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Indigenous Knowledge Systems and Conservation of Settled Territories in the Bolivian Amazon

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Abstract: Landscapes settled by indigenous communities represent nuanced inter-relationships between culture and environment, where balance is achieved through Indigenous Knowledge Systems (IKS). Through IKS, native peoples worldwide live, farm, and consume resources in a manner that is responsive to natural systems and, as such, their lands present less deforestation and more sustainable production per capita than is exhibited by non-indigenous practices. In Bolivia, the Origin Farmer Indigenous Territory (TIOC) communities of Yaminahua-Machineri and Takana-Cavineño, located in the North Amazon, are facing external threats of non-indigenous anthropogenic land use change, such as road-building and industrial-scale resource extraction. In order to understand the potential environmental and cultural loss to these territories, the present work seeks to determine the present, base-line conservation state within these Bolivian communities, and forecast land use change and its consequences until the year 2030. This was undertaken using a three-stage protocol: (a) the TIOC communities' current forest-based livelihoods, characteristics and management were determined using on-site observation techniques and extensive literature review; (b) the historical land use change (LUC) from natural vegetation to anthropogenic use was estimated using multitemporal satellite imagery; and, finally, (c) geographically explicit non-indigenous anthropogenic land-use change threat was extrapolated until 2030 using the GEOMOD modeler from the TerraSet software. Preliminary results show that both TIOCs case-sites are fairly conserved due to their forest dependence. However, deforestation and degradation could be evidenced, particularly within TIOC areas not officially recognized by the central government, due to pressures from surrounding, new non-indigenous settlements, road infrastructure, connection to markets, and the threat of the oil exploitation. Projected LUC suggest serious threats to the unrecognized TIOC areas if community governance is not reinforced, and if extractivist and non-indigenous development patterns continue to be promoted by state and central government.

Keywords: Origin Farmer Indigenous Territory; Bolivian Amazon; Indigenous versus non-indigenous land-use; land use change

1. Introduction

Worldwide, indigenous territories hold and manage between 50% and 65% of the planet's land, despite governments only officially recognizing their tenure as between just 8%–10% [1]. Although there is no single agreed-upon definition of indigenousness, some features have been provided by the United Nations to illustrate the term: self-realization as indigenous nations, community attachment to their original land, different sets of traditions and beliefs, distinct languages and unique cultures, and a perceivable difference in lifestyle and practices distinct from a dominant, colonial culture [2]. Within their territories, indigenous communities live, farm, and benefit from local resources in ways that are drawn from generations of shared-knowledge, passed down via folkways of art, dance, story-telling, and myth [3]. This intimate, nuanced knowledge of their home environment is called, variously, "traditional", "ecological", "non-formal", "indigenous-technical", and "local-wisdom" [4]. Indigenous Knowledge System (IKS) refers to the specific place-understanding of defined communities within their particular geographical setting (ibid) and has been described as "a dynamic web of interconnected biophysical, economic, political and socio-cultural contexts in which people are involved" (Mokuku and Janse van Rensburg, 1997, p. 32) [5]. The people-place symbiosis of IKS has been proffered as an approach for safeguarding natural and cultural resources and capital, such as local customs and habits, food security, climate-change, and biodiversity [3,4] and, unsurprisingly, there have been calls to study, analyze, and extrapolate from IKS to better inform sustainable practice, policy, and education [6]. Even so, there are inherent dangers in inter-lacing indigenous peoples' knowledge and ways with those of external cultures. Even the best intentions of enriching sustainability discourse (whether extrapolating-out from IKS to a different socio-economic setting, or facilitating indigenous practices from outside-in via education or policy) can be fraught with misunderstandings and misinterpretations [6]. This begins to speak to the limits and challenges of addressing indigenous practices through the internationally accepted lens of sustainable development: although the land-based cultures of indigenous peoples may resonate strongly with the ideals of sustainability, they are perhaps best understood as a different framework altogether. By way of explaining this position, it is instructive to compare the indigenous societies of the Bolivian Amazon, as précised in this paper, with the European-derived culture of the rapidly urbanizing central eastern Bolivian city of Santa Cruz de la Sierra—the region's de facto capital city—and the recent efforts to establish policy-led, large-scale sustainable forestry practices in the region.

In the last half-century, Santa Cruz de la Sierra has grown from an isolated frontier town of around 40,000 inhabitants to the 1.5 million-strong center of Bolivia's agri-industrial production zone [7]. Santa Cruz was originally master-planned in four concentric rings with greenbelts situated along the ring roads surrounding the city center, preserving natural areas and providing amenity [7]. This top-down, if well-intentioned, imposition of extensive anthropogenic patterns across a landscape in a relatively short amount of time is familiar in the "developed world", though it often begets unforeseen socio-environmental inequalities, as the relationship between culture and environmental capacity becomes distant and strained [8]. In Santa Cruz, growth has quickly outpaced the plan, and there has been subsequent uneven provision of greenspace, services, housing, and employment [9]. At the same time, there is still rapid densification across the entire urban transect; Santa Cruz was the most rapidly densifying case in a recent study of ten major Latin American cities [10]. The nationally endorsed infrastructural strategies and construction projects outlined in Section 2.2 below, point to ongoing migration into the central eastern region and the city, and further challenges of inequity and imbalance to come, and the urgent need for "sustainable development".

Ciegis et al. (2009) [11] speak to the limits of the broadly accepted definition of sustainable development derived from the 1987 Bruntland Report "development which meets the needs of the present without compromising the ability of future generations to meet their own needs." (World Commission on Environment and Development, 1987: p. 43) [11,12]. Though this term is widely adopted and understood, it best relates to a developed-world view whose main objective is economic development balanced with responsible growth [11,12]. In this frame, sustainable development is operationalized via concepts such as importation versus exportation of materials, cheap and plentiful fossil-fuels, cultural mobility and disposable income, land-use planning and zoning, and asks for reflection, checks, and balances. It is likely that any attempts to move the city of Santa Cruz de la Sierra in a more sustainable direction will be defined and limited by this frame.

This, however, is not the only armature of sustainable environment-human relations that is relevant to central eastern Bolivia. Beyond considerations of urban development, Bolivia emerged in the mid-2000s as a leader in sustainable tropical forestry, in large part because of increased influence of *Ley 1700*, a 1996 forestry law that provided a more pointed and operational reflection on sustainable development as it applies to Bolivian forestry; mandated management plans, inventories, harvest limits, and consideration of indigenous land-rights [13]. Yet, as this paper will show in terms of the extent of extractive practices, this alone may not be enough, as even the best models can still represent a potentially serious and deleterious disruption of ecological capital and closely inter-woven indigenous communities. As pointed-out by Paneque-Gálvez et al. (2018) [14] Amazonian peoples actively manage forests through very different strategies that nimbly adapt on the ground to local ecological conditions and result in a synergistic forest-culture continuum. This indigenous view;

> " ... is originated within the cosmovision of indigenous people, who understand nature as a whole, as life itself. Therefore, nature cannot be instrumentalized on the grounds of further material gains. Consequently, from the indigenous worldview a different model of sustainable development is proposed; one that could be called Integral Development or Ethno-development." Ciegis et al. (2009, p. 31) [11].

It is beyond the scope of this paper to fully articulate or predict the material changes being forecast within the case-site landscapes, and where they might sit within the continuum of outright exploitation, through top-down sustainable development derived from the aforementioned developed-world viewpoint, through to nuanced Ethno-development. Within the context of this volume, this paper touches upon an alternative, indigenous-community view of what a sustainable residential landscape might mean, beyond the developed world's conception of purpose-built homes provided as a commodity largely removed from the landscape and culture that supports and surrounds it.

Given the above, it is not surprising that indigenous settled landscapes present less consumption and deforestation rates, broader forest cover, and a more sustainable production of wood and other goods when compared to areas that are not settled by native peoples [15,16]. This has led some developed-world scholars to explain forest-based indigenous cultures as aligned with forest-stewardship and ecosystem and biodiversity management [17–19]. Studies in Africa [20], simultaneous study cases from India and Chile [21], an extensive longitudinal analysis in Peru [22], and across the tropics [23,24], as well as a study in Bolivia with the Tsimane indigenous community [14], can evidence the overlap between IKS and forest conservation. Consequently, there is recognition, across global sectors and constituencies, that securing indigenous land-rights is a common imperative, and this is increasingly enshrined in international instruments–such as International Labour Organization(ILO) Convention 169 and the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) [25]. Furthermore, supportive state or federal legislation has been enacted in a number of countries, and between 2002 and 2013, 125 million hectares of forest land in lower and middle income countries was recognized as either owned or managed by indigenous peoples [25]. Beyond an ethical imperative of folkway preservation and cultural diversity, the protection and reinforcement of indigenous communities' rights over their ancestral land has been shown to be a powerful instrument against climate change through carbon sequestration [16,26]. For example, world-wide forests to which indigenous peoples and local communities currently have sanctioned/state-recognized tenure, contains over 37.7 billion tons of carbon [25], and at least 24% of all the carbon stored in the tropical soils of the world are beneath community managed land (some 54,546 Mega tons of Carbon or MtC) [27]. Turning our attention to the geographical focus of this paper: the Amazon is the most extended rain forest in the world, and covers approximately 7.4 million square kilometers of South America which represents 5% of the worldwide continental area [28,29]. The Amazon is not only a global carbon sink or source of biodiversity, but also a vital ecosystem that provides oxygen, food, climate regulation, and other important environmental services such as water provision for the continent [30–33]. However, despite its great importance, the Amazon presents increasing deforestation rates escalating from 1.6 million hectares per year in 2015 to 3 million hectares in the year 2018 [34,35].

Since the 1990s, the Bolivian Amazon has shown an increase in its economy due to chestnut production, the improvement of roads to the department of La Paz, and, especially, improved commerce to Brazil [36]. On the one hand, this economical phenomenon has helped to improve income, communication and transportation of goods and services through the region. On the other hand, it has been one of the main causes of land use change from forest to non-forest, with deforestation rates within the Bolivian Amazon basin with fluctuating values of approximately 350,000 hectares in the year 2010, more than 200,000 hectares the year 2014, more than 400,000 hectares the years 2016 and 2017, and almost 300,000 hectares the year 2018 [37–39]. Recently, it has been noted that there is a strong spatial correlation between conservation of old-growth forest and the cultural persistence of traditional ecological knowledge systems among nearby indigenous villagers within the Bolivian Amazon [14]. Given the global importance of the Amazonian basin to global ecological health, and the increasing impetus to ground global initiatives and align national policies in and with indigenous rights, this recent village-by-village based research suggests a need to complement this work, and further the conversation on the current and future relationships between Bolivia's levels of persistent forest-entwined indigenous culture and cosmology, and the state of forest conservation, though reframed to consider federally recognized indigenous initiatives and territories (rather than individual villages). Moreover, investigations of the relationship between IKS and effective forest conservation could be vital in informing the development and management of state-managed land, and the protection of indigenous territories and their IKS. Clearly, there is much to learn: as this article was written, more than 5 million hectares of Amazon forest and dry Chiquitano forest—much of it in Bolivia—burned out of control, representing a catastrophic 230% increase in deforestation over the previous year [40]. The cause: a new federal policy allowing indiscriminate slash and burn practices in order to increase extractive and extensive agriculture and cattle ranching activities [40]. The fire affected individual and collective land (47.3%) as well as state-managed land (52.7%) [40] and was the result of forest-management practices that are a far-cry from the IKS approach. We now turn our attention to the extensive tracts of Bolivian forest lands that—officially or unofficially—lie within the jurisdiction of indigenous peoples and, possibly, their IKS.

From 1996, the land managed under Bolivian indigenous or farmer groups was initially named *Territorio Comunitario de Origen (TCO)*—or Origin Community Territory [41]. The objectives of the TCO were to confer collective jurisdictional rights to indigenous peoples and communities, and with that, to seek the improvement of forests and other natural resource governance [36,42,43]. A decade later, in 2006, the term TCO was changed to TIOC or *Territorio Indígena Originario Campesino* (Origin Farmer Indigenous Territory) [36,43]. Despite the name-change, the chief characteristics remained intact [42–44] (although TIOCs allowed the registration of non-indigenous farmer groups within this category, whereas TCOs did not [41–43]). The TIOCs of the Bolivian Amazon are important to protection and conservation. Although the Bolivian Amazon has historically been an isolated and forgotten landscape with high levels of poverty, this is an ecosystem of great environmental and cultural value [30–32,36]. By 2011, Bolivia held 190 officially recognized TIOCs (i.e., the indigenous peoples and nations that originated in the territory have been officially granted a collective title) with a combined population of more than 530,000 inhabitants [45]. Of this, 55 TIOCs accounting for 168,000 inhabitants are situated within the Bolivian lowlands [45], and this includes territories within the Bolivian Amazon (approximately 142,000 km^2). Specifically, Bolivian Amazon TIOCs includes the total area of the department of Pando, the Iturralde Province of the La Paz Department, and the Vaca Diez and Ballivián Provinces of the Beni Department [30,31].

In Bolivia, land under collective management, such as the formally recognized or titled TIOCs are consolidated collective territories. These areas have undergone, through the state-managed Institute of Agrarian Reform (INRA), a process called *"saneamiento"*, which reviewed, adjusted and recognized the size, ownership, and location of the territory, and then endowed property titles to the community signed by the President [45]). Approximately 1,553 MtC (81%) is contained within these territories' soil, and TIOCs that are yet to be officially recognized contain, approximately, a further 362 MtC (19%) [27]. Unrecognized TIOC is the land area requested by the native indigenous and farmer people, which is generally registered on a map and presented to the INRA for the "*saneamiento*" process. Until the INRA officially recognizes the land area, the TIOC is "unrecognized" [45]. Data shows that land under the jurisdiction of Bolivia's indigenous communities see deforestation rates of around a third of that in land outside of TIOCs [15,16]. These deforestation reductions can be considered as a national environmental benefit, reducing the annual greenhouse gas emissions by more than 8 million tons [9,11]. Nevertheless, despite their high value, TIOCs located in the Bolivian Amazon continue to confront challenges on the control of their territory, and there is an increasing number of threats and external pressure that threaten its physical integrity [46].

Despite the existing literature on deforestation rates in the Bolivian Amazon, there is only limited work addressing the vulnerability that indigenous people managed TIOCs are facing due to new development patterns and land use change, and as mentioned before, this knowledge gap is the focus of our paper. Specifically, we wish to present the actual conservation state and future forecasts for the Yaminahua-Machineri and Tacana-Cavineño TIOCs within the Bolivian Amazon. We understand these TIOCs to be, from an indigenous viewpoint, highly intricate and fragile inhabited landscapes of homes, farms, and communities tightly woven into, and in-balance with, natural systems and processes. In this paper, the extant communities, livelihoods, characteristics, and TIOC forest-management were determined, external land-use change to non-indigenous anthropogenic program was estimated using remote sensing data, and, finally, geographically explicit extrapolation of the deleterious land-use change was conducted until 2030.

Our results show a need for reinforcing TIOCs' governance to help ensure their physical integrity, as the pressures of land-use change due to non-indigenous external pressures can create an "edge effect" that generates a negative impact on their ecosystems and their communities. As such, all of the recent conservation efforts for Bolivian Amazon TIOCs' could be weakened by new patterns of alien development fostered by new national laws. Specific and general recommendations are also discussed based on these findings.

2. Materials and Methods

This study applied a mixed-methods approach including the qualitative research on the perceptions of the indigenous communities' livelihoods and the state of their forests, a multitemporal forest cover analysis of satellite imagery, and a spatially explicit geographical extrapolation of land use change. Previous work by Paneque-Gálvez et al. (2018) and Bottazzi and Dao (2013), both in Bolivia, have applied a similar approach: qualitative tools such as interviews, field visits, participant observation, and land cover analysis, augmenting applied remote sensing procedures for multitemporal Landsat satellite images [14,47]. However, this present work adds to these general mixed-method approaches in two important ways: we report an approximation of our accuracy assessment score regarding the satellite image classification, as suggested by Pontius (2001, 2011, and 2014) [48–50]; and we apply a geographical modeling prediction procedure using the GEOMOD tool, that follows the standard protocol considerations for forest change [51–55] and the correspondent accuracy assessment using the Relative Operating Characteristic (ROC) analysis [48,50,56,57].

In order to determine the TIOC communities' livelihoods and its perceived threats, qualitative research methods were applied such as field visits, non-participant observation, personal communication with different stakeholders, and an extensive literature review. Two field visits in different times of the year were undertaken to both case-study TIOCs. The first expedition took place from April the 6th to the 9th 2018 and included key places in the Bolivian Amazon, such as the town of Guayaramerín (which cross-borders to Guajará-Merín in Brazil), a key-economical center for the north east region of Bolivia. The first expedition showed the particular importance of the chestnut (Brazil nut) economy in the region. Further visits to *Beneficiadoras de Almendras* or *Fábricas* in the town of Riberalta (Beni) demonstrated still further the nut supply-chain in-action. Harvested by indigenous communities of the Amazon forests, the Brazil nuts have to follow an energy and labor intensive process before they are exported to Europe [58,59]. Moreover, in this first expedition, direct communication and non-participant observation techniques were applied while exploring communities belonging to TIOC Takana Cavineño and TIOC Multiétinico II [59].

The second expedition was carried out 19–21 July 2018. In this exploration, a three-hour canoe trip along the Acre River led to the indigenous communities of Puerto Yaminahua and San Miguel de Machineri from the town of Bolpebra [60]. Both communities co-manage the TIOC Yaminahua–Machineri. Field data and image collection, site exploration, and personal communications with different members of the Yaminahua community, including the chief of the community, were undertaken [60], and an exploration to the community of San Miguel de Machineri was conducted after a one-hour canoe ride on the way back to Bolpebra. Although no community members were found in San Miguel de Machineri, it could be evidenced that there are key cultural similarities and differences between the Yaminahua and the Machineri [60]. Among the similarities is that both communities are deeply dependent on their forest, since little evidence of deforestation and forest degradation was evident. Another similarity was the denudation of vernacular architecture. In many areas of the Bolivian Amazon, centralized government plans have replaced native built-fabric for mortar and brick designs, imported from the Bolivian Highlands, and completely alien to these landscapes [60]. Further than their architecture, conversations with the Yaminahuas' people suggested that their community—and that of San Miguel de Machineri—are both struggling to keep their native languages alive, since Spanish and Portuguese are often required to transact the interchange goods and services [60]. One difference was that the Machineri, unlike the Yaminahua, have started to raise cattle and other domesticated species for food security purposes [60]. Both communities now have their own communication tower that allows cell-phone use, and have installed some solar panels in order to charge them along with other devices [60]. All these findings were reinforced by the content analysis of recorded interview videos uploaded on public short documentaries of Yaminahua, Machineri, Takana, and Cavineño people by APCOB (Apoyo para el Campesino Indígena del Oriente Boliviano), CIPOAP (Central Indígena de Pueblos Originarios, Pando, Bolivia), CIMAP (Central Indígena de Mujeres de la Amazonía de Pando, Pando, Bolivia), UNICEF (The United Nations Children's Fund, New York, NY, USA), and UNFPA (United Nations Population Fund, New York, NY, USA) [61–65].

In order to determine deforestation rates in indigenous managed territories and other types of native-community land management, satellite multi-temporal analysis of different land cover was conducted for both TIOCs and their correspondent reference area. A more detail description of the remote sensing procedures can be found in Section 2.4, but with reference to accuracy and reliability, following the recommendations of Li and Eastman (2006), an artificial neural network classifier called SOM (Self-Organizing Map) was used, because it can perform with 1.4–3.3% more accuracy than other standard classifiers such as the Maximum Likelihood that was used by Bottazzi and Dao (2013) [66].

Then, for the extrapolation of non-indigenous anthropogenic Land Use Change (LUC) to the year 2030, the geographical modeler GEOMOD was used, considering estimated deforestation rates from the previous step. GEOMOD was developed by research scientists at the State University of New York, college of Environmental Sciences and Forestry (SUNY–ESF, Syracuse, NY, USA), and is currently available in the GIS software TerrSET developed by Clark Laboratories at Clark University [53,55,67,68]. GEOMOD is a versatile modeler predictor of land use change that has been used for various topics including: the assessment of ecosystem services in the Philippines [69] and China [70]; predicting urban expansion in different countries such as Iran [71,72], Palestine [73], and Puerto Rico [74]; deforestation projections in the Mediterranean [75], India [76–78], Chile [79], Mexico [80], Costa Rica [53], and Papua New Guinea [81]; and for the estimation of carbon baselines for REDD (Reducing Emissions from Deforestation and Forest Degradation) projects [54,56,82] around the world, including Panama [83], Indonesia [51,84], Belize, Brazil, and Bolivia [55].

Data and methods are described in the following sections according to three-pronged research protocol, to report on the current conservation sate of TIOC communities, describe land-use change from non-indigenous anthropogenic program, and provide a future-forecast of further changes to come within a time-frame of 2030. This target year is particularly important because coincide with the world commitment, through the 17 UN Sustainable Development Goals, to achieve a better and more sustainable future for all [85].

2.1. Study Area and Indigenous Communities

At a general scope, the study area is situated within the Bolivian administrative Amazon which is defined by the new Political Constitution of the Plurinational State of Bolivia [86]. Thus, the Bolivian Amazon includes the entire state or Department of Pando, the Iturralde Province of the La Paz state, and the Provinces of Vaca Diez and Ballivián of the Beni Department [86]. At a specific level, this study focused on two *Territorios Indígenas Originarios Campesinos* (TIOC, or Origin Farmer Indigenous Territory) belonging to, respectively, the indigenous groups of the Yaminahua-Machineri in the Department of Pando and to the Takana-Cavineño in the Department of Beni. The TIOCs are separated by more than 320 km within the northern Bolivian Amazon territory (Figure 1).

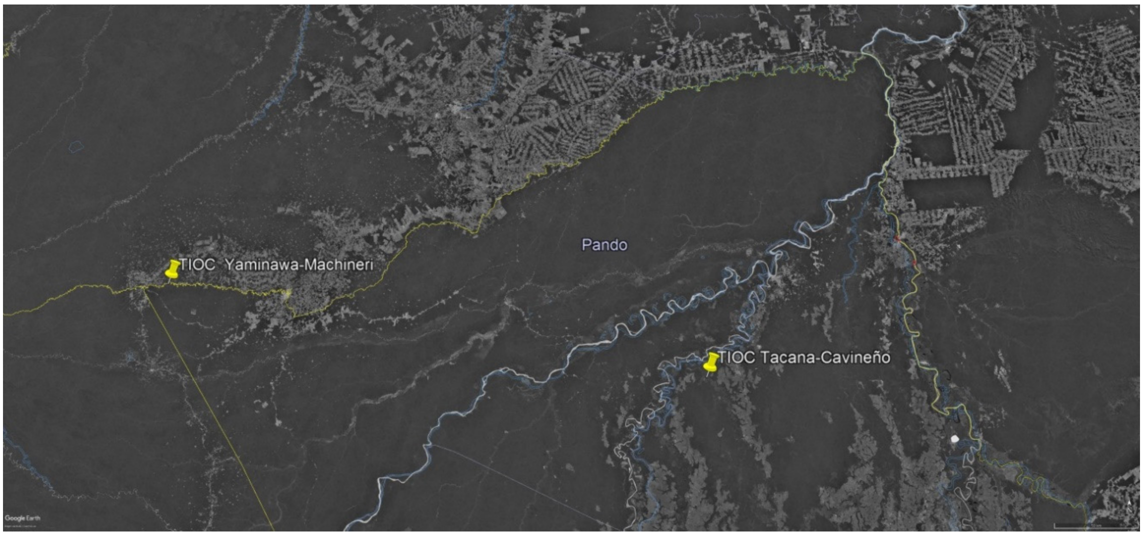


Figure 1. Location of Puerto Yaminahua (Origin Farmer Indigenous Territory (TIOC) Yaminahua–Machineri) (left) in the Department of Pando, and the location of the TIOC Takana-Cavineño (right) in the Department of Beni. Both are in the north part of the Bolivian Amazon delimited by a yellow line [87].

Both TIOCs were chosen because they efficiently and effectively represent a range of current conservation states of, and threats to, native communities in the Bolivian Amazon. The Yaminahua–Machineri TIOC represents territory next to two international borders (Brazil to the north and Peru to the west), where economic activity has had a rapid and significant impact on the landscape; historically, this has been one of the most remote and least navigable places in Bolivia, yet is undergoing waves of external anthropogenic pressure across international borders and, internally, from within the Pando Department. The territory also represents different states of official recognition. On the other hand, the TIOC Takana–Cavineño is typical of a territory that is surrounded by other native community managed areas and thus potentially addresses the effectiveness of agglomerated TIOCs in the protection Amazon forests and culture.

2.1.1. TIOC Yaminahua-Machineri

The TIOC Yaminahua–Machineri, according to the Universal Transverse Mercator (UTM) system, is located in the Zone 19 L between X coordinates: 437,206 m E, Y coordinates 8,790,029 m S, and X coordinates 468,664 m E, and Y coordinates 8,760,287 m S.

After several, decades-long negotiations, the central government officially issued land titles that recognized 24,671.3 hectares under co-management between the Yaminahua and the Machineri under the name of TIOC Yaminahua-Machineri in 2001 [45]. However, from a total of approximately 54,130 hectares that traditionally were also under the TIOC management, the remaining 29,458.7 hectares are still awaiting to be officially recognized (Figure 2) [45,88,89].

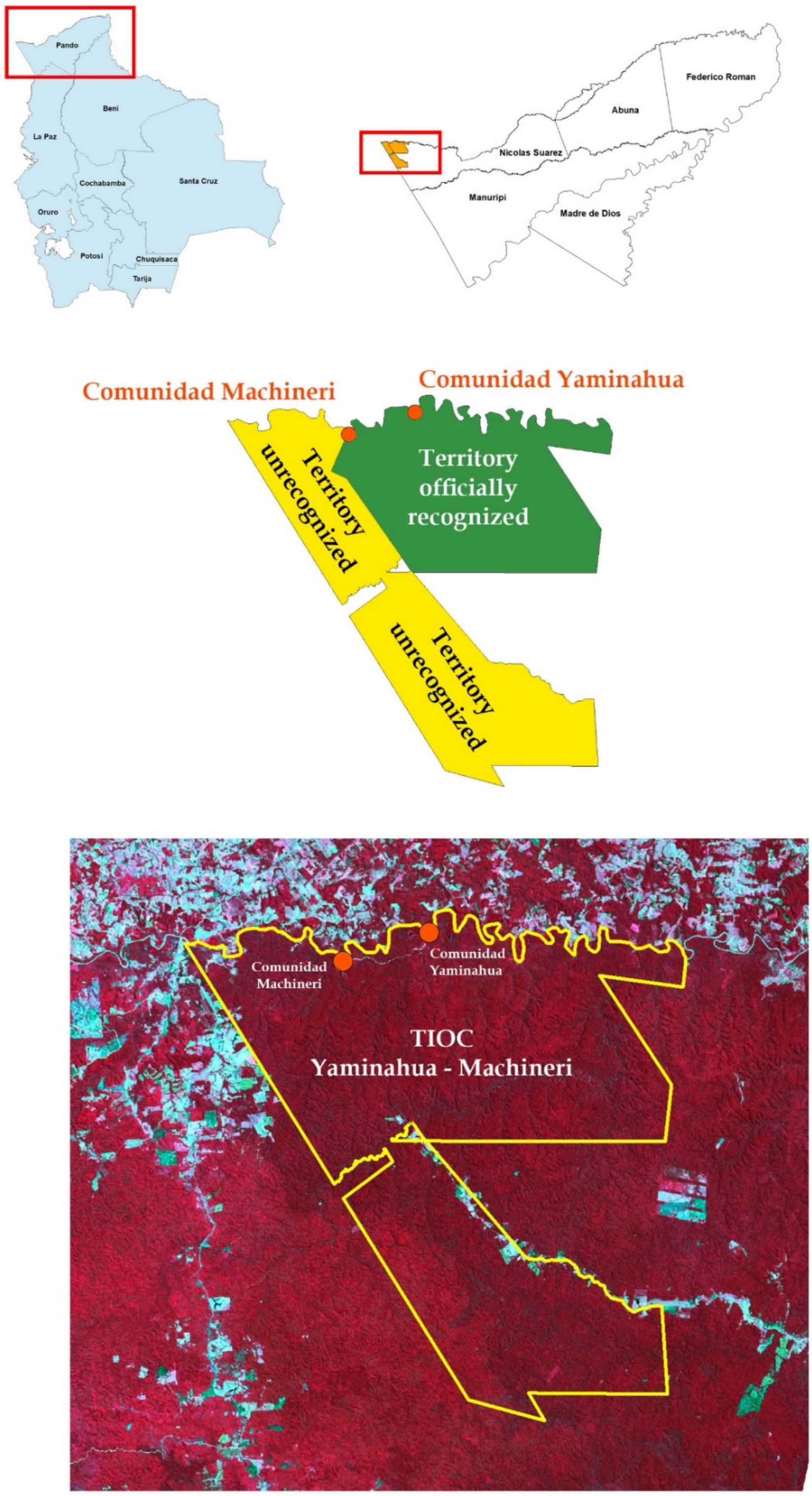


Figure 2. Location of the TIOC Yaminahua-Machineri in the Department of Pando, Province of Nicolás Suarez, and the municipality of Bolpebra. Limits to the north with Brazil and to the west with Peru. The northeastern part of the TIOC has been officially recognized by the central government (24,671.3 ha), but the rest of the territory–to date–has not (29,458.7 hectares) [45,90].

The Yaminahua

Nomads by nature, the Yaminahua had no notion of borders and lived in a vast forested region where Bolivia, Peru, and Brazil now coincide [61]. They have been almost decimated twice; first, between the 1870 and 1914, by the Amazon rubber barons and the *siringureos* (people in charge of rubber extraction) [91–93] and, second, in 1964, due to a new extractivist phase in Brazil that switched the regional economy from rubber extraction to intensive cattle production that destroyed vital forest [93]. Following these set-backs, the remaining Yaminahua moved away from the deforestation and settled in Bolivia around 1976 [93]. They now live in Puerto Yaminahua located in the Bolivian municipality of Bolpebra in the triple border shared by Bolivia (Pando), Peru, and Brazil [94]. They still speak their native language (Yaminahua), along with Spanish and Portuguese [61,88,94], and in 1994, they were officially recognized as a TCO for their agrarian settlement and ownership of the land [93]. Although there might be more Yaminahua people living in Brazil and Peru, its entire Bolivian population consists of just approximately 39 individuals [45,88,91,94]. Their main settlement activities consist of gathering, hunting, fishing, the sale of crafts and Brazil nuts, and eventually the sale of labor to Brazil [88,91]. Access to health services is difficult: the closest medical attention is some 120 km away in Cobija and is only accessible by land during dry season, or via a 20 hour boat trip through the Acre River [93,95].

Given its small numbers, the Yaminahua is one of the most vulnerable indigenous communities in Bolivia. Although some of their traditions, language, and vernacular architecture are being forgotten, their Indigenous Knowledge System of ways to see, connect, and conserve their forests are maintained by the TIOC to this day (Figure 3) [61,94]. However, external threats of non-indigenous activities, such as illegal loggers, hunters, and settlers, still put the integrity of the TIOC at risk [90,93]. In addition, even greater external threats, such as new highways and concessions for oil exploitation overlapping the TIOC territories, are a latent menace.

(**a**) (**b**)

Figure 3. (**a**) Rivers are the highways to most of the indigenous communities in the Amazon, including the Yaminahua. Most of the time, their only way to get access to markets and hospitals are many hours of canoeing along the Acre River. During dry season, they move to the cities by long drives by car on dirt roads. As with other indigenous groups, the Yaminahua have not forgotten about their connection to their forests and rivers. (**b**) Sadly, the Yaminahua community, constituted by only 39 members, is one of the most vulnerable indigenous groups in the country. Their language and culture is threatened, as is their vernacular architecture. The central government's national housing project is pushing alien designs, materials, and spatial organization over traditional approaches and techniques.

The Machineri

Although they share their territory with the Yaminahua, the Machineri is a distinct indigenous community with its own language [62]. Also nomads, they have been present in the tripartite region for 2500 to 5000 years [90]. During the time of Spanish colonization, their skills as river navigators made them intermediaries of different products through the region [90]. By the early 1980s, the Machineri had largely migrated from Brazil to Bolivia [62,90,91,95], and the present Bolivian Machineri community includes around 200 people living in San Miguel de Machineri in the Bolivian municipality of Bolpebra, approximately 8.4 km west of Puerto Yaminahua by canoe [62,91]. The closest town is Assis in Brazil, some four hours to the west by boat [91].

Similar to the Yaminahua, the Machineri want to preserve their native language and culture. Since 2014, and with support from different institutions, they have had bi-lingual teachers at the local school teaching children the original language and culture [96]. Along with the Yaminahua, the Machineri share concerns with illegal loggers and settlers as a constant threat to their forests [62]. However, unlike the Yaminahua, the Machineri's IKS tends to encourage a more diverse range of productive community activities and sustenance: cattle management and fish production alongside Brazil nuts harvest, wood usage under sustainable forest management, gathering, hunting, subsistence agriculture, and trading of labor and products to Brazil [62] (Figure 4). The Machineri were one of the first indigenous communities to implement a solar-powered system, a drinking water system, and a health post [62].

(**a**) (**b**)

Figure 4. (**a**) A Yaminahua mother and her five children waiting in San Miguel de Machineri for land transport to Cobija, the closest big city in Bolivia, some 80 km away. The Machineri community showed evidence of water storage systems and solar panel and communication systems. (**b**) It was again evident that the original landscape of vernacular architecture and natural biodiversity has been replaced by brick and mortar constructions and the presence of big and small cattle for food security.

2.1.2. TIOC Takana-Cavineño

The TIOC Takana-Cavineño, according to the Universal Transverse Mercator (UTM) system, is located in the Zone 19 L between X coordinates: 747,602 m E, Y coordinates 8,760,287 m S, and X coordinates 801,257 m E, and Y coordinates 8,655,206 m S.

The TIOC Takana–Cavineño was officially recognized by the Bolivian central government in 2007, as 801 people from indigenous communities inhabiting owning some 271,049.5 hectares (Figure 5) [45,90].

Figure 5. Location of the TIOC Takana-Cavineño in the Department of Beni, Provinces General Ballivián, Vaca Diez, and Yacuma in the municipalities of Santa Rosa, Riberalta, and Exaltación. This TIOC was officially recognized by the Bolivian central government in 2007 as 271,049.5 hectares.

The Takanas

There are approximately 7000 Takana people living in different communities along the states of Pando, La Paz, and Beni on the North Bolivian Amazon Region [63]. As with many other native Amazon communities, the Takanas used to be predominantly nomads practicing hunting, fishing, and gathering in a symbiotic lifestyle with their forests and rivers [63]. They used the forest as a source of clothing, food, building-materials, and weapons [63]. Brazil nuts, Heart Palm, honey, and turtle eggs were part of their diet [90], and they used to construct their own bows and arrows to hunt in a collective strategy [63,90] and designed sophisticated fishing techniques [63].

However, after the influence of various events, such as the Spanish missions on the 18th century, the booms of quinine around 1832 and rubber between 1880 and 1914, and colonizing settlements on their territories during the last century, the Takana started to change some aspects of their culture, adapting new lifestyles and forgetting some traditions [63,90]. Farming, the adoption of the Spanish language, and the use of currency to access clothes, food, and education represented the most significant cultural changes [63,90]. Meanwhile, due to the deterioration of their forests and rivers, many male individuals were forced to travel away from their families in search for jobs [63,90]. This phenomenon is becoming more common in native Amazon communities where the rate of forest destruction and degradations is more evident [63].

Despite these cultural adversities and pressures to their traditional IKS, the Takana are making a great effort to keep their traditions alive [63]. There are still elders and crafts-people with ancient knowledge that share their ways, including house-building, tool-crafts for hunting and fishing, and the Takana language itself, which, is increasingly being practiced and preserved by younger generations [63]. As is often the case, the landscape itself—the settled territory—is the main source of life and the key component to the maintenance of indigenous culture and economy. The Takana are still largely dependent on forest-based activities such as fishing, hunting, wood harvests, and the commercialization of Brazil nuts (Figure 6) [63,97].

(a) (b)

Figure 6. (**a**) The Takanas and Cavineños' Indigenous Knowledge System (IKS) maintain landscapes with vernacular architecture harmonizing colors, shape, and materials with their environment. (**b**) In a similar way, the IKS represents a vital symbiosis between forests, rivers, and the human community.

The Takanas are now organized in two core organizations: the OITA (Indigenous Takana Organization) and the CIPTA (Indigenous Council of the Takana People) that, together, represent their demands to the central government [90]. In 2002, most of the Takana communities officially received land titles recognizing their territories [90].

The Cavineños

The Cavineños' natural habitat was located in the various ecosystems found around the Beni and Madidi rivers that connect northern La Paz to Beni [64]. Again, the Cavineño is also a differentiated native group that has a particular language that is also under threat of disappearance [90]. Today, there are approximately 2000 Cavineño people distributed in approximately 30 communities, of which the majority (27 communities) live in the state of Beni, and the rest in Pando and La Paz [90]. The communities self-arrange themselves in extended family groups resulting in vital, productive entities that share labor and then distribute the results among all members of the group [64,90]. Although they maintain the figure of a "*Cacique*" as chief of the community, the Cavineños' order still follows an ingrained, ancient respect for the great wisdom of all their elderly [64,90]. A Spanish mission, *Misión Esmeralda*, was the first to contain the Cavineños in 1764 [90]. Then, in 1834, the mission was moved next to the Beni River due to constant invasions from the Cavineños' enemies, the *Ese Ejja jas* and *Toromona* [64]. The new mission was called *Misión Cavinas* and held approximately 1000 natives [90]. During the rubber exploitation boom, the mission became a great farm, focused mainly on agriculture and cattle production in order to provide food for the surrounding rubber-related industry [90]. *Franciscanos* (Spanish priests) used the intensive labor from the Cavineños in exchange for gun-powder, fabrics, and agricultural tools [64,90]. In 1910, the *Franciscanos* managed to acquire the land endowment of approximately 70,000 hectares from the government [90]. In 1941, the Spanish priests left the country, and North American priests from the order of Maryknoll came to Bolivia to replace them [90] and the relationship between the Cavineños and the church rapidly deteriorated. From this point, the natives started to establish and settle new communities away from the mission and sold their labor to other *barracas* or *siringueros* [64].

In 1973, before returning to the United States, the Maryknoll order sold some land to Cavineños individuals, though their rights as landholders were not, at the time, recognized by the church nor the government. Nevertheless, the Cavineños prospered and they continue to base their livelihood on the practices of agriculture, hunting, fishing, and gathering [64,90]. They also maintain practices of traditional medicine along with modern medicine [65,90]. They have particularly developed their agriculture in riparian zones, putting in practice slash and burn techniques to cultivate corn, rice, sweet potato, walusa potato, yucca, banana, peanut, watermelon, and tomatoes [90]. They have also learned skills for rubber extraction (from the time of the Barracas), and the harvest of Brazil nuts (from the time of the missions) (Figure 7) [64,65].

Since the later part of the 20th century, the growing rate of deforestation and the presence of more logging-companies in the region, it has become harder for the Cavineños to have access to wild meat from the forests [64] and, as a consequence, they have intensified fishing and the raising of domesticated cattle, sheep, pigs and poultry [64]. Additionally, similar to the Takana, the degradation of their natural resources have often forced the men to leave their families and communities in order to find jobs and earn money to buy food, clothes, tools, and other goods and services [65]. This placed the integrity of their families and the continuation of the community culture in peril [64,65].

Today, the Cavineños are organized as OICA (Indigenous Cavineña Organization) which is also affiliated to CIRABO (Indigenous Central of the Bolivian Amazon Region) located in the municipality of Riberalta (Beni) [90]. There are still many communities that lack of access to electricity and drinking water, and only some communities have health-posts and schools [90]. They finally received their land titles in 2007, and now Cavineños co-manage TIOCs with the *Esse Ejja*, *Takana*, and a distinct territory of 468,117 hectares [65,90]. Unfortunately, the TIOCs are being invaded by illegal loggers, highway construction companies, and oil companies [64,90]. Despite all these threats to their culture and natural resources, the Cavineños want to recover both, and still conserve IKS beliefs of respect to the forests where the life spirits live [64,65].

(**a**) (**b**)

Figure 7. (**a**) A Brazil nut tree standing among the rest of the forest. Brazil nut exports represent part of the 2.3% of the national Bolivian GDP as a forest-friendly sustainable economy [98]. (**b**) However, a road system, which is part of the Corredor Norte's central government development plan, is being connected to the Brazil–Peru inter-oceanic highway. Although it is still a dirt road at the time of writing, it is likely to become a busy, metaled road supplanting the canoe as the chief means of transport and facilitating the driving forces of deforestation.

2.2. National Threats to Bolivian Amazon TIOCs

It is generally known that one of the main drivers for Bolivian deforestation is the presence of roads, especially in tropical areas [99–101]. These disruptions, in the form of spatial data added to other biophysical drivers, can be used as input to a geographic modeler that will then predict the likelihood of disturbance in a given study area. It is also known that oil exploration and extraction is one of the most invasive and destructive activities in tropical forests [102–104]. Apart from other threats on a smaller scale, the Northern Bolivian Amazon faces three major threats, as manifested in a national plan: the North Corridor, the Oil Extraction Block Madre de Dios, and the expansion of the extensive-extractive agricultural and livestock frontier [40,97,105,106].

2.2.1. North Corridor

The *Corredor Norte* or North Corridor, is the construction of a system of highways that will connect the highland city of La Paz to the Amazon in Guayaramerín in Beni, and a branch connection from Guayaramerín to Cobija in Pando [105]. This in turn, will connect to an international highway called *Carretera Interoceánica* or Interoceanic Highway, which connects Brazil to Peru and tangentially touches the town of Cobija in Bolivia (Figure 8) [105]. Its construction started in 2009 [105,107], and the corridor affects both TIOCs case-sites to different degrees.

The influence of the Interoceanic Highway extends to a distance of 100 km either side of the highway itself, including the departments of Pando and La Paz [105]. The corridor initiative seeks to be part of a bigger plan called *Iniciativa para la Integración Regional Sudamericana* (IIRSA) or Initiative for the South American Regional Integration; a pan-continental effort to construct a network of highway infrastructure connecting centers of gas, oil, minerals, wood, and other natural resources in 12 South American countries including Argentina, Chile, Uruguay, Bolivia, Peru, Brazil, Ecuador, Surinam, Guyana, Paraguay, Colombia, and Venezuela [105,108]. The construction of the North Corridor in Bolivia is highly controversial, as it would have irreversible repercussions on the economy, the culture, and the ecosystems of the Bolivian Amazon, such as the degradation and loss of raw materials, the destruction of forests and rivers, pollution, and threats to indigenous communities [105].

Figure 8. The Interoceanic Highway route (shown in purple) connects productive towns in Brazil (Portobello, and Assis), Bolivia (Cobija), and Peru (Iberia and Tambopata). Shown in blue; the North Corridor connecting the city of La Paz to the Northeast Amazon cities of Riberalta and the border city of Guayaramerín with Brazil (Beni). Shown in red; the branch road from El Chorro (Beni) to Cobija (Pando) [105,107,109,110].

2.2.2. The Oil Extraction Block Madre de Dios

Once the country with the second greatest natural gas reservoirs in Latin-American, it has been evident that, over the last years, the oil and gas reservoirs in Bolivia have significantly decreased [111–113]. As a result, since 2015, the central government has approved new legislation expanding oil exploration into Protected Areas and Indigenous Territories particularly in the Bolivian Amazon (Figure 9) [97,106,111,114].

This controversial legislation has, to date, allowed an oil frontier expansion that overlaps 37.6% of all the titled TIOCS in Bolivia, representing about 8 million hectares of indigenous territories in which exploration and exploitation activities is now allowed [114]. State-driven oil company *Yacimientos Petrolíferos Fiscales Bolivianos* (YPFB) along with its international partners, can now, without prior consultation with indigenous communities, undertake seismic activities for further extraction [97].

Both of the TIOCs case-sites of this study are overlapped by this concession to oil exploration. In fact, in the southern parts of the TIOC Yaminahua–Machineri, there has already been an example of conflict with the TIOC Tacana II where oil exploration activities started in 2008 [97]. In this conflict, indigenous communities asked YPFB to respect a distance of 65 m from every Brazil nut tree for seismic detonations, no seismic activities during the harvesting season of Brazil nuts (December–April), and a comprehensive environmental study on Brazil nut trees and others important species [97]. Nonetheless, state-driven YPFB have failed to accomplish all the agreements [97].

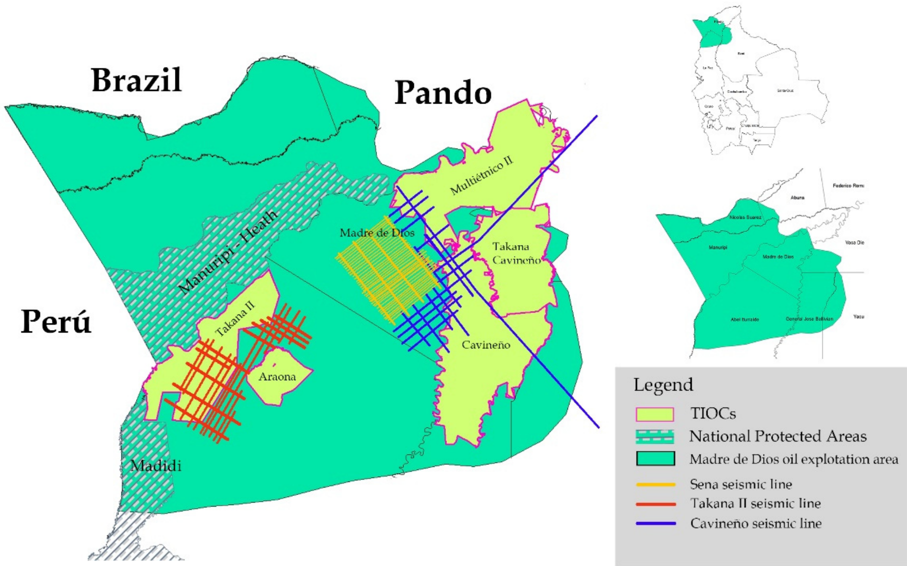


Figure 9. According to Colque and Paniagua (2019), the oil exploration area called Madre de Dios, is part of a central government plan to intensify the oil exploration and exploitation on the west part of the Bolivian northern amazon. Orange, red, and blue colored grids represent overlapping seismic lines on protected areas and TIOCs. Both TIOCs, the Yaminahua–Machineri and the Takana–Cavineño will be affected [97].

2.2.3. The Expansion of Extractive and Unsustainable Agriculture and Cattle Ranching

The need for energy alternatives in the face of the evident decline in fossil fuel reserves has resulted in crop-forests of soy and other monocultures to produce biodiesel and other additives [40,111,113,115], facilitated by Law 1098 (September 2018) [116]. Elsewhere, in order to benefit big agribusiness exports of meat to China, and benefit new settlers in the Bolivian Amazon and Chiquitano dry forest, the Bolivian central government has, since 2013, issued a set of national laws that permit slash and burn practices along with forest deforestation and degradation [40]. These pieces of legislation, inter alia: Law 337 (2013), Law 502 (2014), Law 739 (2015), and Law 952 (2017) for food production and forest restitution [117–120]; Law 741 (2015) that authorizes forest clearance or deforestation of up to 20 hectares for small properties and/or collective properties for agricultural and cattle ranching activities [121]; and the Supreme Decree 3973 (2019) that allows deforestation and fires in the department of Beni for extractive agricultural activities on private and community land [122]. This facilitation of extractive and unsustainable land-practice risk indigenous territories, as evidenced in the aforementioned fires [40].

2.3. Multitemporal Satellite Imagery and Other Spatial Data

Satellite imagery of the case-site territories was downloaded from the United States Geological Survey (USGS) open access repository, using its search tool Earth Explorer [123,124]. Multispectral imagery of 30 m of resolution from missions Landsat 8 OLI/TIRS and Landsat 4-5 TM in GeoTIFF format were used [123,125]. All the imagery were geometrically improved and atmospherically corrected to Level 2 by the USGS before downloading [125].

The most recent images available were used for the two TIOC case study sites, mainly from 2013–2018 for Yaminahua–Machineri, while older imagery was used as comparison references, and 2003 and 1998 for the TIOC Takana–Cavineño. Additionally, Digital Elevation Maps (DEM) from the ASTER Global Digital Elevation Model (ASTGTM) in GeoTIFF format of 1 arc second, were downloaded from the USGS website, then resampled to 30 m of spatial resolution, and finally merged to cover both TIOCs [124,126]. Imagery for the study area corresponded to the DEM scenes ASTGTM_S13W067, and ASTGTM_S12W067 [124,126]. Table 1 shows the satellite scenes used for each year of analysis based on the trajectory, place, day, and hour of the acquisition by the Landsat sensor.

Table 1. Landsat 30-m spatial resolution satellite imagery used for the analysis of each TIOC by year, multispectral sensor, and its trajectory [1].

TIOC	2018 L8 OLI/TIRS	2013 L8 OLI/TIRS	2003 L 4-5 TM	1998 L 4-5 TM
Yaminahua-Machineri	P: 2 R: 68 6/September P: 3 R:67 6/September P: 3 R: 68 6/September	P: 2 R:68 31/July P: 3 R: 67 22/July P: 3 R:68 22/July	P: 2 R: 68 20/July P: 3 R: 67 27/July P: 3 R: 68 27/July	
Takana-Cavineño	P: 1 R: 68 23/August P: 233 R: 69 1/September	P:1 R: 68 19/September P: 233 R: 68 3/September		P: 1 R: 68 15/July P: 233 R: 68 8/July

[1] P = Path; R = Row.

All of the raster satellite scenes, including DEM, were projected to the datum WGS84 of the Universal Transverse Mercator coordinate system (UTM) Zone 19 South, which coincide with both of the study areas. For this, the Raster Projection tool of the ArcGIS software was used [127].

In addition, other complementary spatial information was downloaded in Shapefile format from other specialized open access repositories. The first repository belongs to the *Red Amazónica de Información Socioambiental Georreferenciada* (RAISG) (Amazon Network of Geo-referenced Socio- environmental Information) [128]. The second is the *Centro Digital de Recursos Naturales* (CDRNB) (Natural Resources Digital Center) [129]. Additionally, updated information about country, departmental, and municipal limits was downloaded from the Office for the Coordination of Humanitarian Affairs (OCHA) and GeoBolivia [130]. The road-information was based on the reports provided by the *Administradora de Caminos de Bolivia* (ABC, La Paz, Bolivia) (Bolivian Roads Administrator) from official sites [107]. Finally, some updated spatial information about secondary roads and rivers had to be identified by triangulating information from PDF files, Level 2 raster-based maps, and Google Earth, and integrated as new spatial information the geographical database. Table 2 shows the files, sources, and websites from which the geographical information was downloaded.

Table 2. Source and content of the spatial information used in the present work.

Repository	Content	Source
Amazon Network of Geo-referenced Socio-environmental Information (RAISG)	Vías en Amazonía Territorios Indígenas Concesiones Petroleras	FAN (2015) [131] SNID (2005) [132] y INRA (2015) [89] FAN (2015) en base a YPFB (2012) [133]
Natural Resources Digital Center (CDRNB)	Vías Principales Vías Secundarias Centros Poblados Límite Nacional Límites Departamentales Límites Municipales Ríos Mayores Ríos Menores Cuencas Cuencas nivel 4	ABC (2008) [134] ABC (2008) [135] INE (2001) [136] MDS (2004) [137] y GeoBolivia (2019) [130] MDS (2004) [138] MDS 2004, incluye población INE 2000–2010 [139] SUNIT y SITAP (2009) [140] SUNIT y SITAP (2009) [141] FAO (1993) [142] VCRR (2008) [143]
Office for the Coordination of Humanitarian Affairs (OCHA)	Administrative Boundaries	OCHA, HDX, GeoBolivia [130]
Bolivian Roads Administrator (ABC)	Red Vial Fundamental (PDF)	ABC (2019) [107]

2.4. *Land Use Change from Forest to No-Forest in the TIOCs Region*

In this section, four steps to obtain deforestation rates for TIOC Yaminahua-Machineri and TIOC Takana–Cavineño, based on the satellite analysis, will be detailed: (1) definition of the study boundaries for both TIOCs; (2) the improvement of satellite imagery; (3) the classification and merging of satellite images; and (4) the estimation of anthropogenic land use change rates. A detailed description of these steps follows.

2.4.1. Definition of the Study Area Boundaries

For both TIOC case-studies, a study area was considered in the analysis within a certain circular radius to obtain a 360-degree view approximation of the potential land use change from all directions. For the Yaminahua–Machineri, the officially and not-officially recognized territories comprised the total polygons of the TIOC, and the contiguous surrounding areas constituted the overall study area. Overall, eight zones were encompassed within a 45.5 km radius from a geographic center at the municipality of Bolpebra. The study area includes, to the north, the Brazilian state of Acre, to the west the Peruvian state of Madre de Dios, to the east, the Bolivian municipalities of Bolpebra, Cobija, and Porvenir, and to the south, the Bolivian municipality of Filadelfia (and the extensive Bolpebra) (Figure 10).

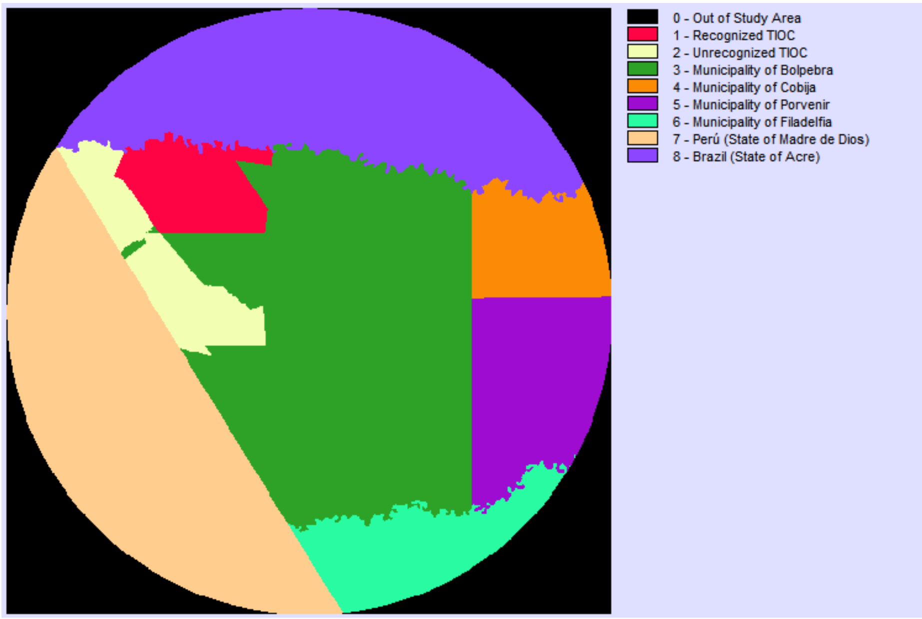


Figure 10. Study region conformed by the Yaminahua–Machineri TIOCs (Labels 1 and 2), and other six reference areas including international areas of Brazil (Acre State, label 8), and Peru (Madre de Dios State, label 7). The Bolivian municipalities of Bolpebra (label 3), Cobija (label 4), Porvenir (label 5), and Filadelfia (label 6) were also taken into consideration to evidence land use change pressures from these municipalities towards the TIOCs.

For this case, the international limit with Brazil (the route of the Acre River) was re-digitized into a new shapefile using official open information from the Bolivian government, Level-2 satellite imagery from the USGS, and Google Earth [87,125,130,137,139]. A similar procedure was followed to digitally redefine the Tahuamanu River at the south of the area, which comes from the Peruvian state of Madre de Dios and crosses east, separating the Bolivian municipalities of Bolpebra and Porvenir to the north and Filadelfia to the south. Overall, the reference area is very rich, representing an officially recognized TIOC next to an unrecognized TIOC, surrounded by two international socio-economic dynamics as well as state-managed land. State-managed land, or *Tierras Fiscales* in Spanish, belongs to a central government domain under departmental or municipality jurisdiction. State-managed land could be either available for endowment in favor of native indigenous or farmers people or could not be available for endowment such as protected areas, timber and non-timber concessions, and public domain areas [45]. The central government agency, National Institute of Agrarian Reform (INRA, La Paz, Bolivia), is in charge of state-managed land endowment through a process called *"saneamiento"*, only if the land accomplish a Social Economic Function (*Función Económica Social*—FES). According to the Bolivian Constitution [86], the Social Economic Function is the "sustainable use of the land by native indigenous peoples, community farmers, or carried out on small properties, and constitutes the source of subsistence and welfare and socio-cultural development of its owners..()..

in the development of productive activities, according to its greater capacity for use, for the benefit of society, or interests of its owner" (Article 397, 1st and 2nd paragraphs). However, in the last years, there is evidence that INRA stopped verifying the FES, which encouraged the appropriation of fiscal lands for extensive agro-industrial production and new settlements with great consequences for the forests and the environment increasing deforestation rates [40,144]) of different Bolivian municipalities.

For the case of the Takana–Cavineño, the study area was encompassed by a radius of 47.2 km from the geographical center set to the officially recognized TIOC. The other three officially recognized TIOCs included in the study area were the TIOC Multiétnico II, administered by the indigenous groups Esse-Ejja, Tacana and Cavineño to the north, the TIOC Cavineño to the west and south, and the TIOC Chácobo–Pacahuara to the east. Additionally, unrecognized TIOCs and state-managed land were considered in the reference area (Figure 11).

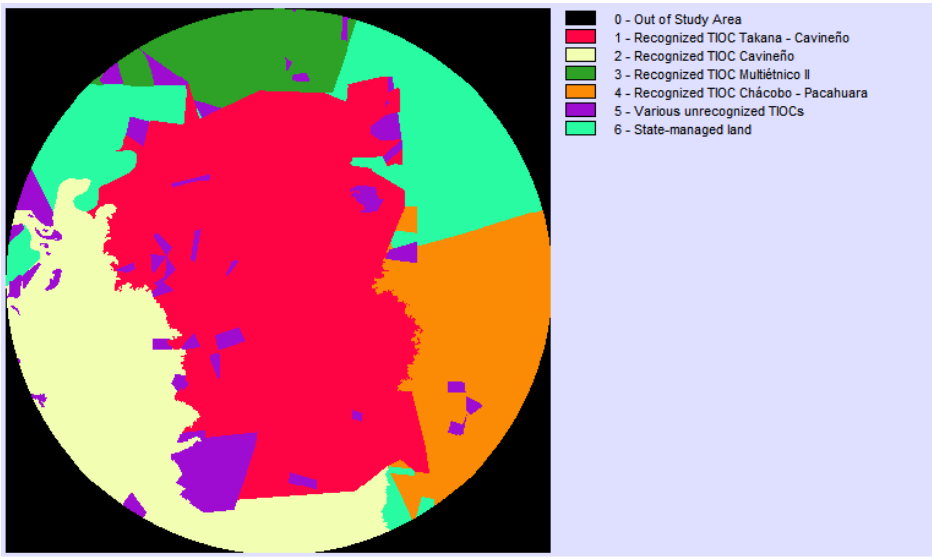


Figure 11. Study region including the Takana-Cavineño TIOC (Labels 1), and other reference areas including other officially recognized TIOCs: Cavineño (Label 2), TIOC Multiétnico II (Label 3), and TIOC Chácobo–Pacahuara (Label 4). Unrecognized TIOCs (Label 5) and state-managed land (Label 6) were also included in the spatial analysis.

For both cases polygons (in shapefile format) of the Indigenous Territories, including the TIOCs, were obtained from the Amazon Geo-referenced Socio-environmental Information Network (RAISG) that uses official Bolivian government information from the Agrarian National Institute (INRA, La Paz, Bolivia) and the National Information System for Development (SNID, La Paz, Bolivia) [89,132,145]. All the polygons were checked and adjusted to obtain clean shapefiles.

Based on the geographical delimitation of the study areas, a spatial reference grid for raster working space analysis was prepared using the software TerrSet as follows (Table 3) [68]:

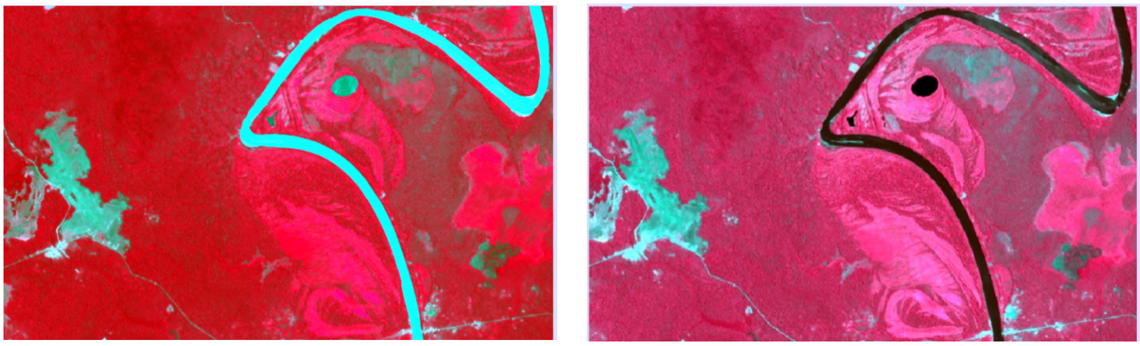
Table 3. Spatial reference grid for raster analysis for both study areas.

Spatial References	TIOC Yaminahua–Machineri	TIOC Takana–Cavineño
	Values	
Number of columns	3150	3033
Number of rows	3150	3033
Reference System	UTM 19-S	UTM 19-S
Units	meters	meters
Minimum X coordinate	727,999.9801647	429,878.7500000
Maximum X coordinate	822,499.9801647	520,868.7500000
Minimum Y coordinate	8,640,903.0455630	8,719,806.0000000
Maximum Y coordinate	8,735,403.0455630	8,810,796.0000000
Y resolution	30	30
X resolution	30	30

2.4.2. Improvement of Satellite Imagery

The satellite scenes (Table 1) were improved using the Principal Component Analysis (PCA) module from the software TerrSet [68]. For the multi-temporal analysis, the PCA provided forward and inverse transformation with t-mode (treats each band as a variable) in order to remove noise from the images [68]. For the forward t-mode, the unstandardized type of a covariance matrix was selected and produced six components for the Landsat 4-5 TM images, and seven components for the Landsat 8 OLI TIRS images. Depending on the results from the Forward T-mode, the first two or three components explained from 95 to 99 percent of the total variance in the original set, which means that the rest of the components could be dropped for noise removal [68].

Eight of the scenes were improved using three components produced by the inverse T-Mode procedure (2018: 01/68, 02/68, 03/67, 03/68; 2013: 03/67, 03/68, 233/68; and 2003: 02/68); six of the scenes were improved using two components (2018: 233/68; 2013: 01/68; 2003: 03/67, 03/68; and 1998: 01/68, 03/68), and one image was processed with no improvement due to its original quality (2013: 02/68). The main criterion for selecting the number of components was the result of different multispectral band combinations in order to distinguish water bodies (Figure 12).



(**a**) (**b**)

Figure 12. Comparison between two false color map compositions, both created by the combination of the bands 5 (NIR–Near Infrared), 4 (Red), and 3 (Green) from imagery of the 2013 Landsat 8 OLI/TIRS mission: (**a**) to the left, image created using the first three components of the PCA analysis and (**b**) to the right, image created using the first two components produced by the PCA. Note that the image on the right (**b**), which is product of the inverse t-mode module using the first two components, shows an enhanced contrast between water bodies (black and dark areas), savannas (darker blue green areas), and anthropogenic land use change (bright blue areas). Images of 2013 for the Takana–Cavineño TIOC downloaded from the United States Geological Survey (USGS) webpage [124].

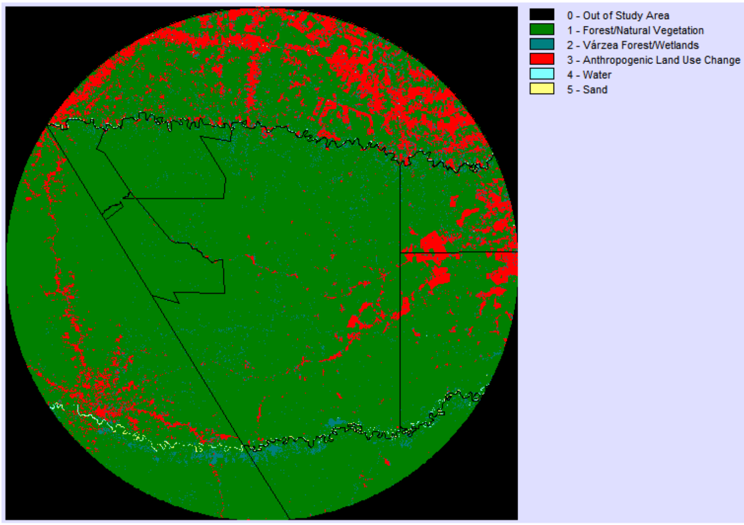
2.4.3. Classification and Merging of Images

The supervised classification took three steps. First, the definition of training sites considering general classes for land cover. For this study, the most important features to define were anthropogenic land use change and natural vegetation. In this way, the classes considered for the TIOC Yaminahua–Machineri were: 1 = Forest, 2 = Várzea Forest/Wetlands, 3 = Anthropogenic Land Use Change, 4 = Water, 5 = Sand, 6 = Clouds (when present), and 7 = Cloud Shadows (when present). The classes for the TIOC Takana–Cavineño were: 1 = Forest, 2 = Savannas/Cerrado forest, 3 = Várzea Forest/ Wetlands, 4 = Anthropogenic Land Use Change, and 5 = Water. The polygon digitization tool was used to assign classes over different band combinations using the software TerrSet.

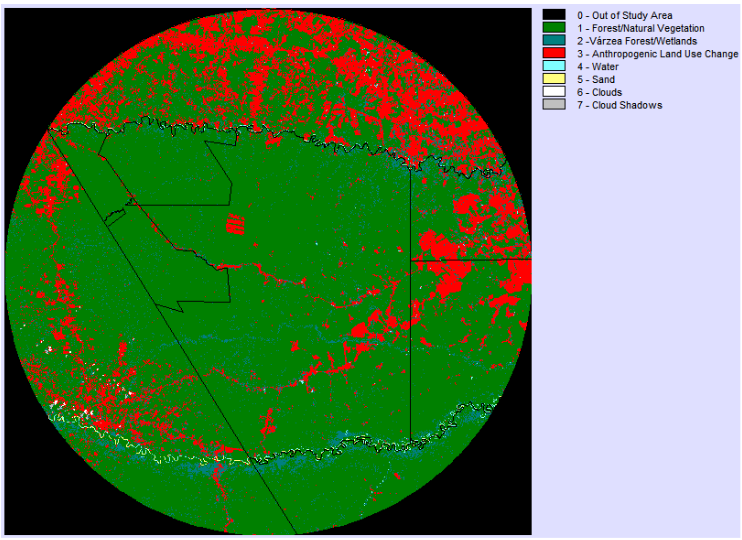
To reduce uncertainty in the identification of each class process, simultaneous comparisons with different band combinations (For example bands 4, 3, and 2 for Landsat 4–5 TM images, and bands 5, 4, and 3 for Landsat 8 OLI/TIRS), the open platform Global Forest Watch, Google Earth, and the Vegetation Map of Bolivia were conducted [38,87,146].

Secondly, the classification process was conducted using the Kohonen's Self-Organizing Map (SOM), an artificial neural network classifier also available in the software TerrSert. There is evidence that the neural network SOM can perform with 1.4%–3.3% more accuracy than other supervised standard classifier [66]. Finally, the misclassified pixels were digitally corrected using digitizing polygons and then conducting raster reclass operations to assign the proper numeric value to these pixels.

At the end of this process, for the Yaminahua–Machineri study area, each of the three scenes that corresponded to a specific year (2003, 2013, and 2018) were mosaicked into one and then clipped according to the spatial study area delimitations (Figure 13). In the same way, two scenes corresponding to each year (1998, 2013, and 2018) for the Takana–Cavineño area were mosaicked and clipped accordingly (Figure 14). The Mosaic tool was used to merge the images and then the Overlay tool was applied along with a general Mask file to delimitate the study area, as part of the TerrSert software toolbox.

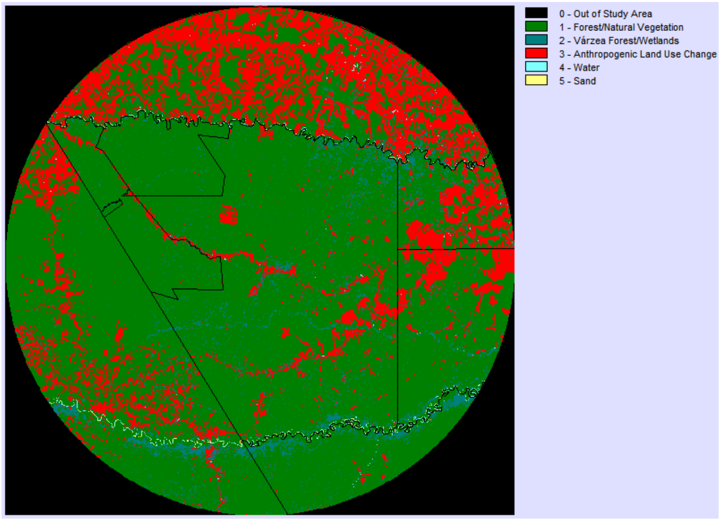


(**a**)



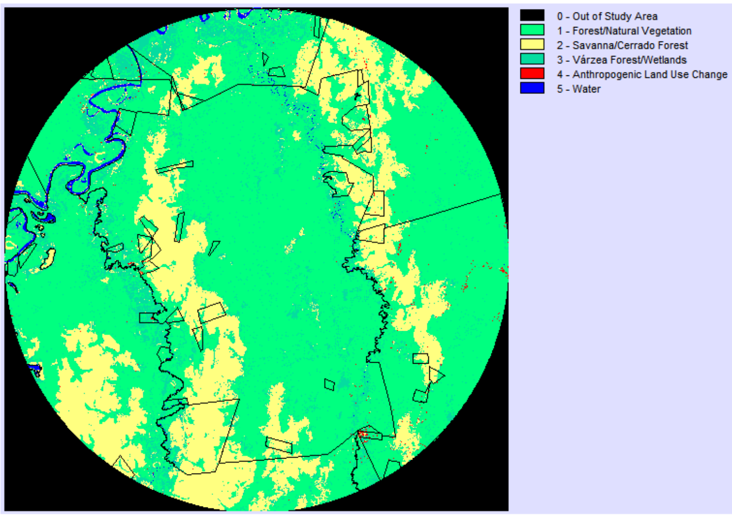
(**b**)

Figure 13. *Cont.*

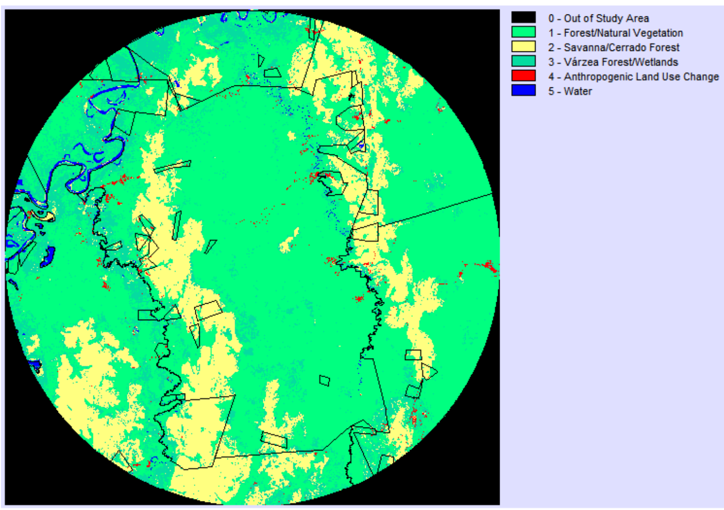


(**c**)

Figure 13. Study area including official and unrecognized Yaminahua–Machineri TIOCs. Classified maps of: (**a**) 2003; (**b**) 2013, and (**c**) 2018.

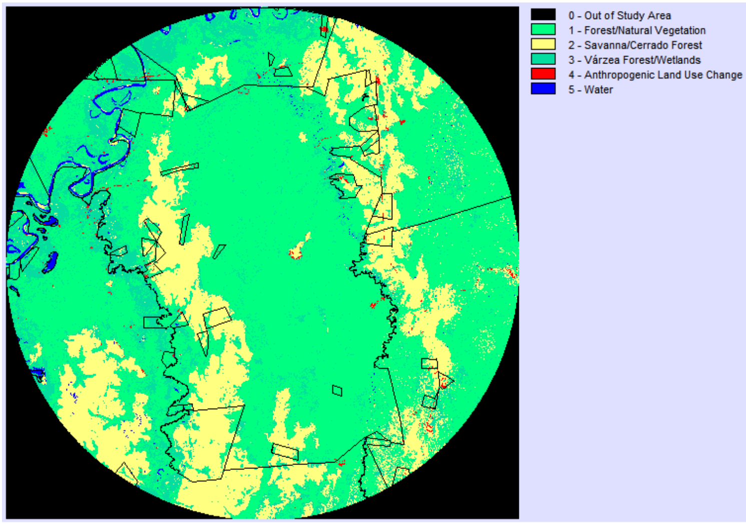


(**a**)



(**b**)

Figure 14. *Cont.*



(**c**)

Figure 14. Study area including Takana–Cavineño TIOC. Classified maps of: (**a**) 1998; (**b**) 2013, and (**c**) 2018.

An accuracy assessment technique was conducted after a similar classification protocol was followed in a study of the protected area Lomas de Arena in Santa Cruz, Bolivia. For this, a section of a finer resolution image (1.24 m) from Google Earth was manually digitized, assigning a specific class cover to each distinguishable area. This image was rasterized (30 m) and considered as the ground truth image or reference map. Then, the ERRMAT (Error Matrix Analysis) tool from the software TerrSet was used to create an error matrix between the categorical map, product of the classification protocol, and the ground truth image [68]. The results showed that the classification accuracy was over 81% [147]. Because similar steps of the supervised classification process were followed in the present work, it can be expected similar or higher levels of accuracy.

2.4.4. Estimation of Anthropogenic Land Use Change Rates

The anthropogenic land use change rate was estimated following two steps: first by determining the surface of forest cover during three periods of times in each specific study zone, and a quantification of the number of hectares corresponding to cover forest and cover loss for each study zone using the surface calculation tool of the software TerrSet; secondly, with this information, the formulas of annual rate of change of forest recommended by Puyravaud were applied [148]:

$$r = (1/(t2 - t1)) \times \ln(A2/A1), \quad (1)$$

$$r = (A2 - A1)/(t2 - t1) \quad (2)$$

Formula (1) uses the information of the forest area at the initial time (A1), forest area at the final time (A2), at an initial time (t1), and in a final time (t2). The rate is expressed in percentage (%), which allows to make standardized comparisons between different areas.

Formula (2) uses similar information as formula (1), except the result is expressed in hectares per year (ha/year).

The deforestation rate considered for the extrapolation of land use change was estimated using the forest cover information from the oldest scene and the most recent one. This approach follows a recommendation from a study that conducted a sensitivity analysis of various deforestation rates as product of different time periods [52].

2.5. Land Use Change Extrapolation to Year 2030

In order to predict the spatial land use change for both TIOCs to year 2030, three steps were taken. First, suitability maps (maps of potential land use change) were generated by the GEOMOD modeler on the TerrSet software during the calibration process. The suitability maps were created based on initial time maps, different stratifications of the study area, and different driver maps with biophysical information organized in categories of 100 as input maps. Tables 4 and 5 describe the driver maps used to obtain the suitability maps for both study areas. The explicit driver maps can be found on Appendix A as Figures A1 and A2.

Table 4. Spatial pattern driver images used in the calibration procedure of the geographic modeler GEOMOD for the Yaminahua–Machineri study area.

Analysis Zone	Number of Categories	Interval Distance	Min Value	Max Value
			m	
Digital Elevation Map	100	2	169	398
Distance to Bi-oceanic highway	100	539	0	53,928
Distance to Corredor Norte roads	100	809	0	80,911
Distance to secondary roads	100	322	0	32,208
Distance to highly populated centers	100	849	0	84,898
Distance to medium-populated centers	100	470	0	47,064
Distance to low-populated centers	100	980	0	98,010
Distance to administrative borders	100	188	0	18,816
Distance to major rivers	100	279	0	27,896
Distance to secondary rivers	100	198	0	19,774

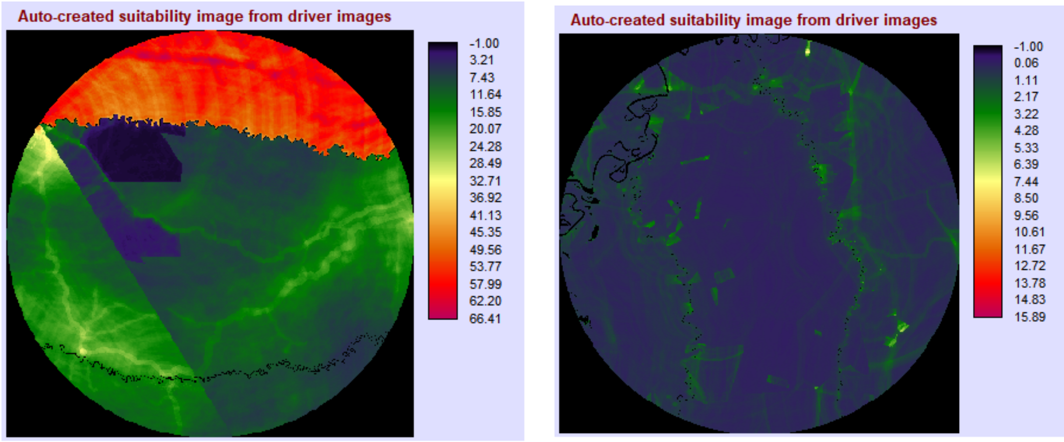
Table 5. Spatial pattern driver images used in the calibration procedure of the geographic modeler GEOMOD for the Takana-Cavineño study area.

Analysis Zone	Number of Categories	Interval Distance	Min Value	Max Value
			m	
Digital Elevation Map	100	2	69	278
Distance to populated towns	100	495	0	49,513
Distance to Corredor Norte roads	100	766	0	76,619
Distance to secondary roads	100	481.5	0	48,146.3
Distance to administrative borders	100	297	0	29,732
Distance to main rivers	100	925	0	92,517
Distance to secondary rivers	100	375	0	37,487

Second, the selection of the suitability map with the best fit of spatial agreement of projected land use change based on an accuracy assessment was made using the Relative Operating Characteristic (ROC) statistic available in the TerrSet software. The ROC statistic assesses the validity of a location prediction model by comparing a suitability image and a reference image [48,50,57,68]. If the ROC output produces an Area Under the Curve (AUC) with a value of 1, this indicates that there is a perfect spatial agreement between the reference map and the suitability map [48,50,57,68]. Hence, a perfect prediction power was obtained. On the other hand, an AUC value of 0.5 is the agreement that would be expected due to pure chance [48,50,57,68].

Figure 15 show the two suitability maps chosen for the geographical extrapolation, and Tables A1 and A2 (Appendix B) describe the ROC results for each stratification combination.

The suitability maps with higher ROC statistics and with the most recent reference images were selected based on the recommendations of a sensitivity analysis study that tested different reference area with different suitability maps zone stratifications [52].



(**a**) (**b**)

Figure 15. Suitability maps generated by the calibration process in the geographical modeler GEOMOD and selected from other maps with lower ROC scores. The higher values on the suitability maps correspond to areas most likely to change class from forest to no-forest: (**a**) to the left, selected Suitability map for the Yaminahua–Machineri TIOCs. It is evident that the Brazil's part of the study area has the highest probabilities of land use change occurrence along with the cities of Iberia in Peru (southwest), and Cobija in Bolivia (northeast) as development poles; and (**b**) to the right, the selected suitability map for the Takana–Machineri TIOC. This map suggests low chances of land use change occurrence across the study area.

3. Results

3.1. Land Use Change from Forest to No-Forest in the TIOCs Region

The results suggest that TIOCs that are officially recognized by the central government present a good conservation state and the lowest deforestation rates (Tables 6 and 7). Additionally, TIOCs surrounded by other officially recognized TIOCs are fairly protected in contrast to those TIOCs that are surrounded by international and national development sites and state-managed land. Unrecognized TIOCs can witness deforestation rates similar to unprotected state-managed land. This implies the effect of the IKS reinforced by government recognition, which is the holistic understanding of forests as a life resource that should be carefully managed.

Regarding the TIOC Yaminahua–Machineri, on the one hand, the lowest deforestation rate registered belonged to the official TIOC area (−0.01%). On the other hand, the highest deforestation rate registered in the scene belonged to the Brazilian state of Acre (−2.46%). Unfortunately, the deforestation rate of the unrecognized TIOC (−0.32%) is comparable to rates on the state-managed land of the municipalities of Bolpebra (−0.31%) and Porvenir (−0.38%). Within the borders of Bolivia, the highest anthropogenic land use change rate was found in the municipality of Cobija (−1.43%), even higher that the rate estimated in the Peruvian state of Madre de Dios (−0.65%).

Table 6. Deforestation rates for the Yaminahua–Machineri TIOC study area.

Analysis Zone	Forested Area 2003	Forested Area 2013	Forested Area 2018	Deforestation Rate (2003–2018)	
	———	ha	———	ha/Year	%
1–Official TIOC	25,455	25,382	25,398	−3.8	−0.01
2–Unrecognized TIOC	29,051	28,362	27,682	−91.2	−0.32
3–Municipality of Bolpebra	186,484	180,359	178,115	−557.9	−0.31
4–Municipality of Cobija	24,600	20,429	19,845	−317.0	−1.43
5–Municipality of Porvenir	45,566	43,343	43,066	−166.7	−0.38
6–Municipality of Filadelfia	38,357	38,043	38,034	−21.5	−0.06
7–Peru (State of Madre de Dios)	142,222	132,514	128,937	−885.6	−0.65
8–Brazil (State of Acre)	85,065	69,879	58,829	−1749.3	−2.46

Table 7. Deforestation rates for the Takana-Cavineño TIOC study area.

Analysis Zone	Forested Area 1998	Forested Area 1998	Forested Area 2018	Deforestation Rate (1998–2018)	
	ha			ha/Year	%
1–Official TIOC Takana-Cavineño	221,882	224,309	222,402	26.0	0.01
2–Official TIOC Cavineño	96,804	99,530	98,026	61.1	0.06
3–Official TIOC Multiétnico II	37,863	38,198	38,514	32.6	0.09
4–Official TIOC Chácobo-Pacahuara	75,927	76,104	70,089	−291.9	−0.40
5–Various Unrecognized TIOCs	21,788	22,808	22,577	39.4	0.18
6–Municipality of Riberalta	77,821	79,886	76,598	−61.2	−0.08

The TIOC Takana–Cavineño, an area surrounded by other officially recognized TIOCs, presented consistent forest gain patterns. This means that after the land is used by the indigenous peoples, vegetation is then allowed to take over. All the TIOCs, including the non-official ones, have shown evidence of forest gain, except the recognized TIOC Chácobo–Pacahuara (−0.4%) in which deforestation rates are higher than rates estimated on the state-managed land of the municipality of Riberalta. It is important to mention the positive correlation between the existence of the Corredor Norte roads (although still undeveloped dirt tracks at this time) and the proximity of deforestation patches.

3.2. Land Use Change Extrapolation on the TIOCs Study Region until the Year 2030

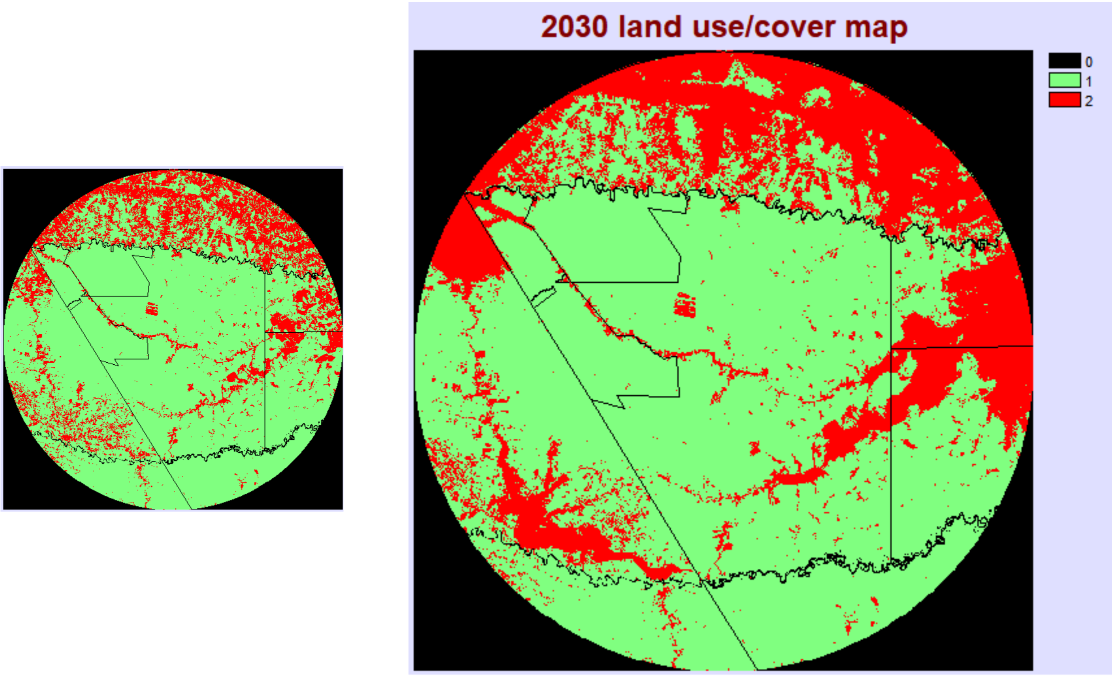
Both TIOC's LUC projections up to 2030 suggest that officially recognized indigenous territorial holdings will tend to be associated with sustained forest cover. As discussed above, the field-visits suggested the close-relationship and co-dependence between native cultures and indigenous knowledge systems and settled landscape-type: forests and rivers being particularly important. In short, it appears that, historically and in the future, indigenous knowledge systems, if reinforced by official land-rights recognition, can greatly contribute to landscape conservation of the Bolivian Amazon. However, leaving all the conservation efforts to IKS may not be enough, alone, to ensure long-term landscape health.

In the case of the Yaminahua–Machineri communities, they have demonstrated that their IKS has been fairly effective in its protection and conservation of forests in a cross-border area with dramatic contrast in land use change patterns. However, for the 2030 scenario, the TIOCs in this study area are—relatively speaking—in greater danger of non-indigenous LUC, because it is located among three massive development centers in Brazil and Peru, and domestically out of Cobija. These centers are intensely pushing inwards towards the Bolpebra municipality, and to the recognized and unrecognized TIOCs (Figure 16). The development of the road system and lack of government recognition and associated support will very likely impact the north of the unrecognized TIOC by 2030. It is evident that the immense pressure from Peru and Brazil will pierce the territory creating a sort of "suction tunnel" that will facilitate trade and forest extraction from within Bolivia, and further weaken the fundamental cultural components of the IKS on land governance.

From the east, the dramatic expansion of the urbanization from the Bolivian city of Cobija will play a fundamental role in the LUC development patterns that will connect Bolivian markets with the Peruvian city of Puerto Maldonado, which is connected at the same time with the bi-oceanic international highway system. Improvement on the actual road system, such as pavement implementation and width extension, could significantly accelerate and worsen deforestation and forest degradation patterns.

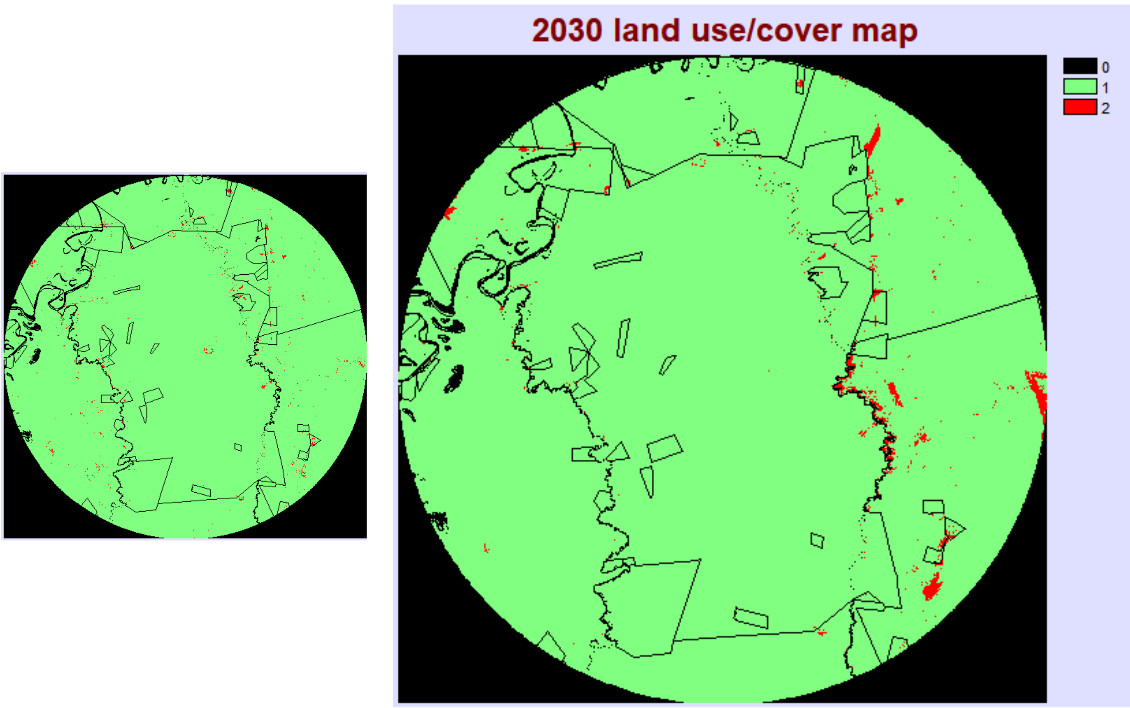
The case of the Takana–Cavineño communities provides evidence that officially recognized TIOCs maintain their territory with little to no deforestation especially if, as is this case, a TIOC is also surrounded by other official recognized territories where indigenous settlement and land management can facilitate patterns of vegetation regrowth or negative deforestation rates.

Moreover, although road infrastructure is considered one of the main driving factors for deforestation, the cluster of recognized TIOCs around the Takana–Cavineño demonstrates that deforestation is fairly controlled despite the presence of the Corridor Norte road system (Figure 17).



(**a**) (**b**)

Figure 16. Study area for the TIOCs Yaminahua–Machineri. Class 0 = Out of Study Area; Class 1 = Forest/ Candidate Area for Land Use Change; and Class 2 = Anthropogenic (projected) Land Use Change: (**a**) to the left, image of forest and no-forest areas of 2018; (**b**) to the right, projected anthropogenic land use change to the year 2030.



(**a**) (**b**)

Figure 17. Study area for the TIOCs Takana-Cavineño. Class 0 = Out of Study Area; Class 1 = Forest/ Candidate Area for Land Use Change; and Class 2 = Anthropogenic (projected) Land Use Change: (**a**) to the left, image of forest and no-forest areas of 2018; (**b**) to the right, projected anthropogenic land use change to the year 2030.

However, based on the historical deforestation rates, the 2030 forecast suggests that non-indigenous LUC may take place, first, in the officially recognized TIOC Chácobo Pacahuara, and then in state-managed land of the municipality of Riberalta. The explanation for this projection could include variables and dynamics specific to this particular TIOC that are quite different to other TIOCs with lower deforestation rates, and this difference requires further investigation.

It is also important to understand that not all TIOCs are surrounded by other recognized TIOCs in the Amazon, as is the case of the Takana–Cavineño, nor are they located in the midst of a tripartite area of aggressive international development centers as is the case of the Yaminahua–Machineri TIOC. Both study cases represent particularly interesting, if somewhat extreme, examples of TIOCs under contrasting conditions, and further work is necessary to understand forecasts for TIOCs in other, perhaps less dramatic, circumstances to understand the fuller picture.

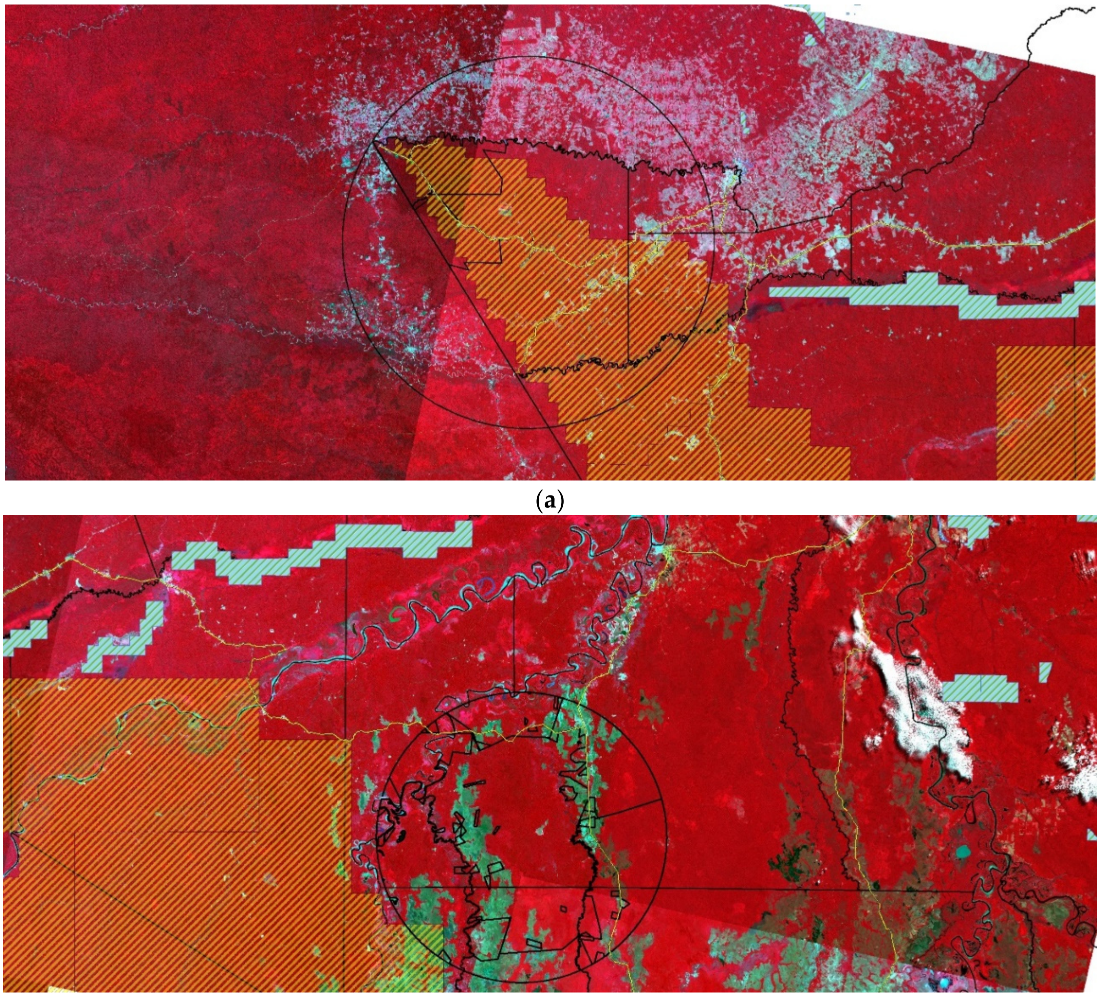
Furthermore, these projections were based on the assumption that things will continue under a business as usual scenario based on current political, administrative, and biophysical conditions. Any change in these variables such as enhancing of road systems, or the appearance of new settlements should be updated and included for new geographical predictions.

4. Discussion

Historically, Bolivia's economy has been predominantly extractivist; it has been blessed, or cursed, to have rich-mineral deposits, gas and oil reservoirs, and other natural resources. History has demonstrated that human development indicators and sustainable development goals have yet to gain much traction. Up to the present day, oil exploitation and the sale of natural gas to Brazil and Argentina are Bolivia's main Gross Domestic Product (GDP) contributors (~32%) [98]. Mining exploitation provides the second biggest GDP contributor (Zinc Ore 17%; Gold 13%; Precious Metal 6.5%; and Raw Tin 4.5%) [98]. Although natural resource exploitation and extrativism are an ingrained part of the country's development agenda, their markets are no longer as strong as they were [115]. Yet, the current need to meet immediate fossil fuel export commitments to Brazil and Argentina [115,149,150] are forcing the legal opening of protected areas and indigenous communities lands [97,106,114].

Figure 18 shows infra-red map compositions (Bands 5, 4, and 3) of both TIOCs study areas, the same that are overlapped with oil expansion blocks layers (orange blocks), mining blocks layers (light blue blocks), and road systems (yellow lines). Such alarming patterns speak to a grave concern: if Bolivian Amazon (and other) TIOCs are going to endure, this will only be because of government support when highways, oil exploration, mining, cattle expansion, and promotion of biofuels such as ethanol [151] are big driving factors for the economy and IKS degradation. Furthermore, pernicious activities, such as illegal mining or fake legal logging in the Bolivian Amazon, as outlined in the study of Brancalion et al. (2018), require careful monitoring to safeguard ecosystems and IKS [152]. Another point of consideration is the exposure of indigenous people to a commodity-based and transactional market economy. Reyes García et al. (2012), in their study of 87 Bolivian Amazon Tsimane villages, found that exposure to traders, loggers, cattle ranchers, highland colonist farmers, and other non-indigenous peoples was linked to unregulated natural resource extraction [153].

Curiously, despite all the central government policies promoting deforestation and disruption of indigenous territories over the last 15 years, such as the Supreme Decree 2549 (2015) for oil exploration expansion, or the constant promotion of expansion to the cattle frontier in Supreme Decree 3973 (2019) that has allowed 9 to 10 million hectares of deforestation; forest friendly economies such as Brazil nut, cashews, and coconuts exportation still makes-up the 2.3% of the national GDP [98,106,154]. Bolivia exports yearly over 24,000 tons of Brazil nuts to the United States, Germany, the United Kingdom, the Netherlands, Italy, and very soon to China [97]. Bolivian Amazon forests and their associated environmental services where protected by IKS and folk-ways, are contributing to the mitigation of climate change [15,26,27], and they represent a great potential to investigate and leverage significant forest-friendly economies. However, this would only be possible if it were to be part of a new paradigm of development for the country, and one that would need to make the leap from exploitation to something akin with the aforementioned cosmovision of indigenous people from Ciegis et al. [11].



(a)

(b)

Figure 18. Infrared map compositions (Bands 5, 4, and 3) where photosynthetic activity is shown in reds, savannas/cerrados are in opaque green-blue shades, and anthropogenic land use change in light blue patches. Roads are yellow lines, oil concessions are orange blocks, mining camps in light blue blocks. Note that the Yaminahua–Machineri TIOC (**a**) is under direct threat from oil exploitation, and the Takana–Cavineño (TIOC) (**b**) is under partial threat from the same.

Although this is somewhat aspirational, this paper at least points the way to some actionable steps in the right direction, as does previous work and actions drawn from across the world, which suggest that IKS integration into land-use policy and practice is achievable. Our work suggests that Bolivian Amazon TIOCs need full government support to officially recognize all their land. This recommendation is compatible with the work of Blackman et al. (2017), whose findings in the Peruvian Amazon affirm that the recognition of indigenous territories reduced forest clearing by more than 75% and forest disturbances by two-thirds in just two years [22]. Furthermore, a national program to support and reinforce indigenous communities land governance could well be founded and justified simply in the fact that IKS can be a cost-effective approach to ensuring forests' environmental services, and help catalyze local green-economies [24]: for example, and specific to the Bolivian Amazon, there is a need to incentivize and enhance Brazil nut exportation and increase its representation in the national GDP. Examples from elsewhere—for example Huntintong (2000) and McCarter et al. (2014) [155]—have demonstrated the fertile cross-pollination of the highest-technologies and the most authentic folkways to nurture best land-culture relationships, and there could be opportunities for the development of Amazon research facilities and academic centers to promote technology and understanding transfers with IKS. There could also be better integration of forest carbon-based markets such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) to incentivize Bolivian Amazon forest protection and maximize benefits to indigenous community-managed forests. While the main critiques of market-based conservation strategies such as REDD and the Noel Kempff Mercado Climate Action Plan in Bolivia [52] are based on a lack of effective indigenous participation and the commoditization of mother earth (which is why the Bolivian constitution currently does not allow REDD+), the work of Schmitt and Mukungu (2019) in the Democratic Republic of Congo shows that successful project interventions can and should consider free and prior consent, recognition of knowledge and community rights, and the involvement of communities in all steps of the monitoring process [156]. Studies conducted by Schroeder and Gonzáles (2019) based on REDD+ experiences in Colombia and Bolivia, affirm that Traditional Ecological Knowledge (TEK) could be a potential resource to help understand the complexity of the forest systems and enhance ecological and community benefits [157]. In order to avoid short-sighted vision that prioritize economic capital for a few people over collective natural capital (and which can lead to the devastation seen this year), a new national vision, forged by a systems thinking approach, is needed. For instance, the work of Puc-Alcocer et al. (2019) in the Maya area of Mexico, proposed more inclusion of IKS in the making of conservation policies for rainforests points the way [158]. In short, the paper recognizes the need for sea-change shifts away from an extractive economy to a whole-sale leveraging of IKS thinking at the highest-level of government that is already underway in other parts of the world. This is compatible with the idea of Nobre et al. (2016), who proposed:

> " ... a new development paradigm ... () ... in which we research, develop, and scale a high-tech innovation approach that sees the Amazon as a global public good of biological assets that can enable the creation of innovative high-value products, services, and platforms through combining advanced digital, biological and material technologies of the Fourth Industrial Revolution in progress." [159]

Finally, in order to ensure a quality of life, it would be necessary to complement the country's economic metrics of success with Happy Planet, Human Development, and Environmental Impact Indexes, concepts that are already embodied in Amazon indigenous communities who have endured through time, and safeguarded this vision inherited from their ancestors in their IKS or way to see the world.

Reccomendations and Further Research

More research is needed on indigenous-managed TIOCs in the Bolivian Amazon from a holistic perspective, addressing land governance components and the relationship with the biophysical environment. This will add to the knowledge of the benefits of a more symbiotic communion between community and landscape. It was beyond the scope of this paper to offer a précis and forecast of different TIOC situations and circumstances, and how this might correlate with future land-use patterns and change and, in particular, the threat of outside development pressures and the loss of valuable forest cover. We would recommend that estimation of deforestation rates, and geographical modeling projections of the same of TIOCs are conducted at least every five years to incorporate updated drivers, reduce uncertainty in the estimations, and inform stakeholders of damages, risks, and opportunities. Could this date be used to enrich, rather than replace, IKS and folk-wisdom? Could precise spatial resolution satellite maps analysis along with pertinent accuracy assessments help indigenous-managed communities to self-monitor and manage their territories? Further research can reduce uncertainty levels by using finer resolution imagery (<30 m) for the classification and its corresponding accuracy assessment, and increase the number of land cover classes for geographical prediction using neural networks and Markov chain based modelers such as the Land Change Modeler

(LCM) or Markov Modeler, both available on the TerrSet software. Furthermore, whether the selected modeler is GEOMOD or LCM, both assume the continuation of patterns extrapolated from historical data, and will therefore project land use change in a "business as usual" scenario. Future work may address this methodological limitation considering a forecasting approach that accounts for multi-level alternative scenarios, drawn-from regional, ground-truthed, empirical evidence of external events such as the occurrence of deforestation in TIOCs as a function of oil and mining activities, and the sudden expansion of the extractivist agriculture frontier including slash and burn episodes. This will nuance the forecasted range of scenarios for which TIOCs, academia, society, and multilevel government institutions can prepare for, and takes into account matters of resilience (as well as sustainability), and the recovery of these forest systems from major disruptive events, such as the devastating fires we have seen in recent months.

For future TIOC research, we also recommend that the Institutional Analysis and Development Framework (IAD), as proposed by Elinor Ostrom in 2005, is incorporated. The IAD can be used to identify key, nuanced variables that impact the collective governance of common natural resources [160,161]. This will help to better understand the "on-the-ground" factors responsible for subtle differences in forest conservation even between recognized TIOCs, such as the ones of the present study with low deforestation rates, and the also recognized TIOC Chácobo Pacahuara with deforestation rates with even higher deforestation rates than land without any sort of institutional protection.

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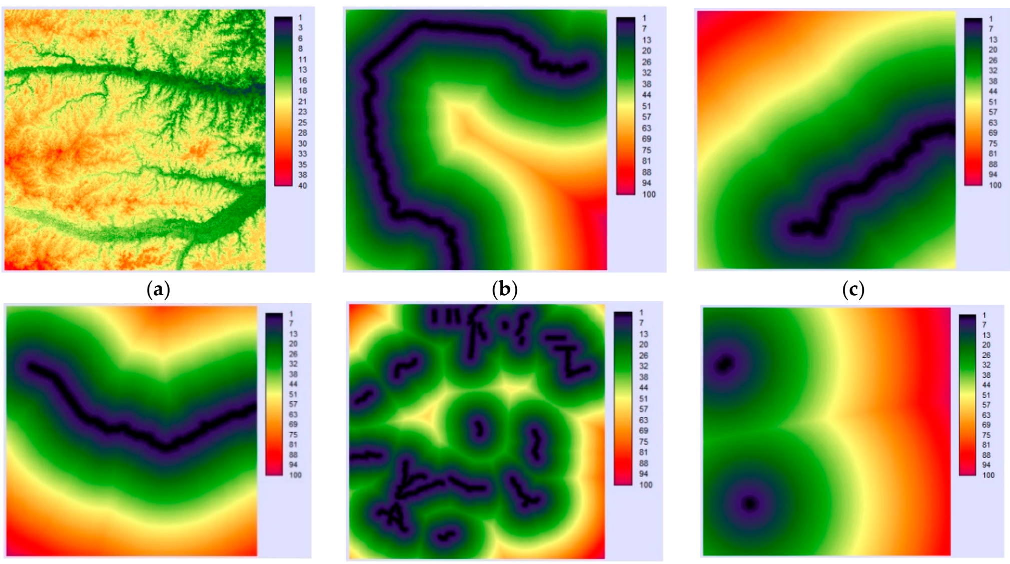
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A



(a) (b) (c) (d) (e) (f)

Figure A1. *Cont.*

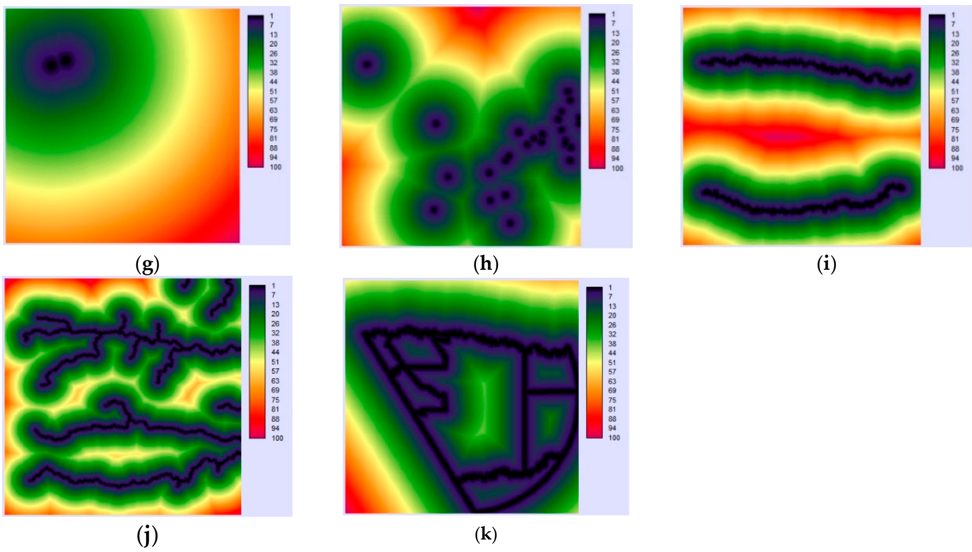


Figure A1. Driver maps used on the calibration process for the GEOMOD projection to year 2030 for the Yaminahua-Machineri TIOC: (**a**) Digital Elevation Map, (**b**) distance to bi-oceanic highway, (**c**) distance to the Corredor Norte highway system, (**d**) distance to fundamental road network, (**e**) distance secondary roads, (**f**) distance to highly populated centers, (**g**) distance to low populated centers, (**h**) Distance to medium populated centers, (**i**) distance to major rivers, (**j**) distance to secondary rivers, and (**k**) distance to administrative limits.

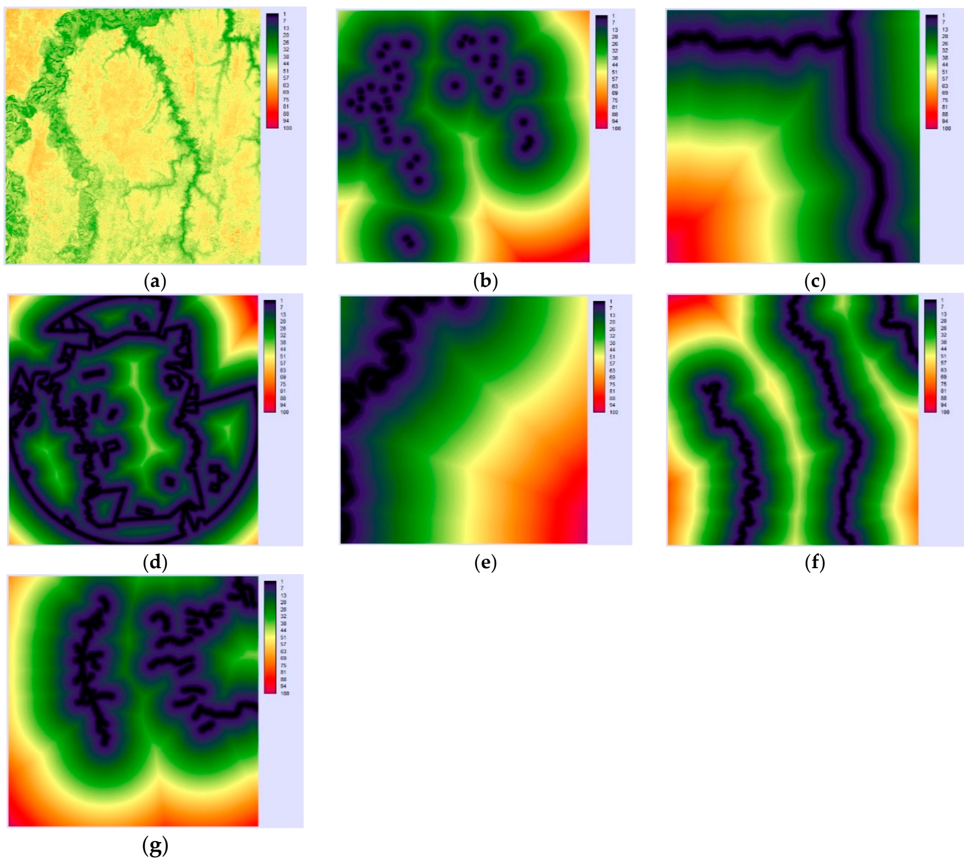


Figure A2. Driver maps used on the calibration process for the GEOMOD projection to year 2030 for the Takana–Cavineño TIOC: (**a**) Digital Elevation Map, (**b**) distance to populated centers, (**c**) distance to the Corredor Norte highway system, (**d**) distance to administrative limits, (**e**) distance to major rivers, (**f**) distance to secondary rivers, and (**g**) distance to secondary road system.

Appendix B

Table A1. ROC (Relative Operating Characteristic) scores based on beginning landuse image for the Suitability Map and strata image combinations for the Yaminahua–Machineri study site.

Beginning Landuse Image for Calibration Process	Strata Image Combinations on Suitability Maps	ROC Value for Reference Image	
		2003	**2018**
2003	Seven individual zones	0.889397	0.852537
	Three zones separated by countries	0.892819	0.863404
	Joint TIOCs and three countries	0.893725	0.861102
	Separated TIOCs and three countries	0.893964	0.861277
2018	Seven individual zones	0.877221	0.867673
	Three zones separated by countries	0.877388	0.870434
	Joint TIOCs and three countries	0.880581	0.871916
	Separated TIOCs and three countries	0.880804	0.874492

Table A2. ROC scores based on beginning landuse image for the Suitability Map and strata image combinations for the Takana–Cavineño study area.

Beginning Landuse Image for Calibration Process	Strata Image Combinations on Suitability Maps	ROC Value for Reference Image	
		1998	**2018**
1998	Six zones	0.857328	0.722349
	Four zones	0.828743	0.718536
2018	Six zones	0.794960	0.887050
	Four zones	0.763244	0.874470

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