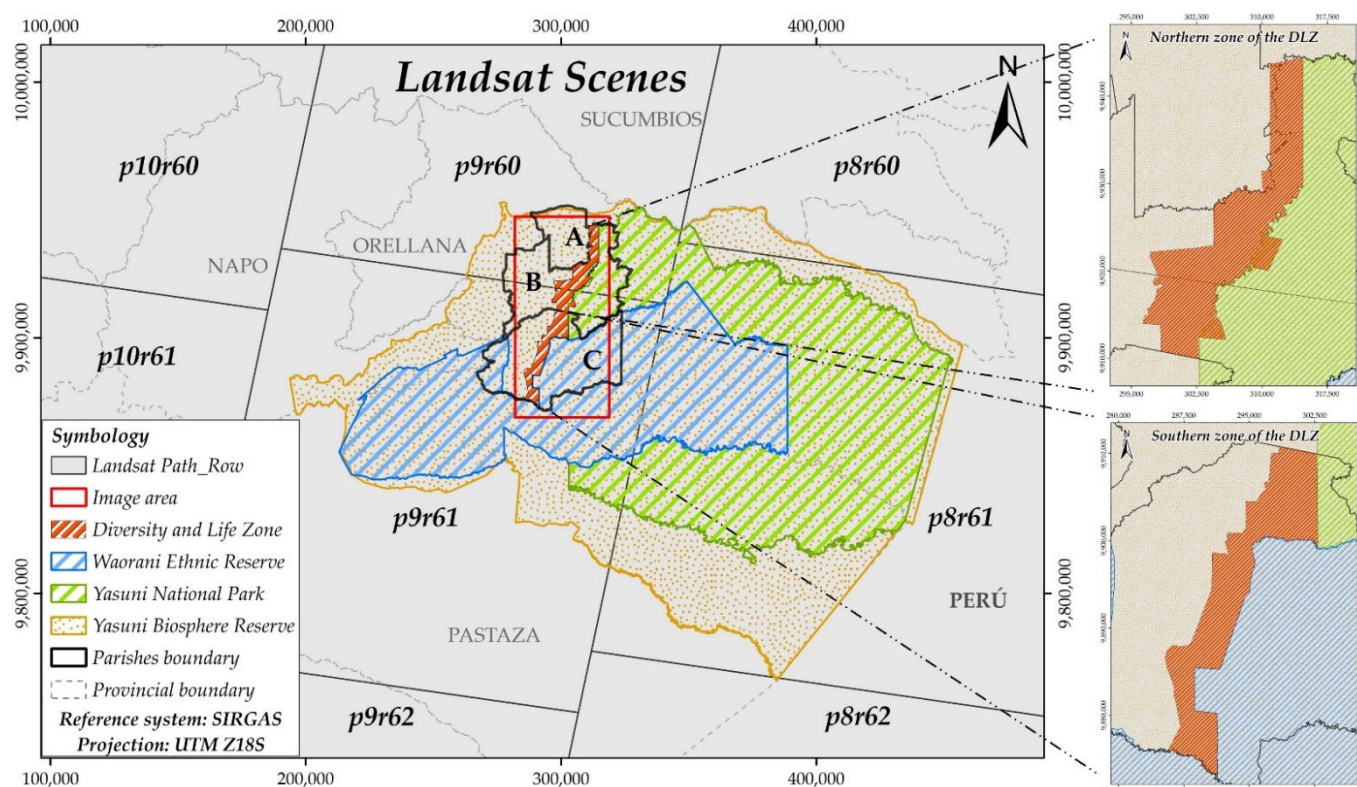


Figure 2. Footprint of the two satellite images (Landsat 5, 7, and 8) in the Zone of Diversity and Life of the Ecuadorian Amazon Region. Parish boundaries: (A) Taracoa, (B) Dayuma, and (C) Inés Arango.

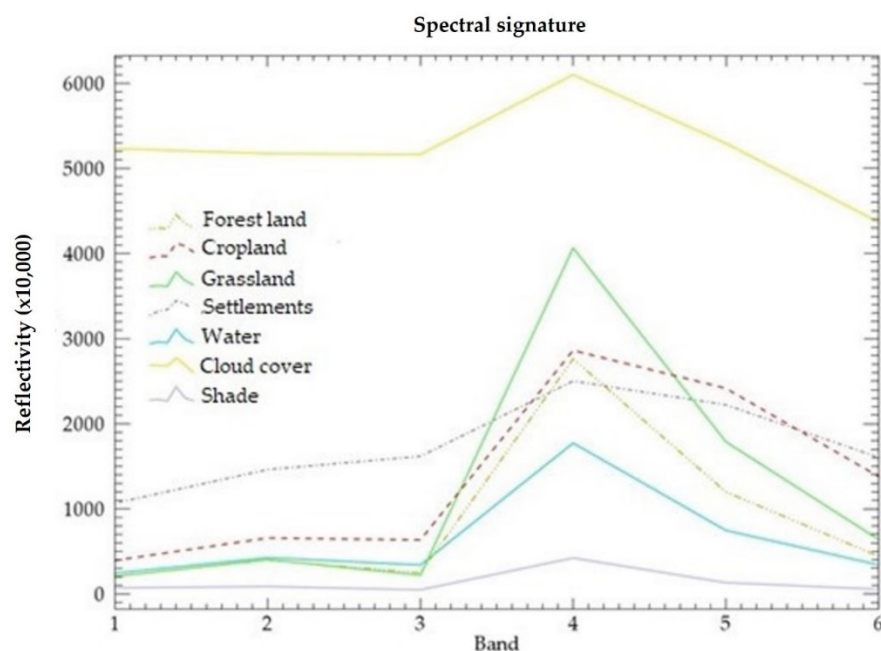


Figure 3. Typical spectral signature resampled from Landsat 8 (2018) imagery for the Life and Diversity Zone, Yasuni Biosphere Reserve of the Ecuadorian Amazon Region.

Table 2. Land use and land cover (LULC) classification scheme.

Class	Description	Example of Aerial View	Training Samples/Year
Forest land	A group of trees, with a minimum canopy cover of 30%, upper stratum height of at least 5 m and with a minimum area of 10,000 m ² (1 ha).		685 (1999) 669 (2009) 479 (2018)
Cropland (Traditional production system)	Areas under cultivation, such as monocultures and agroforestry systems where the vegetation structure does not meet the definition of forest land. This class also includes areas of planted grassland with mainly livestock uses or which are in a rotational system between grassland and crops.		248 (1999) 340 (2009) 371 (2018)
Grassland	Areas that are not considered to be agricultural areas. It also includes areas where the vegetation structure does not meet the definition of forest lands and which are expected to remain so without human intervention.		222 (1999) 394 (2009) 309 (2018)
Settlements	Areas mainly occupied by dwellings and buildings (roads) destined for communities or public services.		129 (1999) 187 (2009) 171 (2018)
Water	Area that is covered or saturated with static or moving water, natural or artificial, that rests on the earth's surface for all or part of the year.		138 (1999) 104 (2009) 187 (2018)

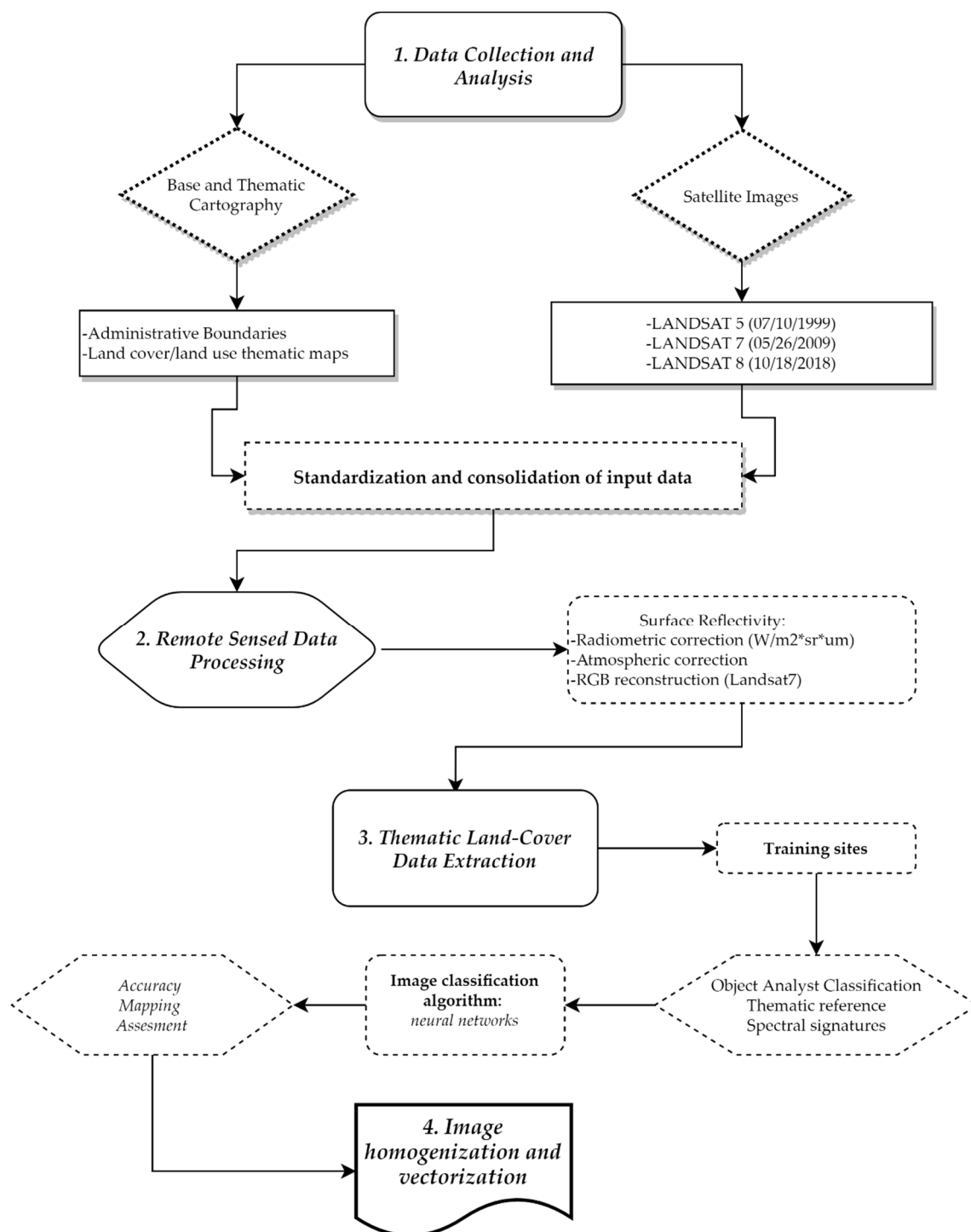


Figure 4. Workflow for the LULC methodology, in the period from 1999–2018.

2.2.1. Data Collection and Analysis

Different Landsat satellite images were obtained from an altitude of 705 km and an inclination of 98° , with a periodicity of 16 days. The LULC spatial dynamics were analyzed using a time-frame of approximately 20 years (1999–2018), downloaded from the United States Geological Survey (USGS) Earth Explorer (<https://earthexplorer.usgs.gov>, accessed on 17 July 2019), with a spatial resolution of 30 m (Table 1). Two satellite images were used for each year of the study (Figure 2). The images were selected by trying to minimize the presence of clouds as much as possible, considering that the Ecuadorian Amazon Region,

is located in the intertropical convergence zone, which is why it has the highest cloud cover in the world [60].

The descriptive statistics calculated were as follows: (1) global precision, which is the fraction between the correctly classified samples and the total pixels of the error matrix, being considered as a confidence or reliability interval, which can be obtained under a level of significance; (2) and the kappa index, which measures the difference between the agreement and the one that would be expected by means of randomization, trying to delimit the degree of adjustment due only to the accuracy of the classification [61] and the precision of the producer, which is the probability of correctly labeling a pixel of class X_i , whereas user precision measures the probability that a pixel labeled in class X_i actually corresponds to that class.

2.2.2. Data Processing for Remote Sensing

The images were standardized, reprojected into the planar coordinate system (SIRGAS, UTM Zone 18S/EPSC:31993), and duly corrected, minimizing atmospheric disturbances, thus allowing the data to be as close as possible to an ideal acquisition [61]. The first step was to perform a radiometric correction, which allows for the conversion of digital counts to physical magnitudes, specifically radiance values ($W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$), and then, through the use of radiative transfer models, mitigate the atmospheric effect, and thus obtain surface reflectivity values. Only for the Landsat 7 image, due to image stripes with no data related to the SLC-off failure (aer 2003), a simple interpolation was applied, which replaces empty pixels with their neighbors. Such a technique is called Neighborhood Similar Pixel Interpolation (NSPI) [62].

2.2.3. Thematic Land Cover

Prior to the extraction of information per se, the thematic legend was structured at a scale of 1:100,000, by identifying the following classes: forest land, cropland (as a traditional production system), grassland, settlements, and water (not identifying areas under the wetlands class) (Table 2). This classification is similar to level II of public institutions: the former Ministry of Agriculture, Livestock, Aquaculture and Fisheries (MAGAP), at present known as the Ministry of Agriculture and Livestock (MAG); the Ecuadorian Ministry of Environment, Water and Ecological Transition; and the former Ecuadorian Space Institute (IEE), now called the Military Geographic Institute (IGM) [63,64].

Subsequently, training samples were selected, using as secondary information, such as the land use and land cover map produced by SIGTIERRAS of Ecuador (<http://ide.sigtierras.gob.ec/geoportail>, accessed on 23 October 2019), scale 1:25,000. The number of training samples selected for every image ranged from 138 to 394 (Table 2). In addition, an object-based segmentation was applied to the input images prior to the application of the classification algorithm, and type spectral signatures were obtained from the images themselves (Figure 3), thus mitigating to the maximum error that could be made when selecting the samples.

The training samples collected were spatially distributed across each of the images, and, in terms of quantity, and were between 10a and 100a pixels [65], with “a” being the number of bands, hence the number of pixels fluctuated between at least 60 and 600 for each class. These samples were evaluated with the Jeffries Matusita index.

Once the key information was collected, the neural network classification technique was applied using layered feedback, making use of a logistic-type activation function, a hidden layer, and a training rate of 0.2. The neural network classifier simulates the biological processes of the human brain, through the multiple interconnections between neurons, also called interconnected processing nodes, which are used to develop models [66].

It is composed of three layers: the input layer represented by the training samples or data, from which the algorithm is learned; the hidden layer, where the weights are adjusted iteratively to provide an approximate output close to the desired one; and the output capacity that houses the results achieved [61]. The process culminates when an

acceptable error is reached, thus being able to use this network in future predictions with an independent data set [67].

Subsequently, using the test samples (different from training samples), we evaluated the accuracy of the results obtained, through the following parameters: overall accuracy (OA) and kappa coefficient (K). All of this process was carried out in the ENVI 5.3 software.

2.2.4. Homogenization and Vectorization of Images

Finally, a smoothing filter was applied to the classified images to obtain greater homogenization and eliminate possible noise, and the product obtained was converted into vector format. The main steps of the data input and data processing are summarized by the workflow in Figure 4. According to Lencinas and Siebert [68], for scales of 1:100,000, the minimum mapping unit is 5 ha; however, to avoid loss of the extracted information, 1 ha was taken as the minimum unit as the image resolution was 30 m pixel⁻¹.

3. Results and Discussion

3.1. Land Use and Land Cover (LULC) in the Life and Diversity Zone (1999–2018)

The validation of the LULC classifications and analysis in the DLZ, which was divided into northern and southern segments, is detailed below with respect to the overlap with the parishes of Taracoa, Dayuma, and Inés Arango (Figure 1).

3.1.1. Validation of Classifications

Overall, the LULC classification levels for the dates range between 98.0% and 99.6%, with Kappa concordance indices between 0.97 and 0.99. The accuracies per individual LULC class (i.e., user accuracy (UA) and producer accuracy (PA)) are shown in Table 3. According to the minimum accuracy of 85% set in the Anderson classification scheme, these Kappa values are satisfactory in all four classes [69].

Table 3. Evaluation of the accuracy of the LULC classification in the Diversity and Life Zone in the Yasuni Biosphere Reserve of the Ecuadorian Amazon Region.

Class	1999		2009		2018	
	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)
Forest land	100.00	98.48	100.00	97.94	100.00	100.00
Traditional production system	98.83	97.13	97.40	99.47	100.00	97.78
Grassland	99.31	98.62	96.02	100.00	100.00	100.00
Settlements	96.08	98.00	96.06	92.42	96.91	100.00
Water	96.70	100.00	93.85	88.41	100.00	100.00
Global precision OA (%)	98.8		98.0		99.6	
Concordance (Kappa)	0.98		0.97		0.99	

PA: producer accuracy; UA: user accuracy.

Once the training ROIs were defined and prior to performing the digital classifications, a spectral separability analysis was performed, taking the Jeffries–Matusita distance as an indicator, which must be greater than 1.8 to consider the absence of confusion between classes.

There are multiple ways that allow us to assess the reliability of results. One of them is through field campaigns or through information from official sources prepared close to our study. However, due to not having this possibility, we decided to make a comparison with the map of use and coverage of SIGTIERRAS, prepared in 2015, obtaining a degree of similarity of 88.7% (34,472.2 ha of 38,857.5 ha of DLZ) with respect to the classification of the image of the year 2018. It should be noted that the cartography prepared by the SIGTIERRAS is the only one available from the VDF. In addition, the technique used to derive the said product was visual interpretation using orthophotos.

3.1.2. Land Use and Landcover Change (LULC)

A. Northern zone of the DLZ (Dayuma and Taracoa Parishes)

The downward trend of forest land and the upward trend of the other classes are evident in Tables 4 and 5, together with Figure 5, which summarize the LULC from 1999 to 2018 based on five classes extracted from the northern zone of the DLZ (the parishes of Dayuma and Taracoa). Furthermore, the spatial representation of LULC types from 1999 to 2018 is shown in Figure 6. In the year 1999, the LULC pattern as a percentage of the total area surveyed was dominated by forest, covering 95.73% of the total area surveyed, followed by herbaceous vegetation (1.74%), traditional production systems (1.41%), water (0.75%), and settlements (0.05%). Trend changes were observed for all LULCs in the years 2009 and 2018.

In the DLZ, from 1999 onwards, forest land decreased by 4.95% and 8.57% in 2009 and 2018, respectively (Figure 5), which is consistent with the trend reported by several authors who stated that deforestation is increasing in tropical forests [70,71]. As widely reported in the literature, Western Amazon has been recognized for decades as one of the 14 major deforestation fronts globally [72,73]. In fact, Ecuador, Peru, and Bolivia are three of the 15 countries that have lost the highest amount of primary forest area between 1990 and 2015 [74]. In the Ecuadorian Amazon Region, the perimeters of protected areas and intangible zones were reported to be more vulnerable to deforestation [56] and problems have been intensified by oil activity [7,75–77], access to road systems [78–80], and by conversion to agriculture [81–84]. Furthermore, these areas experience the dynamics of timber supply from small producers (mestizo settlers and indigenous) to urban centers [85], as Amazonian cities are the first link to final markets through an extended intermediation network [86]. The precarious formal obtaining of deeds for indigenous and settler lands is a weakness in the DLZ, as it has been recurrently demonstrated that formal land deeds are an effective means of buffering deforestation in much of the Amazon biome [87,88].

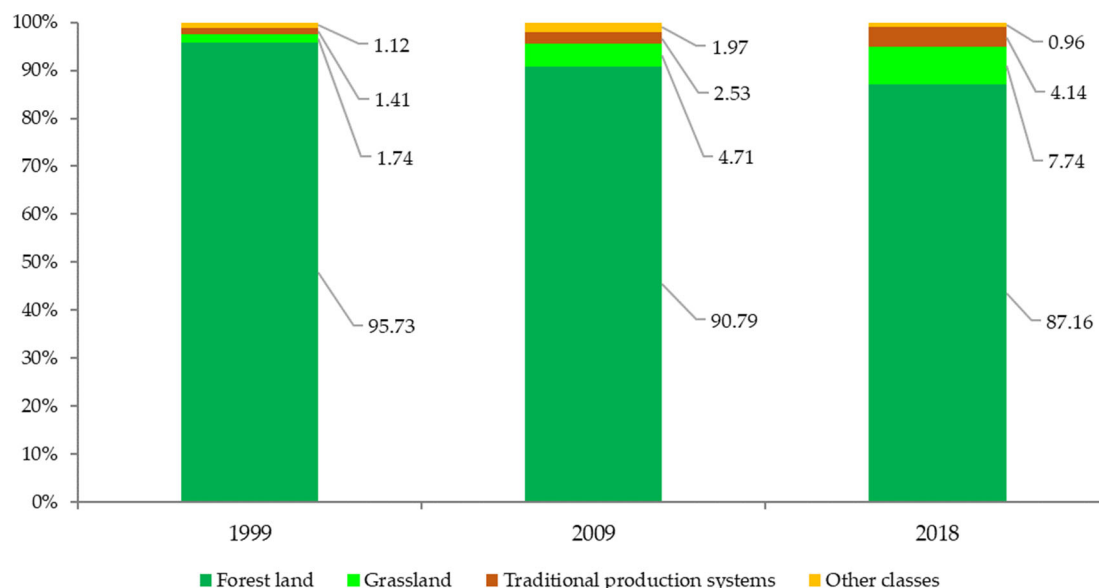


Figure 5. LULC graph for 1999, 2009, and 2018 in the DLS's northern zone (Dayuma and Taracoa parishes) in the Yasuní Biosphere Reserve of the Ecuadorian Amazon Region.

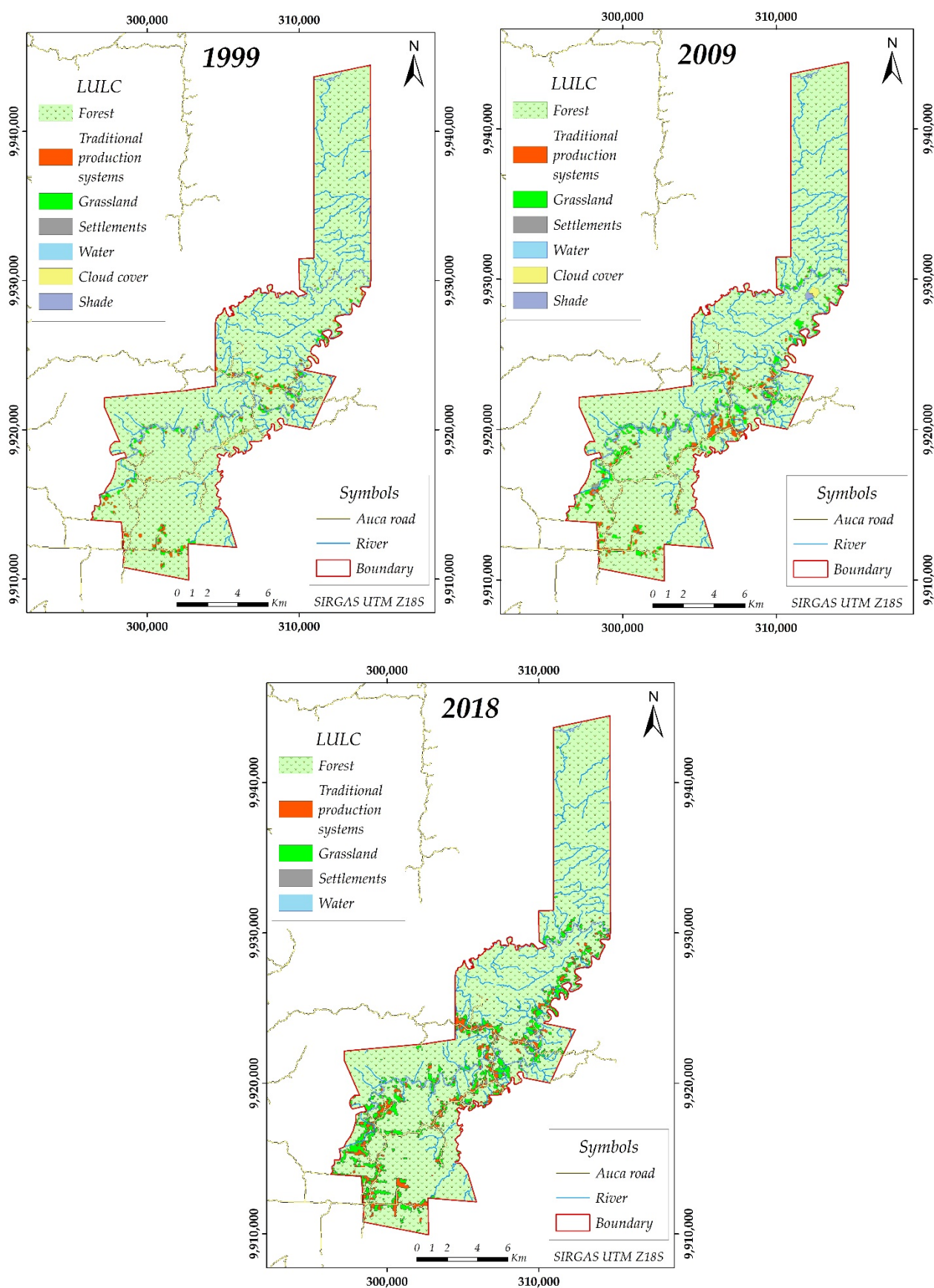


Figure 6. LULC maps for 1999, 2009, and 2018 of the DLZ's northern zone (Dayuma and Taraoa) in the Yasuni Biosphere Reserve of the Ecuadorian Amazon Region.

Table 4. LULC classification results of 1999, 2009, and 2018 images, showing the area of each class and percentages per class in the DLZ's northern zone (Dayuma and Taracoa) in the Yasuní Biosphere Reserve of the Ecuadorian Amazon Region.

Class	Area in 1999		Area in 2009		Area in 2018	
	ha	%	ha	%	ha	%
Forest land	20,089.97	95.73	19,052.13	90.79	18,290.13	87.16
Traditional production system	296.34	1.41	531.48	2.53	868.36	4.14
Grassland	365.75	1.74	989.21	4.71	1625.22	7.74
Settlement	9.63	0.05	123.39	0.59	72.12	0.34
Water	156.67	0.75	220.05	1.05	129.49	0.62
Cloud cover	42.66	0.20	40.92	0.20	0.00	0.00
Shade	24.30	0.12	28.14	0.13	0.00	0.00
Total	20,985.33	100.00	20,985.33	100.00	20,985.33	100.00

Table 5. Results of the LULC classification for 1999, 2009, and 2018 images, showing the area changed and percentages in the DLZ's northern zone (Dayuma and Taracoa) in the Yasuní Biosphere Reserve of the Ecuadorian Amazon Region.

Class	1999–2009		2009–2018		1999–2018	
	Area		Area		Area	
	ha	%	ha	%	ha	%
Forest land	−1037.84	−4.95	−762.00	−3.63	−1799.84	−8.58
Traditional production system	235.14	1.12	336.87	1.61	572.02	2.73
Grassland	623.46	2.97	636.01	3.03	1259.47	6.00
Settlement	113.76	0.54	−51.27	−0.24	62.49	0.30
Water	63.38	0.30	−90.56	−0.43	−27.18	−0.13

In relation to the classification of traditional production systems for the years 2009 and 2018, there were increases of 2.53% and 4.14%, respectively (Table 4). Overall, from 1999 to 2018, there was an increase of 2.73% (Table 5). The dynamics of agriculture are mostly concentrated near roads (Figure 6), driven by farmers' colonization, which is attributed to different state laws [89,90] and the beginning of oil extraction [91], which promoted migration to the Ecuadorian Amazon Region and impacted on land use [92], leading to deforestation and land use change [93]. This LULC dynamic has been the main source of food and livelihood for rural households, a condition very similar to what happened in the Brazilian Amazon during its colonization processes [94]. At present, white, mestizo, and indigenous migrants carry out unsustainable farming practices, mainly based on conventional intensive agriculture using agrochemicals in their production systems, probably influenced by the generation of higher incomes, availability of credit, government social transfers, and land use patterns towards monocultures [95]. However, this type of intensification also brings health issues to the indigenous and migrant settler population [96] as well to ecosystem degradation [97,98].

The expansion of herbaceous vegetation areas from 1990 to 2018 (Table 4) and between analysis periods (Table 5) evidences a 5-fold and 2-fold lower proportion in 1990 and 2009, respectively, compared to 2018. These results may reflect the shift from subsistence to market agriculture in migrant settler and indigenous populations, driven by the diversification of economic and agricultural risk [99], and may also be influenced by the precarious sustainability of traditional production systems, namely: Kinkore (Waorani), Aja (Shuar), Chakra (Kichwa), and agroforestry systems (migrant settlers) assessed under social, environmental, economic, and governance dimensions [37,38,100].

In terms of infrastructure, the results obtained (Tables 4 and 5) and represented in Figure 6 corroborate with the dynamics analyzed in Dayuma in 1982, 1990, 2000, and 2014 [77]. There is evidence of the expansion of road systems as well as non-indigenous and

indigenous settlements due to oil activity and processes of migration and colonization [77]. Similar dynamics have occurred in Machadinho D'Oeste (abbreviated as Machadinho), a municipality located in the state of Rondônia in the southwestern part of the Brazilian Amazon. Machadinho lies within the so-called “deforestation arc”, the area with the highest historical rates of primary forest conversion in the Brazilian Amazon [101]. Likewise, in western Uganda, migration has transformed the forest landscape into patches of subsistence production systems in the area surrounding Kibale National Park, causing substantial impacts on biodiversity and the climate [102]. Furthermore, it has been shown that rapid population growth in tropical countries will significantly increase the intensity of deforestation by 2030 [103]. This poses a major challenge for practitioners seeking to balance rural development and conservation policies in indigenous territories and mega-diverse areas [39].

The inter-annual variations (Table 5) demonstrate that the forest land has steadily decreased, reaching a loss of 1799.84 ha during the period studied, representing approximately 9% in the DLZ's northern zone. It has been replaced with areas related to human intervention, e.g., settlements, traditional production systems, and grassland.

The variation of the water (with a surface area totaling <2% of the total DLZ and an inter-annual variation of <0.5%) is mainly due to the complexity of detecting it in the satellite image, since the spatial resolution of the image is 30 m versus 60 m, which is the average width of the meandering rivers in the study area, requiring several pixels to identify an object.

Another way of showing the dynamics between classes is through spatial analysis, where the geospatial location of each class plays a key role. Between 1999 and 2009, there was an 8.58% change in cover type (1798.82 ha); between 2009 and 2018, the change totaled 12.16%; and over the entire period studied, it was 15.39%. Specifically, 87.39% (17,556.6 ha) of the forest land's initial area (20,089.97 ha) has remained intact during the period 1999–2018.

B. Southern zone of the DLZ (Inés Arango Parish)

LULC analyses in the DLZ's southern zone (Inés Arango Parish) do not differ from the results obtained in the northern zone (Dayuma and Taracoa). In addition, the spatial representation of LULC types from 1999 to 2018 is shown in Figure 7. Starting with a study area of 17,872.17 ha, the LULC pattern in 1999 was dominated by forest land (95.29%), followed by grassland (2.51%), traditional production systems (0.71%), water (0.31%), and settlements (0.14%) with a minor difference by class of 0.44%, 0.77%, 0.44%, and 0.09%, respectively, compared to the northern zone. Tables 6 and 7, together with Figure 8, summarize the dynamics of LULC from 1999 to 2018, based on the five classes extracted from the southern zone. As regards the southern zone in 2018, there was a minor difference between the classes studied with respect to the northern zone: forest land (4.41%), traditional productive systems (2.08%), grassland (1.89%), settlements (0.14%), and water (0.29%). These differences in LULC between DLZ zones may arise from the places' distances to the most densely populated areas (Figure 1) and poor road conditions (Via Auca). These results are consistent with the theory that the closer populations live to towns or cities, the greater the transformation of forest land to other uses [77], given that an increase in geographic accessibility provides an incentive to expand agriculture and reap rewards from the sale of timber products and agricultural crops in market centers and via product intermediaries [104].

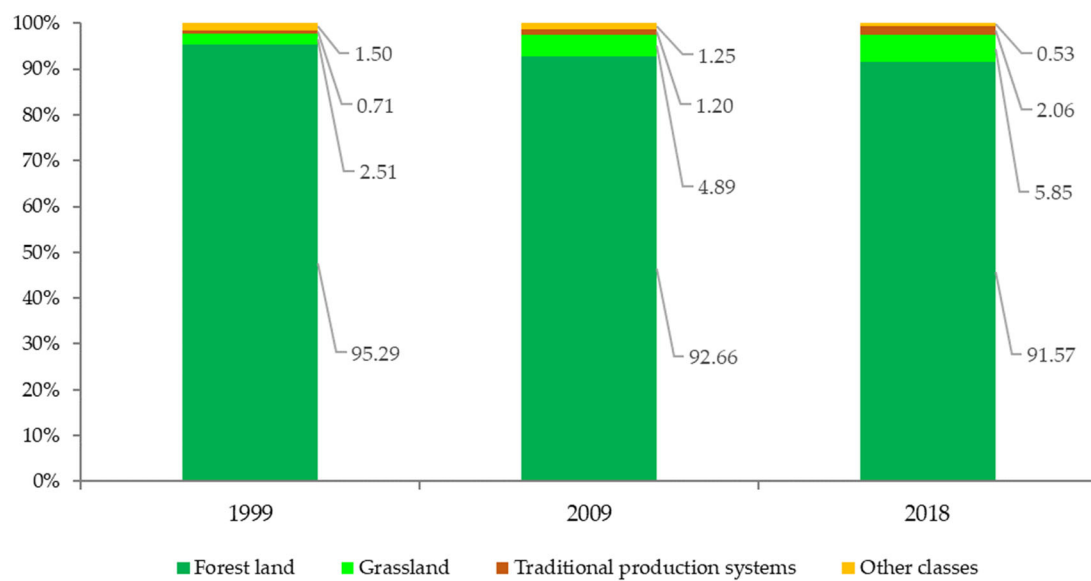


Figure 7. LULC graph for 1999, 2009, and 2018 of the DLZ's southern zone (Inés Arango Parish) in the Yasuní Biosphere Reserve of the Ecuadorian Amazon Region.

Table 6. LULC classification results for the 1999, 2009, and 2018 images, showing the area of each class and the percentages per class in the DLZ's southern zone (Inés Arango Parish) in the Yasuní Biosphere Reserve of the Ecuadorian Amazon Region.

Class	Area in 1999		Area in 2009		Area in 2018	
	ha	%	ha	%	ha	%
Forest land	17,030.23	95.29	16,560.08	92.66	16,364.74	91.57
Traditional production system	126.11	0.71	214.83	1.20	368.25	2.06
Grassland	449.33	2.51	874.55	4.89	1045.51	5.85
Settlements	24.21	0.14	62.21	0.35	35.16	0.20
Water	54.89	0.31	151.23	0.85	58.51	0.33
Cloud cover	150.07	0.84	6.84	0.04	0.00	0.00
Shade	37.33	0.21	2.43	0.01	0.00	0.00
Total	17,872.17	100.00	17,872.17	100.00	17,872.17	100.00

Table 7. Results of the LULC classification for 1999, 2009, and 2018 images, showing the area changed and percentage in the DLZ's southern zone (Inés Arango Parish) in the Yasuní Biosphere Reserve of the Ecuadorian Amazon Region.

Class	1999–2009		2009–2018		1999–2018	
	Area		Area		Area	
	ha	%	ha	%	ha	%
Forest land	−470.15	−2.24	−195.35	−0.93	−665.50	−3.17
Traditional production system	88.72	0.42	153.43	0.73	242.14	1.15
Grassland	425.22	2.03	170.96	0.81	596.18	2.84
Settlement	38.00	0.18	−27.05	−0.13	10.95	0.05
Water	96.34	0.46	−92.72	−0.44	3.62	0.02

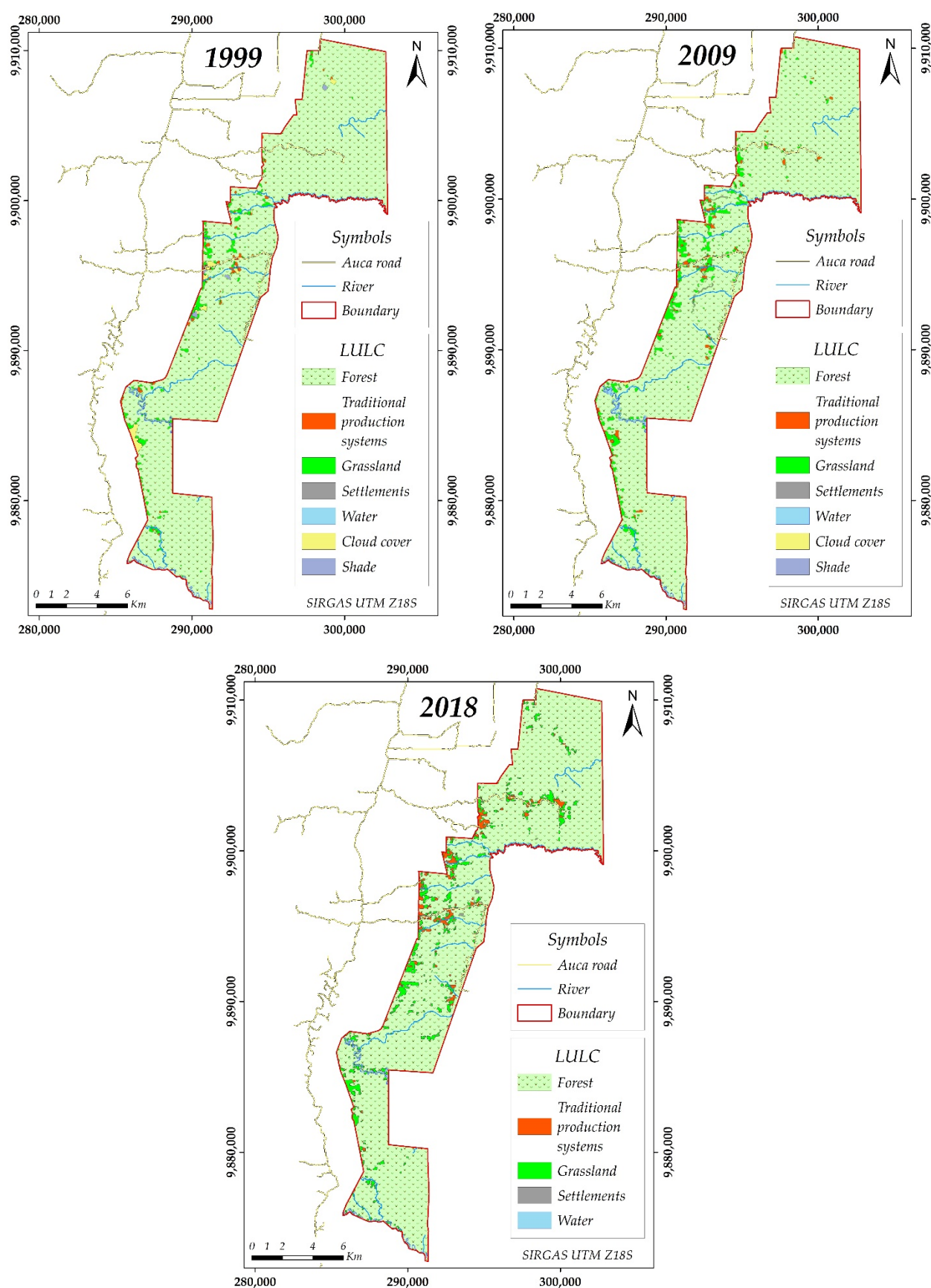


Figure 8. LULC maps for 1999, 2009, and 2018 of the DLZ's southern zone (Inés Arango Parish) in the Yasuni Biosphere Reserve of the Ecuadorian Amazon Region.

Regarding the forest land, there is evidence of a decrease in its surface area (Tables 6 and 7), even though there are controls enforced upon the commercialization of timber and its legality [105]. In tropical countries, timber legality control is costly and often quite ineffective, hence local participants constantly find ways to circumvent the law, as timber contributes to the income of mestizo settler and indigenous populations [106]. Almost all participants in the timber value chain in the Ecuadorian Amazon Region, Peru, and Bolivia comply to some extent with the law but also engage in some illegal practices [107,108].

Regarding traditional productive systems, between the periods 1999–2009 and 2009–2018, they increased by 0.33%, reaching 1.15% in the period 1999–2018 (Table 7). Considering that most of the inhabitants in the southern zone are migrant settlers and their main livelihood derives from oil company wages, productive systems have been lost, mostly due to the abandonment of agricultural land driven by socio-economic factors [109], evidenced by the increase in grassland (Table 6). Similar scenarios can be found in the Albertine Graben region on the border between Uganda and the Democratic Republic of Congo, where oil activity has generated negative social and environmental impacts [110,111], potentially eroding the relationship between people and local-national government, creating economic distortion, increased corruption, and internal tensions [112]. Additionally, the abandonment of agricultural land has increased the workload for women [113,114].

The study of LULC in the northern Ecuadorian Amazon during 1973, 1986, 1989, 1996, and 1999 [113] agrees with the dynamics of the settlements class in the northern and southern zones of the DLS (Figures 6 and 8, respectively). Similar landscape alterations are evident from the LULC study in oil block No. 47, located in the province of Orellana (Ecuadorian Amazon Region) [16].

The geospatial dynamics between all classes shows a variability of 6.46% (1154.31 ha) between 1999 and 2009, 8.56% between 2009 and 2018, and 11.27% over the entire period studied. As for forest land, 92% (15,665.86 ha) of its initial area (17,030.23 ha) was kept intact during the period 1999–2018.

3.1.3. Hotspots of LULC within the DLZ

In the DLZ, four LULC hotspots were identified: two in the north (Figure 9) and two in the south of the DLZ (Figure 10). The dynamics of the LULC hotspots found follow the patterns of the road networks built by the oil companies [115,116], and the banks of the rivers [117]. LULC hotspots are home to indigenous populations (Waorani, Shuar and Kichwa) and migrant settlers (Figure 1) native to the Andes and the coast of Ecuador [118]. Similar LULC dynamics are found in the Apyterewa Indigenous Land (Eastern Brazilian Amazon), where the Parakanã indigenous group inhabits and the LULC change correlates with the roads and rivers of the Xingu River basin [119].

Among the indigenous peoples who inhabit the LULC hotspots, it is observed that in the territory occupied by the Waorani indigenous people, there is minimal alteration of the forest landscape. (Figure 9—Hotspot 1), which correlates with the manifesto that the Waorani, who live near the Via Auca, depend on the paid positions of the oil companies and there is little or no interest in the production of food in the Kinkore [120] and there is extensification of the Ajas (Figure 10—Hotspot 1) in the territory occupied by the Shuar indigenous, who migrated from the south of the Ecuadorian Amazon Region [121].

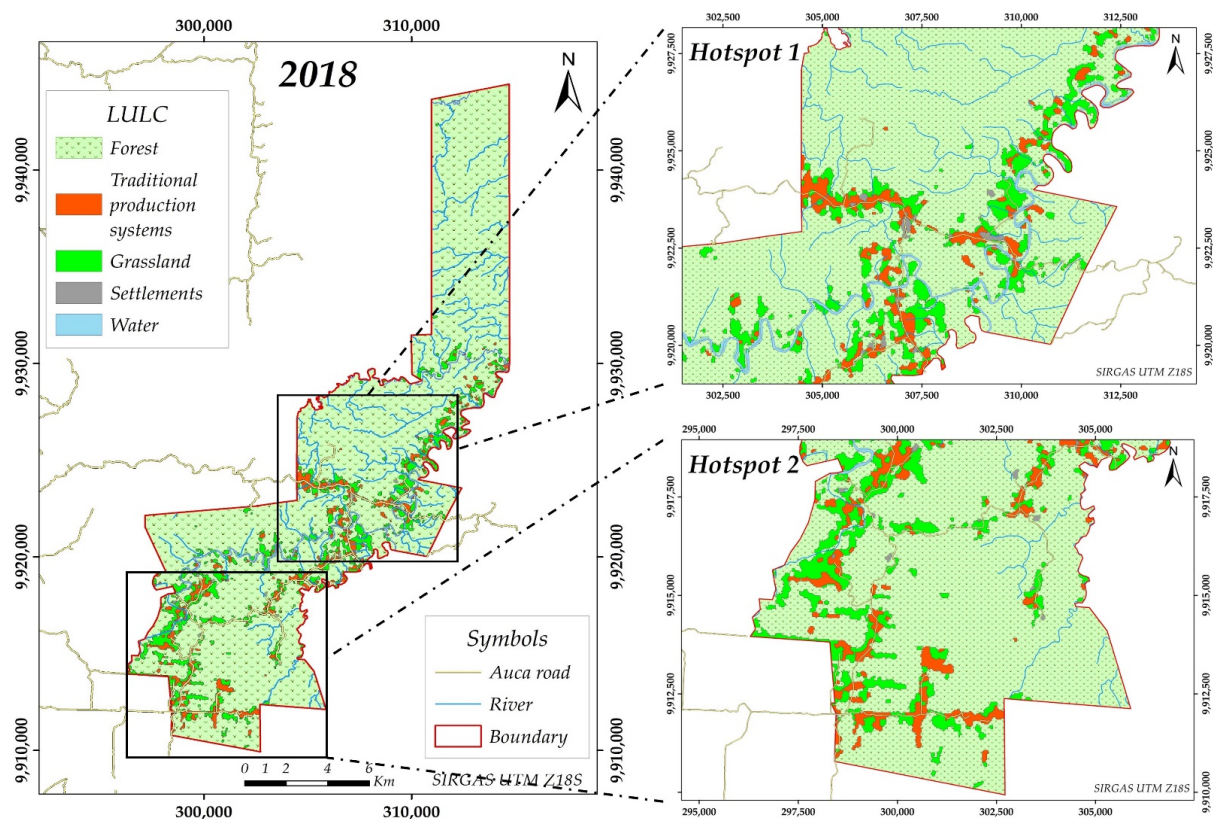


Figure 9. LULC hotspots in the northern zone of the DLZ (Dayuma and Taraoa) in the Yasuní Biosphere Reserve of the Ecuadorian Amazon Region.

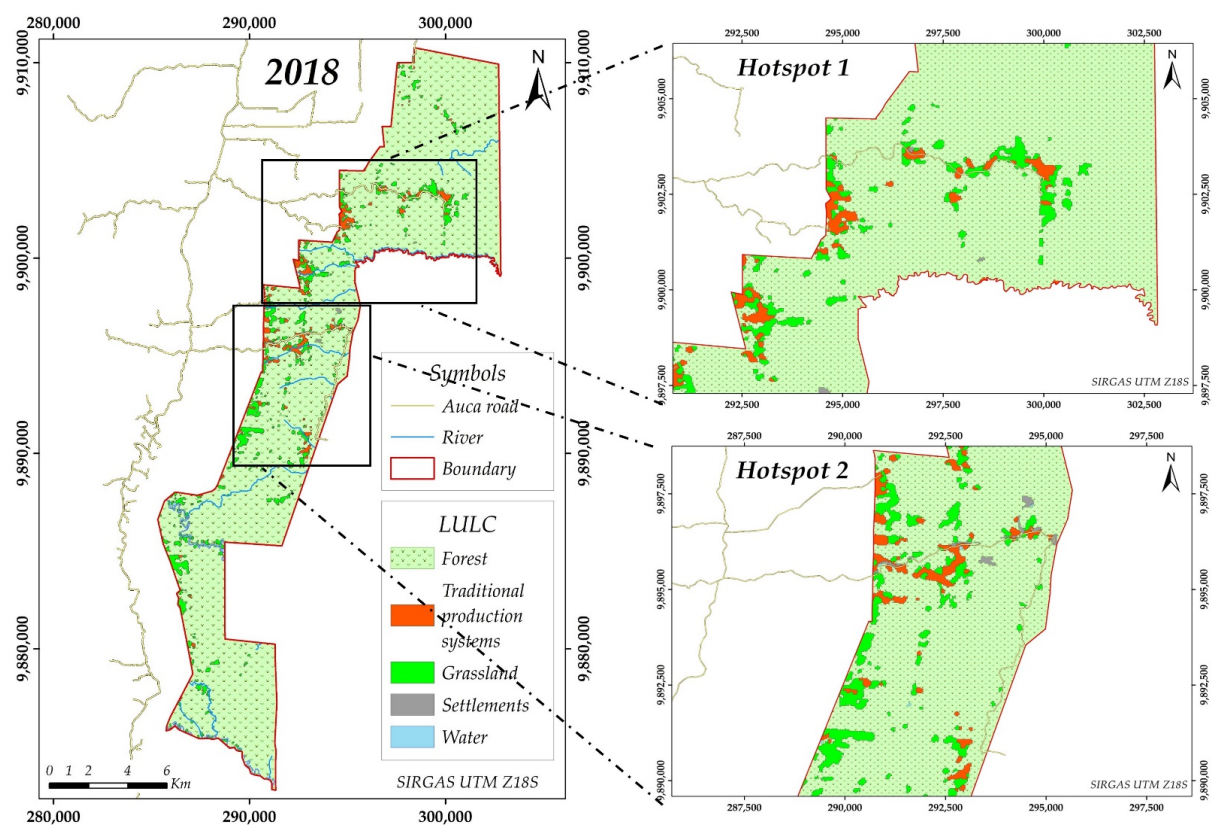


Figure 10. LULC hotspots in the DLZ's southern zone (Inés Arango Parish) in the Yasuní Biosphere Reserve of the Ecuadorian Amazon Region.

3.1.4. Potential Policy Implications for Sustainable Land Use in the DLZ

The results show changes in the LULC dynamics from 2009 to 2018, where an increase in deforestation and an expansion of different traditional production systems are evident. Ecuador's current agricultural policy has proposed sustainable agriculture and the rescue of traditional production systems as a tool to achieve food security, poverty alleviation, and environmental conservation [122]. Nonetheless, it is necessary to put these statements into practice by taking different local realities into account, as in those described in the DLZ, by implementing real actions in a participatory manner between indigenous and migrant settlers, with the aim of establishing sustainable intensification practices that will allow migrant settlers and indigenous populations to increase their income without having to do so at the cost of increasing the surface area [123]. What is more, these results suggest an evaluation of financial incentive programs that could reduce deforestation in this area, especially in terms of use and distribution, as well as in the analysis of priority areas at risk of deforestation, including the DLZ [56].

The Forest Incentives Program or “Socio Bosque” consists of the transfer of a direct monetary incentive per hectare of native forest and other native ecosystems to individual landowners or indigenous communities that protect these ecosystems, through voluntary conservation agreements [124], with the values of the monetary incentives depending on the range of hectares conserved (Table 8) [125]. According to our findings, this program should be reviewed in order to refine its approach, as its spatial distribution has not prioritized the most vulnerable areas, which could lead to a limited effect on reducing future deforestation. Although the implementation of this program has been a beneficial example of public policy aimed at environmental conservation and rural poverty alleviation, we consider it vital to revise the program to integrate factors, such as vulnerability to deforestation and alternative territorial management strategies that go beyond conservation and address sustainable land management in the DLZ [126].

Table 8. Monetary incentive levels provided in exchange for enrollment.

Range of Hectares		Quantity (USD)
1	20	60.00
1	50	30.00
51	100	20.00
101	500	10.00
501	5000	5.00
5001	10,000	2.00
>10,001		0.50

Individuals with less than 20 hectares in their total land title are provided with additional financial incentives.

In general terms, the advancement of the agricultural frontier, and the increase in deforestation and infrastructure in the DLZ is evident. To this end, the achievement of SDG 15 must be promoted by improving the quality of governance in terms of production and conservation of natural resources, as these elements are key to minimizing land-use change [126]. It is essential to implement practical actions aimed at the sustainability of traditional production systems worked in by indigenous and migrant settlers [38,100] in order to achieve the Sustainable Development Goals for 2030, for example, the promotion of field schools that encourage the rescue of these traditional systems, as well as the consumption of food products from the systems.

4. Conclusions

The spatial analysis, based on open-access spatial data from Landsat mission, made it possible to quantify and map the pattern of LULC in the Yasuni Biosphere Reserve's DLZ by focusing on changes in the northern and southern zones. Spatial analysis on a time scale of 20 years (1999–2018) allowed identification of LULC changes in sensitive areas, including the detection of important hotspots of deforestation. Spatial analysis and

mapping of LULC changes within the DLZ provide a basis for strategic and inclusive territory planning, management, and decision-making both for biodiversity conservation and human rights protection, by improving livelihood strategies for indigenous Waorani, Shuar, Kichwa, and migrant settler communities, and as a tool for precautionary protection measures for uncontacted indigenous peoples. Additionally, the use of very high-resolution multispectral satellite imagery can provide more details of the changes in the region. Based on the LULC analyses of Landsat data for the years 1999, 2009, and 2018, it was found that the LULC trends varied; hence, these results provide an important platform for further analysis of LULC.

In the period 1999–2018, most land uses and land cover were transformed into grasslands in the northern and southern zone of the DLZ. This indicates that the expansion of grassland was the result of deforestation, probably due to infrastructure for oil activity and the intensification of traditional productive systems for the integration of indigenous peoples into the market economy, especially in the northern zone of the DLZ. In the southern zone, the LULC values were found to be lower because there is little incidence of oil activities, fewer infrastructures, and the existence of migration processes of migrant settlers to the city. In general, of the assessed LULC classes, they were observed in an upward direction in the DLZ. Therefore, proper management of the DLZ, including land use planning, is required to avoid resource use conflicts between indigenous communities, migrant settlers, uncontacted indigenous peoples, and different local and international actors in the northern and southern zones of the DLZ.

Author Contributions: Conceptualization: M.H.-R., F.C.-T., C.G.H.D.-A., B.T. and S.E.P.; Methodology: M.H.-R., F.C.-T. and B.T.; Software: M.H.-R. and F.C.-T.; Writing—Original Draft Preparation: M.H.-R., F.C.-T. and B.T.; Writing—Review & Editing: M.H.-R., B.T., E.T., C.G.H.D.-A. and S.E.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research carried out with small funds of from the project: “Analysis of sustainability and climate change in indigenous farmers and settlers of the Yasuní Biosphere Reserve, Ecuadorian Amazon” of the Universidad Estatal Amazónica (Ecuador), this research has not received external funds.

Acknowledgments: We want to thank the Universidad Estatal Amazónica and Military Geographic Institute, (Quito–Ecuador) for the support, for the realization of this research.

Conflicts of Interest: The authors declare no conflict of interest.

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