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Land-Use and Land-Cover Change in the Páramo of South-Central Ecuador, 1979–2014

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Abstract: Land use and land cover were mapped between 3500 and 5000 meters above sea level m.a.s.l. in the Río Chambo basin in south-central Ecuador from Landsat MSS, TM, ETM and OLI imagery acquired between 1979 and 2014. The area mapped has been dominated by páramo and a variety of agricultural land uses since 1979. The main land-use transitions have been from páramo to agriculture, native forest to páramo and agriculture, and agriculture back to páramo. Significant areas of páramo have remained unchanged over the 35-year period analyzed, while the area of native forest has declined and that of bare soil increased. Plantations of non-native timber species increased from 1979 to 1999, but their area has now declined. Most land-use transformations have occurred at lower elevations in the 3500–5000 m.a.s.l. range. This is particularly the case for the loss of native forest and the degradation of páramo and agriculture to areas of bare (eroded) soils. A drivers-based approach revealed that these land-use transformations were related to import substitution and afforestation policies geared toward internal markets, exports and environmental conservation.

Keywords: land-use and land-cover change; páramo; drivers; forestry policy; Surface Reflectance Calibrated Image Archive; Ecuador

1. Introduction

Páramo ecosystems provide highly significant environmental and economic benefits in Colombia, Ecuador, Peru and Venezuela. They are areas of high biological diversity and plant endemism [1–7]; and provide a wide range of ecosystem benefits, particularly those related to the water cycle and carbon storage [8–15]. Approximately 10 million people live in the Northern Andean páramo and the socio-economic decisions they make lead to a wide range of land uses and transitional pathways between land uses. In the Andes, human interaction with land has a long and culturally important history [16–21], but in recent decades new land uses and trajectories of change have emerged. These have been driven by new socio-economic and political influences [22], and are occurring in landscapes in which climate change is taking place at unprecedented rates in the history of human occupation of the páramo [23–25].

Hofstede et al. [26] argue that the Ecuadorian páramo has experienced more change than the páramos of Colombia and Venezuela. Almost three quarters of it had been converted to other types land cover types at the start of this millennia, most of which can be attributed to the expansion of cultivation and the intensification of grazing—the two historical tenets of land-use change in the páramo. Conservation concerns are becoming critical, intact páramo ecosystems account for 5% of Ecuador's land area and only 40% have protection status [27]. In Central Ecuador, páramo and native forest ecosystems have decreased by 0.8% and 2.1% per annum respectively between 1963 and 1991 [28], while in the Pambamarca region of northern Ecuador 19.4%–24.3% of páramo was lost between 1988 and 2007 [29]. Between 1975 and 2001, the extent of pasture increased at the expense of páramo and there was considerable forest fragmentation in southern Ecuador [30]. These dramatic changes in native vegetation in the high Andes in the late 20th and early 21st Centuries have been attributed to changes in land-use practices after the 1954 land reform [31]. These changes have increased soil erosion rates and negatively impacted on the hydrological and carbon cycles [8,9,14,31–39]. It has been argued that land-use policies, deforestation, urbanization, and the movement of people are the root causes of degradation in this ecoregion [40]. The conservation concerns arising from this, and the compromised ability of the páramo to provide ecosystem benefits [28,40–42] at local to regional scales, has led the Ecuador Ministry of Environment to establish the SocioPáramo Program, as part of the Socio Bosque Program [43] as a way of trying to conserve the remaining forests in the páramo [44].

The research reported in this paper investigates land-use change in an area of páramo in central Ecuador since 1979. It focuses on a recently recognized knowledge gap in páramo studies, i.e., a spatially-explicit analysis of the drivers that influence land-use decision-making in the ecoregion [30]. The research was conducted in part of Ecuador's páramo that has received very little attention from the land science community—the Río Chambo basin—and used remotely sensed data as its primary data source. Its use in land-use change studies of the páramo has been limited [29,30], especially in comparison to its use in Ecuador's Amazon and coastal regions. It has been argued that this is due to complexities in topography and atmospheric conditions [45–47], which are often not tackled due the constraints of many research projects [48] and limited accessibility to field sites [30].

The geographical focus is on land-use changes in the 3590 km^2 Chambo river basin located in Chimborazo Province (Figure 1) between 1979 and 2014. The Río Chambo drains into the Río Pastaza—a large tributary of the Río Marañón in the western Amazon Basin. Elevations in the basin range from 2080 to 6310 m.a.s.l. However, the area studied is mostly located above the upper treeline and is mainly a mosaic of rural land uses, except for the peri-urban fringes of the city of Ríobamba and the adjoining towns (Figure 1). The National Institute of Census and Statistics classified 52.3% of the area's population as rural in 2015 [49]. Many inhabitants have strong multi-generational associations with the region, and approximately 70% of them depend directly on the páramo and associated ecosystems for food, forage, timber, drinking water and irrigation [50]. As is the case with most Andean communities, agriculture is a key element of people's cultural identify. Nonetheless modernization and development agendas have made ingress into traditional communities and contemporary landscapes, and though tradition still strongly influences land-use practices there are unambiguous elements of modernization

Figure 1. Location map.

2. Data and Methods

Landsat MSS, TM, ETM+ and OLI data (Table 1) were the primary image data sources, and in using these the research exploited an important new source of atmospherically-corrected imagery for land-change detection and environmental monitoring—the Surface Reflectance Calibrated Image Archive [51–53]. This archive is provided by the USGS as part of the Landsat Surface Reflectance Climate Data Record (Landsat CDR), which is generated by the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) [54]. It is available through the Earth Explorer portal (https://earthexplorer.usgs.gov). Images in this archive are calibrated to surface reflectance using a model based on physically based measurements of land surface properties. The calibration involves conversion of top-of-atmosphere reflectance before the effects of the atmosphere are removed to produce at-surface reflectance [55]. Data are supplied in either a Universal Transverse Mercator (UTM) or Polar Stereographic (PS) format [54] and are well suited to observing and analyzing land cover changes. This is in part because Landsat TM and ETM+ image data have been used extensively in land cover analyses. In addition, the fact that these data are atmospherically-corrected and georectified will save land scientists significant amounts of time in image processing. Finally, the planned inclusion of MSS will encourage some land scientists to extend analyses backward into the 1970s. While TM, ETM+ and OLI imagery in the Landsat CDR have the same spatial resolution, MSS data are not included in the archive at the present time. Therefore, the 1979 MSS image used in this research was converted from radiance data to a surface reflectance image using a combined Dark Object Subtraction and Cos (TZ) approach [56] normalized to account for seasonal changes in the Earth-Sun distance and solar elevation using standard image parameters. The equation used was:

$$\mathrm{PBandN} = (\pi \times (\mathrm{L}\lambda - \mathrm{L}\lambda\mathrm{SHV}) \times \mathrm{d2})/(\tau\mathrm{v} \times (\mathrm{ESun}\lambda \times \mathrm{Cos}\theta\mathrm{S}) \times \tau\mathrm{z} + \mathrm{Edown}) \quad (1)$$

where:

PBandN = Reflectance for Band N (at-surface reflectance);

Lλ = Spectral radiance at the sensor's aperture;

LλSHV = Spectral radiance at the sensor's aperture for the SHV (path radiance or upwelling diffuse sky irradiance);

d = Earth-Sun distance in astronomical units;

ESunλ = Mean solar exoatmospheric irradiance (solar spectral irradiance);

θS = Solar elevation in degrees;

τv = Atmospheric transmittance in the sensor direction;

τz = Atmospheric transmittance in the illumination direction;

Edown = Downwelling diffuse sky irradiance.

In addition, this image was resampled to 30 m spatial resolution to enable change analysis to be carried out at the same spatial resolution.

Table 1. Image data used to map land use in the Chambo basin.

Date	Satellite/Sensor	Spatial Resolution (m)	Download Details
4 February 1979	Landsat 2/MSS	80	8-bit quantized radiance data
18 December 1991	Landsat 5/TM	30	Surface reflectance calibrated images from Landsat Higher Level Science Data Products archive
14 November 1999	Landsat 7/ETM+	30	
30 October 2014	Landsat 8/OLI	30	

All image data were georectified to UTM projection WGS84, Zone 17 South. Páramo, native forest, forest plantations, cultivated areas, bare soils, urban areas and wetlands were mapped from the 2014 OLI image using a maximum likelihood supervised classifier. Training sites of up to 20 pixels were identified from orthorectified high spatial resolution aerial imagery of the basin [57] and field data [58]. The supervised classification initially mapped 14 classes, including cloud and unclassified pixels. The 14 classes were then grouped into classes that are meaningful in terms of land use and land cover in the Andes. Two digital masks of areas <3500, and >5000 m.a.s.l. were used to discriminate between the páramo and other ecoregions. A similar approach was used to map páramo ecosystems in the Pambamarca region [29] and southern Ecuador [30]. A 'cloud mask' was created by combining any parts of the páramo (i.e., the elevations between 3500 and 5000 m.a.s.l.) that were obscured by cloud or cloud shadow in any of the four images.

Accuracy assessment was carried out on the land-use map derived from the 2014 OLI imagery using Kappa analysis in ERDAS Imagine 15.0, and confusion matrix analysis was done in ArcMap 10.2. This was carried out at 447 randomly selected points using ground information, high-resolution aerial photography and the original Landsat 2014 image. The overall mapping accuracy using Kappa analysis was 87.9%. The highest accuracies by class were for pine plantations (99.0%) and páramo (90.5%), the accuracies of other classes were agricultural areas (83.9%), native forest (82.1%), bare soil (45.5%) and urban areas (43.8%).

A land change dynamics map was created as follows. The pixels in each classified image were assigned a numerical code based on their land use. The four image maps were combined to create a single map in ArcMap 10.2 in which each pixel has a four-digit code: the first digit is for the land-use class in 1979, the second for 1991 and so on. For example, a pixel coded 1111 would indicate páramo in each year sampled, whereas the code 1651 would indicate a pixel that was initially páramo which then become bare soil, then agriculture before finally regenerating back to páramo. The changes in the land-use and land-cover classes for each pixel were then counted to create a four-class image of the number of times a pixel had changed.

3. Results

Land-use mapping and change analysis were undertaken for 122,676 ha of the basin, i.e., the area defined by the <3500 m.a.s.l., >5000 m.a.s.l. and cloud masks. Table 2 shows the areas for each land-use class for each year.

Table 2. Chambo basin: land use and land cover in 1979, 1991, 1999 and 2014 (ha).

Land Use	1979	1991	1999	2014
Páramo	63,073	76,370	74,712	54,733
Native forest	30,795	12,225	9024	8234
Bare soil	3572	2661	3221	11,206
Wetlands	1693	108	1785	31
All natural and semi-natural	99,133	91,454	88,742	74,204
Land Cover	**1979**	**1991**	**1999**	**2014**
Forest plantations	0	2093	4359	519
Agricultural areas	18,745	26,700	28,124	46,473
All modified land uses	18,745	28,803	32,473	46,992

Native forest in this area is dominated by a low (approximately 2–6 m) canopy of broad-leaved shrubs and small trees (cf., Figures 1 and 2 [10] for photographs that compare páramo and native forest). Canopy cover varies from dense, multi-level canopy structures in gullies in well-dissected terrain to simple, discontinuous canopies where they are more accessible and have been modified by people collecting firewood. They differ from the forest plantations which are planted pines (*Pinus patula* and *P. radiata*) with much higher canopies in mature plantations. Agriculture at >3500 m.a.s.l. in this area is dominated by the cultivation of potatoes and other tubers. Most potato fields would have been at various stages of planting when the 1991, 1999 and 2014 images were acquired as the main planting season is from October to December in central and southern Ecuador, but some fields would have a potato crop in them as there is also a minor planting season in June and July [59]. There are no significant areas of permanent crops. The bare soil class includes eroded areas, fields recently prepared for cultivation and areas of recently cleared plantations are included in the bare soil class. Urban areas have been added to the bare soils class because they have very similar spectral properties to bare soil in the area under investigation. Urban areas are uncommon above 3500 m.a.s.l.

More complex patterns of land-use transitions emerge when the inter-image periods are examined. Table 3 shows all the land-use transition pathways identified except those involving wetlands. The wetlands, which mainly comprise small lakes or seasonally and permanently saturated terrain, vary considerably in area (Table 2). Although they are important in generating runoff [60], the wetlands were not mapped as their area is relatively small compared to páramo and native forest, and the climatological and hydrological data required to explain their fluctuations were not available to the researchers at the time the research was carried out.

Table 3. Major land transitions in the Chambo river between 1979 and 2014 by area (ha) and as a proportion of the class at the start of the inter-image period. Wetlands are excluded.

Land-Use and Land-Cover Transition Pathways	Inter-Image Periods					
	1979–1991		1991–1999		1999–2014	
	ha	%	ha	%	ha	%
Páramo to agriculture	11,650	18	7647	10	21,665	29
Páramo to forest plantation	994	2	453	1	288	<1
Páramo to bare soil	518	<1	312	<1	6037	5
Native forest to páramo	14,303	46	2606	21	6570	73
Native forest to agriculture	5216	17	828	7	1883	21
Native forest to forest plantation	2629	9	0	0	117	1
Native forest to bare soil	521	2	46	<1	328	4
Agriculture to páramo	9049	48	9917	37	2280	8
Agriculture to forest plantation	420	2	328	1	49	<1
Agriculture to bare soil	466	3	1216	5	2726	10
Forest plantation to páramo	1044	<1	439	21	360	8
Forest plantation to agriculture	0	0	1044	50	907	21
Forest plantation to bare soil	0	0	24	1	24	1
Unchanged Areas						
Páramo	47,578	75	60,473	79	43,769	59
Native forest	6173	20	4330	35	2901	32

By 1991 páramo, which covered 63,073 ha (51%) of the study area in 1979, had increased by 13,297 ha (61% of the study area) (Table 2). Despite this net increase, 11,650 ha (18%) of páramo had been converted to agriculture over this time period. Forest plantations had replaced a further 994 ha, and 312 ha of bare soil and rock had been exposed by erosion, recently cleared prior to cultivation or had been built on (Table 3). In terms of the native forest, 14,303 ha mapped in 1979 had been converted to páramo, 5216 ha to agriculture, and 2629 ha to forest plantations (Table 3).

Over three-quarters (79%) of the páramo mapped in 1991 was unchanged eight years later. Of the remainder, 7647 and 453 ha had been converted to agriculture or plantations respectively. Bare ground accounted for <1% of the respective areas in 1991 and 1999. A large amount of native forest was cleared between 1991 and 1999, of which 828 ha was mapped as agricultural land in 1999 and a further 2606 ha was páramo. In the eight years after 1991, 9917 ha of agricultural land regenerated to páramo and 1216 ha was exposed through erosion, newly cleared farmland or had been built on. Approximately half the forest plantations that were mapped in 1991 (1044 ha) had been harvested and the land converted to agriculture.

In terms of the natural vegetation, the areas of páramo and native forest declined by 1979 and 8234 ha respectively in the 15 years after 1999. Forest plantations had virtually disappeared from the landscape, most having been converted to agriculture. Transitions from páramo to agriculture and páramo to bare ground accounted for 21,665 and 4067 ha respectively. The regeneration of 2280 ha of agriculture back to páramo was less than in the previous inter-image period, though a further 2726 ha of bare soil had replaced agriculture.

The pathways between agriculture and bare soil require special consideration as these are the two least accurately mapped classes for 2014, indicating potential spectral overlap. The bare soil class includes fields which have not been planted at the time of image acquisition, on the basis that exposed soil and uncultivated fields will be spectrally similar and unlikely to be mapped as different classes by most classification algorithms. The potentially high level of spectral confusion between the bare soil fields and agricultural areas is compounded by two other factors. First, most potato fields in the region in any one year would have been planted anytime between October and December, though a smaller amount would also have been planted in June and July [59]. As the images were acquired in October and February (Table 1), the October to December planted fields would have been in different stages of growth with varying amounts of vegetative cover. The visible green and near infrared components of potato field pixels would have been greatest for the 1979 imagery and least for the 2014 imagery. This explains some of the variability in the transitions from agriculture to bare soil, e.g., the large number of bare soil pixels in October 2014 (when most potato fields would have been bare) compared to November 1999 (when a greater proportion of fields would have been planted and potato plants would have emerged).

The major land-use and land-cover transitions in the Chambo basin have similarities with those in Pambamarca [29], where the main pathways were from páramo to farmland, bare ground and grazing; and bare ground to farmland. Forest plantations and native forests were less important in Pambamarca than in the Chambo basin.

Land-use maps for 1979, 1991, 1999 and 2014 (Figures 2–5) reveal distinct geographical patterns of land-use and land-cover change. The most obvious of these is that there is significantly more native forest on the high ground that forms the interfluve between the Chambo basin and the catchments on the east slope of the Andes than on the high ground to the west, i.e., the continental divide between Amazon and Pacific drainages.

To describe the changes in the spatial patterns of land use and land cover, the area mapped is divided into four blocks (Figures 2–5):

(i) A small block of land to the north between Volcán Chimborazo and Volcán Tungurahua–*the northern block*;
(ii) A small northwest-southeast aligned area in the center west of the basin—*the central block*;
(iii) The continental divide to the west—*the western block*; and
(iv) The interfluve between the Chambo basin and other rivers flowing into the Río Pastaza—*the eastern block*.

The area mapped in the northern block is small and it has persistent cloud cover. The area mapped comprised mainly small patches of páramo, cultivation and bare soil in 1979 (Figure 2) and has remained more-or-less the same since. It lies on the lower slopes of the adjacent volcanoes and comprises fertile Andosols which, because they are adjacent to the towns of San Andrés and Guano and close to Ríobamba, have been utilized intensively for a long time.

Elevations in the central block barely exceed 3500 m.a.s.l., and the area is surrounded by the highly disturbed lower terrain of the Chambo basin. It had a similar mosaic of land uses to the northern block in 1979, and at its lower elevations it had already been extensively disturbed by farmers migrating upslope to clear páramo to create new fields and pastures. By 1991 almost all of the páramo had been replaced by cultivation, though patches of bare soil at lower elevations persisted (Figure 3). Land use patterns in 1999 and 2014 were similar to those in 1991.

In 1979, the dominant land use along the entire length of the continental divide (western block) was páramo, though at its lower margins cultivated fields are noticeable (Figure 2). Native forest was dispersed among the other land uses, as well as in large patches in the center and south at medium and lower elevations. Bare soil was restricted to elevations just over 3500 m.a.s.l. in the center and the south. Changes in the spatial distribution of land use between 1979 and 1991 can be seen clearly when comparing Figures 2 and 3. Agriculture had become the dominant land use, extending onto areas that were formerly native forest, páramo or bare soil. Though areas of bare soil at low elevations had been lost in the center of the block, they still persisted in the south. The loss of bare soils areas be related to the differences in months of image acquisition and the potato planting calendar and therefore is an artefact of the dates images were acquired rather than a permanent land-use trend. The páramo that remained from 1979 was mainly at medium to high elevations. Land-use patterns in 1999 (Figure 4) were like those in 1991, though some páramo had regenerated at medium elevations. The areas of bare soil found in the south of this block at low elevations in 1979 and 1991 had mainly been replaced by cultivated fields in 1999. This lends support to the argument that some of the areas mapped as bare soil are areas of páramo that have recently been cleared prior to cultivation [29]. Nonetheless, highly dispersed patches of bare soil still existed in 1999 along the entire continental divide at low elevations.

Large tracts of páramo and native forest dominated the interfluve (eastern block) to the north of the Alao valley (Figure 2). By 1991 this area had been reduced and that which remained was in relatively large patches at low elevations (Figure 2). Elsewhere agriculture had replaced native forest, at low elevations, and páramo at low to medium elevations. With the exception of some native forest regeneration at similar elevations, the geographical distributions of land use in 1999 and 2014 were similar to 1991.

Large tracts of native forest and páramo dominated land use between the Alao and Cebadas valleys in 1979. However, by 1991 almost all the native forest had been replaced by páramo and cultivation. Páramo and native forest remained the dominant land uses in 1999, though some native forest had regenerated at medium elevations. By 2014 more native forest had reappeared in the landscape (Figure 4), though most of the area was still mapped as páramo or agriculture.

The most southerly parts of the eastern interfluve, south of the Cebadas and Atillo valleys, were dominated by páramo in 1979. This had generally been replaced by agriculture or bare soil, even at high elevations, by 1991 (Figure 3). Páramo recovered and became dominant again in 1999 and 2014, and by 2014 patches of native forest had also regenerated at medium elevations. Within this area there is a broadly triangular area extending northwards into the Chambo basin. This has slightly different land-use patterns to the rest of the southern area. It had less native forest initially and greater amounts of páramo, agriculture and bare soil.

Most pine plantations were created along the eastern block throughout the 35-year period of this study: relatively few forest plantations were mapped along the continental divide in the west or in the northern and central blocks. These plantations were mainly characterized by small patches throughout the páramo at a wide range of elevations and were adjacent to native forests, particularly the upper limits of native forest. In 1991 and 1999 almost all the forest plantations mapped were north of the Cebadas and Atillo rivers. However, even though there were less plantations in 2014, their geographical range had extended by 2014 and they occurred along the entire length of the eastern block.

Figure 6 illustrates the land-change dynamics in the region mapped in the form of a four-class map. These classes range from pixels where there was no change in land use or land cover during the entire 35-year period to pixels that had a different class in each image map. Overall, approximately two thirds of the pixels in the study area underwent at least one land transition between 1979 and 2014, while 26% did not change at all. Slightly less than a quarter (22%) of the pixels mapped as páramo in 1979 did not change over the timespan of this study, compared to only 3% for agricultural areas. A strong association between the dynamics of change and elevation is evident. The pixels showing the greatest amounts of change mainly occur at low elevations and are close to urban areas such as Riόbamba in the north west and Guamote in the south west. Consistency in land use and land cover is mainly a feature of higher elevations or areas with limited accessibility, especially those located in the south-eastern part of the basin.

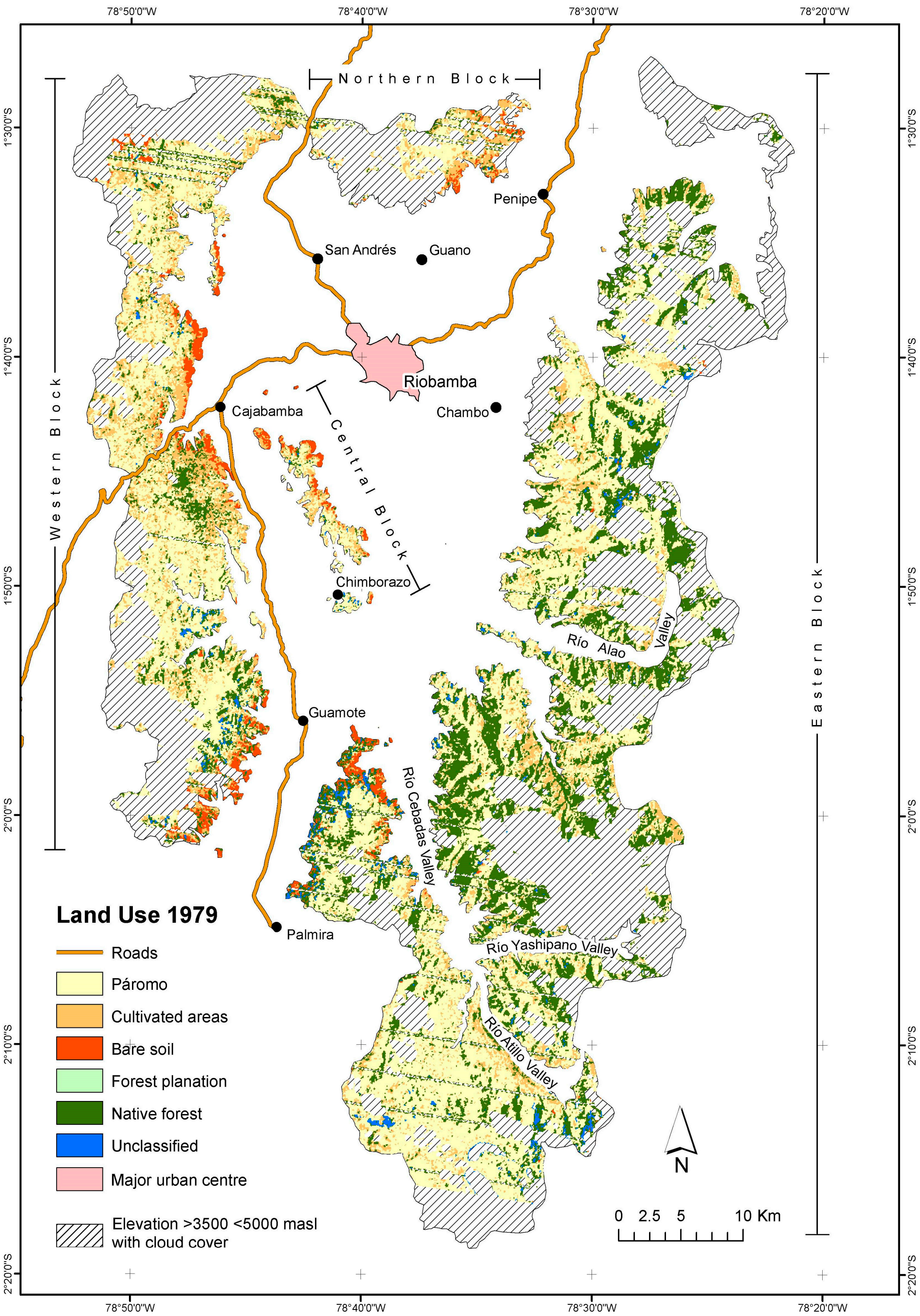

Figure 2. Chambo Basin: land-use, 1979.

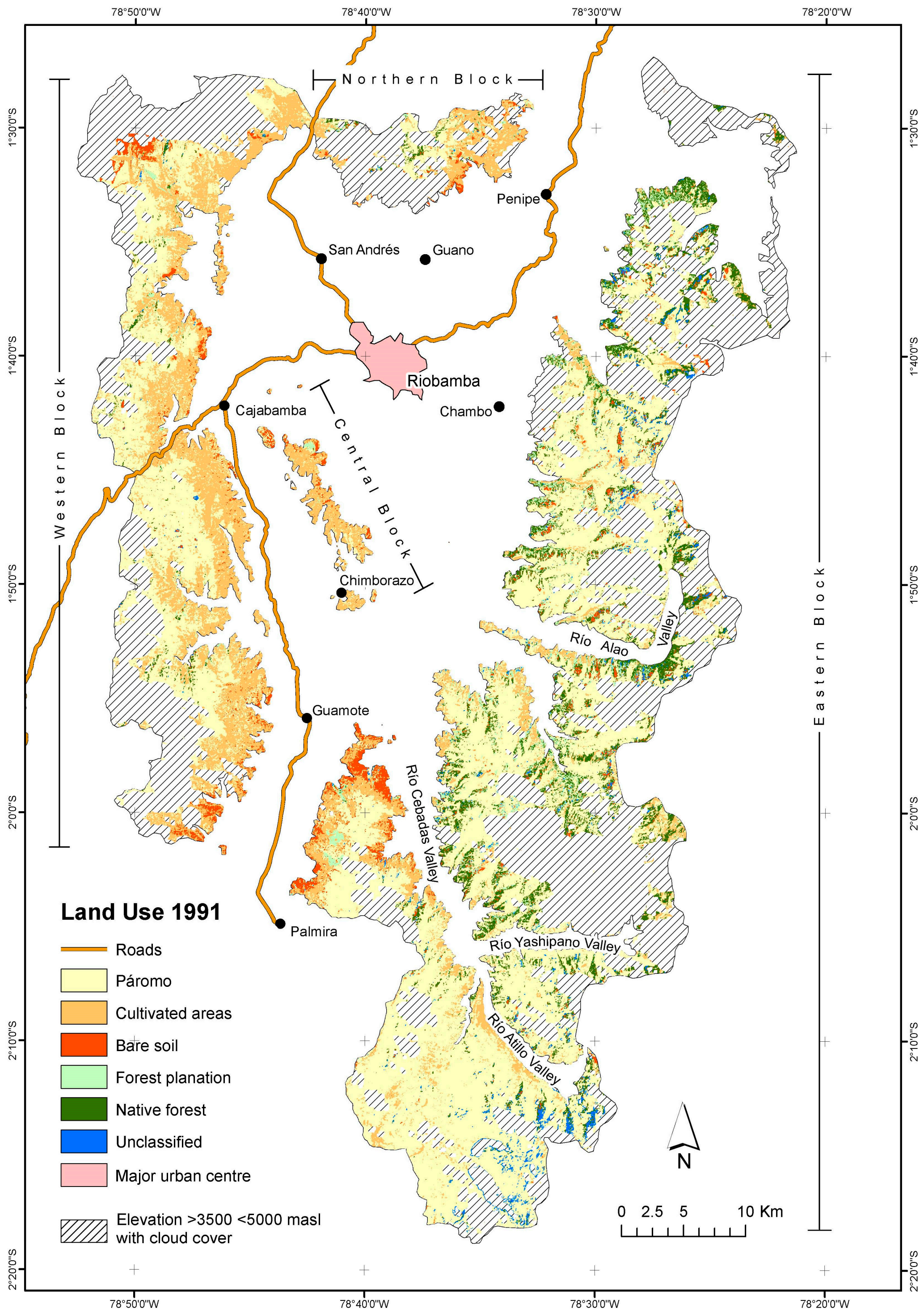

Figure 3. Chambo Basin: land-use, 1991.

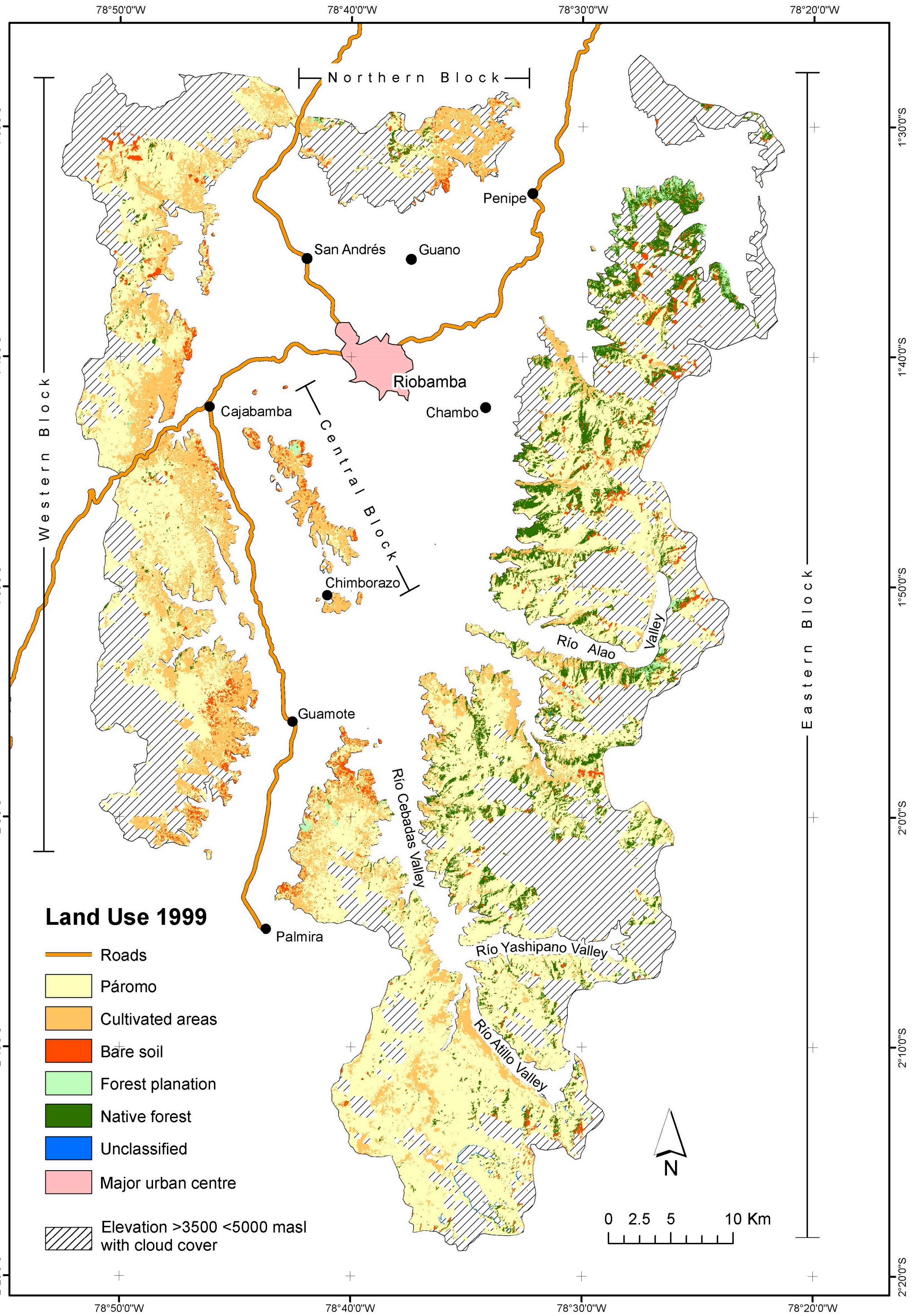

Figure 4. Chambo Basin: land-use, 1999.

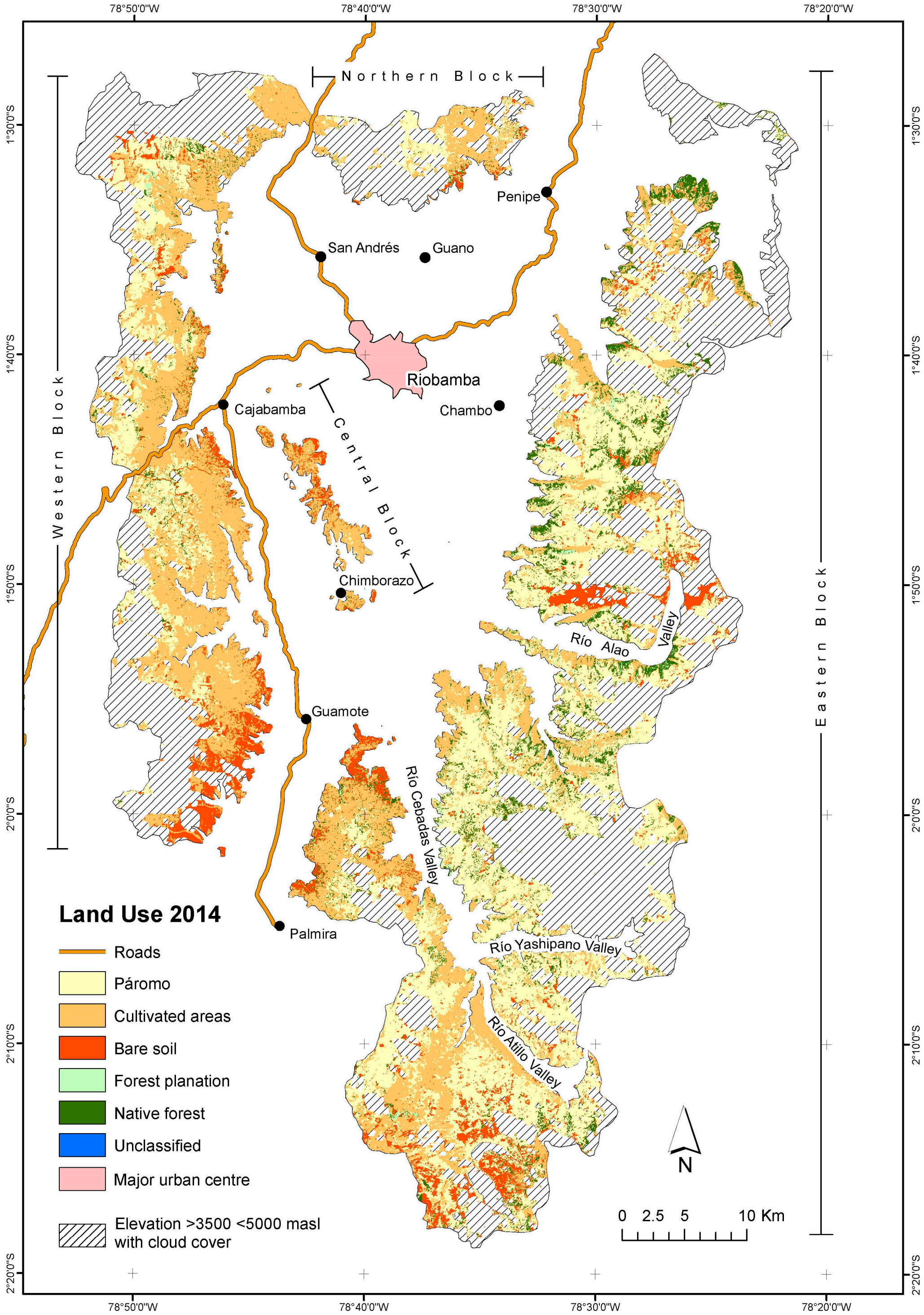

Figure 5. Chambo Basin: land-use, 2014.

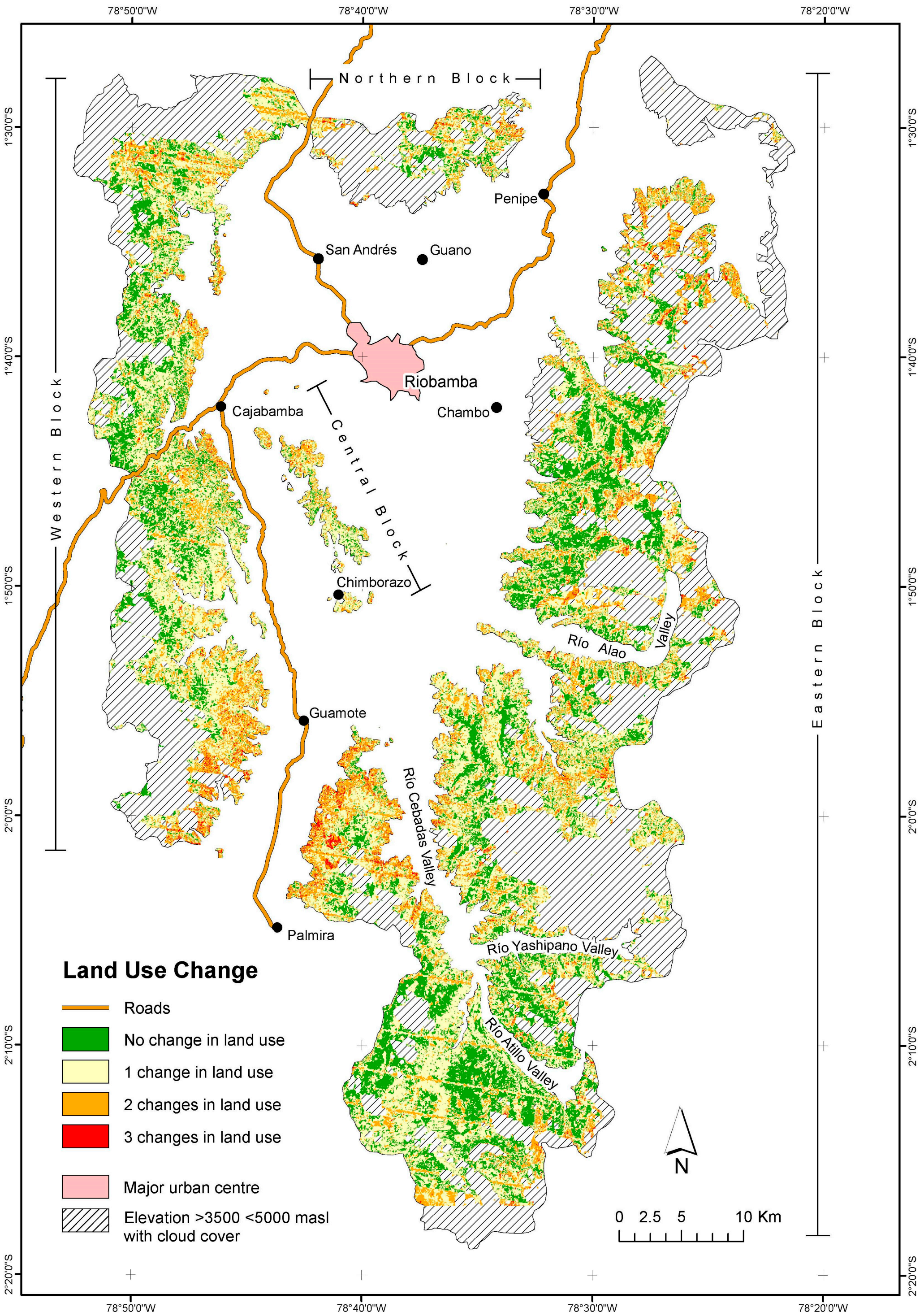

Figure 6. Chambo Basin: land-use change dynamics, 1979–2014.

4. Explaining Land-Use Change in the Chambo Basin

The proportional distribution of land use in 2014 (Table 2) was compared to that calculated by AGUAChambo [50]. Though the two datasets are not strictly comparable (as the latter covers the entire basin rather than being restricted to 3500–5000 m.a.s.l.) the percentage native vegetation cover for the basin quoted by AGUAChambo (52.0%) is in line with the 49.3% in this study. The disparity is either due to differences in assessment methods or the that fact that this research did not include the few remnant patches of native forest that occur below 3500 m.a.s.l. The correspondence between these percentages confirms the decision to map natural vegetation between 3500 and 5000 m.a.s.l. As most modified land uses in the basin occur below 3500 m.a.s.l., it is unsurprising that the percentages quoted by AGUAChambo for modified land uses are higher than those in this research. This is particularly the case for agriculture: 45.2% for the entire basin [50] compared to 32.9% at elevations between 3500 and 5000 m.a.s.l.

Post 1950 land-use change in the area was initially driven by land policies related to agrarian reform and, in the decades that followed, shifts in policies related to economic modernization and trade, forestry as a component of the rural and national economies, and most recently conservation, carbon sequestration and payment-for-ecosystem services (PES) schemes. Demographic change and infrastructure development have been additional influences.

4.1. Drivers of Land-Use and Land-Cover Change: 1950–1979

The land-use situation in 1979 (Figure 2) was the net result of centuries of land transformation and changes brought about by land reform and economic modernization programs from the 1950s onwards. Major land reform in Ecuador took place in 1954. Colonial and post-colonial agricultural systems were abolished with the passing of the Land Reform, Idle Lands, and Settlement Act and the dismantling of the *huasipungo* system. Reforms were administered by the Instituto Ecuatoriano de Reforma Agraria y Colonización (IERAC), who could expropriate and redistribute under- and unused arable (idle) land. The act also made absentee ownership illegal and limited the landholdings to 800 ha of arable land in the *Sierra* (montane Ecuador, which includes the páramo ecoregion) or 1000 ha of grazing land, and established 4.8 ha as the minimum amount of land that could be redistributed during the land reform process. It has been argued that the reduction in the size of landholdings led to an overall decrease in the area grazed and a corresponding increase in the area of páramo cultivated [61]. Revisions to the law in the early 1970s required that all land still held by absentee landlords had to be sold to the tenants, and that squatters were permitted to acquire title to land they had worked for at least three years.

Economic growth under the military governments of the 1970s, was underpinned by a strong import substitution industrialization policy. Its major impact on the páramo was to increase the number of forest plantations to meet the demand for domestic timber and wood exports. Much native forest in the *Sierra* had been cleared in the 1800s to create pastures and provide timber and fuelwood. Eucalyptus trees were introduced in the 20th Century to enhance timber and fuelwood supplies due to the depletion of native forests, and to reduce soil erosion. Evidence of the impacts of land reform and the establishment of plantations for timber on land use in the study area appears on the 1991 land-use map (Figure 3). Small tree plantations, with some larger areas of plantations, are dispersed throughout much of the eastern block at all elevations. These forests were not mapped in 1979, as mature trees had not established by then and they could not be differentiated from native forest and páramo.

4.2. Post-1979 Drivers of Land-Use and Land-Cover Change: Forestry Policies

The two main influences on land use transitions in the study area since 1979 have been the evolution of agricultural systems, changes in forestry policy and population pressure, which themselves reflect changes in socio-economic and natural resource conservation policies. The role of pine plantations in the land-use mosaic of the Chambo basin has been a dominating factor since the 1970s. The post-1960s land reforms and changes in economic policy [17,22,28,61,62] led to the establishment of tree plantations while simultaneously declaring native forests and other natural vegetation, such a páramo, vacant land [31]. Initially this led to significant land-use transitions from páramo and native forest to pine plantations and then, as economic and forestry policies evolved, led to plantations being converted to other uses.

As noted earlier, during the 1970s the Ministry of Agriculture promoted the growth of exotic timber species. However, no plantations were mapped in the Chambo river basin in 1979 (Table 2, Figure 3).

This can be explained by the fact that any pine plantations established during the 1970s would be spectrally indistinguishable from páramo and native forest by the end of the decade. The fact that 994 ha and 2629 ha of the páramo and native forest mapped in 1979 respectively appear as timber plantations in 1991 supports this argument. As already noted, almost all the conversion of páramo and native forest to plantations took place in the east of the basin (Figures 2–5). However, this is not the only reason exotic timber trees are under-represented in the land-use maps and statistics. It has been noted that rural landowners with large landholdings converted large blocks to forest plantations, while those with smaller landholdings planted trees along hedges and roads, and in small thickets [61]. The latter types of locations are below the minimum mappable area of 30 m-resolution imagery [63]. Even so most plantations mapped through the range of elevations in the páramo in the east of the basin in 1991 were relatively small.

Despite these underestimates, trends in forest plantations correspond well to observations that plantations were widespread in the 1970s and expanded in the 1980s [62]. The effectiveness of government plantation programs can be attributed in large part to the fact that they provided high returns to landholders. The Forestry Law of 1981 further supported these programs, as did other programs that were implemented with support from oil revenues and external multilateral cooperation [62]. By the early 1990s, community-owned plantations initiated under the Convenios de Participación program that spilt production revenues equally between landowners and the Ministry of Agriculture, were in place. Other programs also supported plantation forestry at this time, e.g., Fonde Nacional de Forestación (FONAFOR) and an Inter-American Development Bank loan to afforest degraded soils on slopes >30% in low income communities whose lands were located between 3300 and 3700 m.a.s.l). By the 1990s finances had tightened, funding for these programs was reduced and landholder participation rates declined. Responses to the changes in these drivers can be seen in Figures 2–5. Between 1991 and 1999 the dominant land-use transition related to the establishment of plantations was from páramo to plantations (Table 3). In comparison to the 1979–1991 period, no further native forest had been converted to plantations, and the number of established plantations that could be mapped in former páramo areas was about half the amount that had been mapped in 1991 (Table 3). This indicates a continuing focus on tree planting in the remaining páramo against a background condition in which the overall rate of plantation establishment in the basin was slowing down. As was the case in 1991, Figure 4 shows that the plantations mapped in 1999 were still small and restricted to the eastern block of páramo north of the Cebadas and Atillo valleys.

Since 1999 the impetus for plantation establishment has changed from export production to carbon sequestration and conservation aided by government initiatives that have recently incorporated PES schemes [43,64]. As PES schemes were only established near the end of the 1999–2014–time frame of this research, land-use transitions related to plantations between 1979 and 2014 will have been influenced more by the less favorable environment for plantation establishment in place from the 1990s onwards, than by the recent PES paradigm. The conversion of 288 ha of páramo to plantations between 1999 and 2014 compared to 453 ha converted between 1991 and 1999 (Table 3) attests to this. Interestingly, 117 ha of native forest was also converted between 1999 and 2014; compared to none between 1991 and 1999 and 2269 ha between 1979 and 1991 (Table 3). Most of this was south of the Cebadas and Atillo rivers in the eastern block (Figure 5). In each time period examined, >300 ha of plantation was lost, most of which had been mapped as páramo before conversion to plantations (Table 3). It can be argued that these were mature plantations that were harvested in the respective inter-image periods. Plantation establishment, post-timber harvest land-use transitions and net rates of mature plantation establishment are summarized in Table 4.

Trends in the rates of mature plantation establishment and harvesting for the study area are in line with Pangor, to the southwest of the Chambo basin, where pines planted before 1977 had expanded considerably by 1991 but had mainly been harvested before 2001 [30]. The area of páramo in this region decreased at an annual rate of 0.8% per annum between 1963 and 1991, compared to native forest (−2.1% per annum), and agricultural areas (+1% per annum) [28]. These rates are comparable to those in the Chambo basin between 1979 and 2014 where the corresponding rates of land-cover loss for páramo was −0.4% per annum and −2.1% per annum for native forest. In northern Ecuador, the overall net loss of páramo between 1988 and 2007 (22%) [29], was higher than in the Chambo basin between 1979 and 2014 (13.2%): most was lost to cultivation and grazing, but some agricultural areas had been abandoned and páramo had regenerated, as has been the case in the Chambo basin.

Table 4. Chambo basin: summary of land-use transitions involving forest plantations 1979–1991, 1991–1999 and 1999–2014 (ha).

Land-Use Transition Pathways	Inter-Image Period		
	1979–1991	1991–1999	1999–2014
	ha	ha	Ha
All land uses to timber plantations	4.034	835	554
Timber plantations to all land uses	1044	1507	1291
Net establishment of mature timber plantations	+2990	−672	−737

4.3. Demography and Infrastructure Development as Drivers Since 1979

The demographic influences at play in the basin during the period analyzed are difficult to relate to land-use change. Key demographic data for the four cantons in the basin are summarized in Table 5.

Table 5. Chambo, Guano, Pinipe and Riόbamba Cantons: summary population data 1990, 2001 and 2010 censuses.

Canton	Population (1990 Census)	Population Increase 1990–2001 (Persons/Annum)	Population Increase 2001–2010 (Persons/Annum)
Chambo	11,885	+89.8	+159.8
Guano	42,851	+71.1	+551.4
Pinipe	6739	−83.9	+28.2
Riόbamba	225,471	+268.59	+362.9

Riόbamba Canton is significantly larger in terms of population and rates of population increase than the other cantons (Table 4). Some of this growth is due to rural-to-urban migration from surrounding areas inside and outside the Chambo basin, though populations in the surrounding cantons have also generally increased between 1990 and 2001. It is noteworthy that the 1998–1999 banking crisis, which saw between 300,000 and 500,000 people (mainly the urban middle class) leave Ecuador, appears to have had little impact on population growth in Riόbamba.

It is difficult to link demographic trends to land-use change in the páramo because most of the population lives in areas below the lower páramo limit, and only some of these people access or own land above 3500 m.a.s.l. in the study area. This particularly affects urbanization-related drivers of land-use change, as most towns are located below 3500 m.a.s.l. (Figure 1). Given these caveats, there has been a significant reduction in the areas of páramo and native forest in Guano and Chambo Cantons (Figures 2–5) both of which are affected significantly by urban growth and proximate demands for agricultural land and fuelwood supplies, particularly as people access higher elevations to secure these natural assets. The northern block in Guanco Canton (Figures 2–5) has long been utilized quite intensively due to its proximity to the settlements immediately north of Riόbamba. The northern section of the eastern block is mainly in Chambo Canton. In 1979, large tracts of native forest and páramo dominated the areas adjacent to the densely-cultivated lowlands (Figure 2), much of the forest had been lost by 1991 and replaced by cultivation at lower elevations (Figure 3). This spatial pattern remained through to 2014 (Figures 4 and 5) and is indicative of sustained population growth in the town of Chambo, which is located just below 3500 m.a.s.l. (Figure 1), that creates proximate pressures on the natural resource base in the adjacent páramo [61].

The development and upgrading of road networks in the area is perhaps a better indicator of population pressure and land-use change, though of course it also relates to strategic infrastructure development [30]. The encroachment of natural vegetation clearance from valley bottoms to higher elevations along all the major roads that have been constructed in the area since 1979 is clear on all the land-use maps. Highway 35 from Riobamba to Pallatanga, which was a major route before 1979, shows extensive clearance evinced by areas of cultivation and bare soil on high ground adjacent to the road (Figures 2–5). In contrast the Cebadas and Atillo valleys, where the main road from Ríobamba to Macas in the Amazon Basin is routed, only showed signs of native vegetation clearance above 3500 m.a.s.l. in the very north of the valley in 1979. It could be argued that this was due to cultivation pressure from farmers in the adjacent Chambo basin, rather than from the valley itself. However, between 1979 and 1991 increased cultivation pressure along these valleys had stimulated an upward creep of conversion of native forest and páramo to cultivation (Figure 3).

4.4. Limitations

The areal extent and spatial distribution of the main land uses in the Chambo basin corresponds to other research in Ecuador [29,30]. However, it is likely that there are small errors in the areas mapped because the spectral signatures of páramo, low-density native forest, and forest plantations in their early growth and post-harvest stages overlap and form a conitumn of low-density woody (tree or shrub) canopies over bare soil or grasses [65]. Differentiating native forests from mature forest plantations was more difficult than differentiating either native forest and páramo or páramo and plantations. In particular, spectral separation between native forests and plantations in narrow, deep valleys is problematic because of shadowing. This could have been addressed in part if topographic correction had been carried out. However, this may not be a significant issue as plantations are far less likely to be planted in valleys like these due to topographic constraints on tree planting. Generally, these landscape elements in the high Andes are areas of remnant native forest [66]. Agricultural areas were easily differentiated from forest, plantations and páramo, but had similar signatures to bare soil. As there is an element of spectral confusion in mapping these land-use classes their spatial context is important, particularly in identifying cultivated areas [67].

5. Conclusions

Land use and land cover in the páramo of the Chambo basin has undergone considerable change since 1979. These changes have been dominated by a replacement of native forest and páramo by agriculture. The annual rate of native forest loss (−2.1% per annum: 1979–2014) is greater than that of páramo (−0.4% per annum: 1979–2014). Just under a quarter (22%) of páramo ecosystems were unchanged between 1979 and 2014. Most of this occurred at higher elevations, especially in the less accessible south-east of the Chambo basin. Most of the conversion of native vegetation to agriculture occurred at elevations slightly over 3500 m.a.s.l. Forest plantations, which were evident from 1991 onwards, were mainly restricted to the eastern basin. Most of these have now been replaced by regenerating páramo and native forest.

Land-use and land-cover transformations can be explained in terms of shifts in policy drivers, population dynamics and infrastructure development. Land use in 1979 can be linked back to the 1954 land reforms, after which the páramo and native forests were considered unused or underutilized. Import substitution and export polices introduced in the 1970s brought industrial forestry to the basin. However, the earliest dates for pine plantation establishment in the Chambo basin cannot be deduced from the imagery because young plantations cannot be differentiated accurately from native forest and páramo. Mature plantations were mapped from 1991 onwards, and expanded into more southern remote parts of the basin's páramo between 1999 and 2014.

The land-use change trajectories and estimates for the Chambo basin are similar to other studies in the páramo ecoregion of Ecuador, though there are differences due to local geographical variability. Therefore, the research has wider implications for research into, and understanding of, land-use change in the Northern Andean Páramo ecoregion. First, analyses using data from the Surface Reflectance Calibrated Image Archive (SRCIA) simultaneously with a drivers-based temporal framework can be used to understand and map land-use and land-cover change in the rural production systems of the páramo. Importantly, the spatial location of change can be mapped and used to develop a deeper understanding of how these drivers play out in this ecoregion, this is under-researched in terms of land change science. This research proves the potential of the SRCIA as a source for land change mapping in this ecoregion. A major benefit is that the imagery is atmospherically and geometrically corrected. However, to realize its full potential for individual projects, the imagery used needs to be extended backwards in time by using earlier MSS imagery and, where available, aerial photography and CORONA mission data. The value of this archive would be increased considerably if these data were included in the archive itself. In addition, using topographic data to improve image interpretability [30], and integration of these data with fine-scale aerial photography or digital imagery would enable small elements, e.g., trees planted along hedge lines, in this fine-grained land-use mosaic to be mapped more accurately.

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