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Forty-year multi-scale land cover change and political ecology data reveal a dynamic and regenerative process of forests in Peruvian Indigenous Territories

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ABSTRACT

This article explores deforestation and reforestation dynamics over 415,749 hectares of 25 titled Indigenous Community Lands (ICLs) in the Peruvian Amazon over forty years at three scales: total area, regions, and communities. We focus on ICLs as the territorial unit of analysis, as they are increasingly discussed regarding their importance for conservation. Additionally indigenous communities (ICs) are a too-marginalized group in the Amazon that merit more attention. Analyses of this kind are often short-term and use only large-scale Earth Observation methodologies. We use a multi-method approach linking remote sensing with ground verification, and qualitative historical political ecology work with ICs. We find that overall accumulated deforestation was low at 5%, but that when reforestation is considered, net deforestation was only 3.5%. At the community level deforestation and afforestation dynamics are complex, except for one period that indicates a macro state driver in the region. Results suggest inadequate accounting for forest regeneration in deforestation analyses and challenge the notion that presenting stakeholders with accumulated forest loss values is helpful in tropical areas where forests and people are dynamic. Furthermore, our work with communities highlights that categorizing them and their lands as pro-environment or not in general terms is unhelpful for determining fund flows to ICLs for environmental or development purposes.

1. Introduction

It takes a tropical forest in the Amazon a mere 30 years to regenerate to a standard that is viable habitat for native wildlife, is a major carbon sink, and a major contribution to climate change mitigation. It can additionally provide sustainable livelihoods for local people (Chazdon, 2014). There is much debate about which territorial categories and their respective land managers, such as indigenous community lands (ICLs), protected areas, managed concessions, or restoration initiatives, are the most effective in forest conservation. However the bulk of the research investigating the link between these areas and forest conservation has been done using remotely sensed satellite imagery that compares accumulated deforestation values across categories (Vergara-Asenjo and Potvin, 2014; Shi et al., 2016; Fa et al., 2020).

Furthermore, this approach to quantitative analysis often purports to connect tenure regimes and governance with deforestation yet fails to consider evidence that tropical forests can and do regenerate under the right socio-political conditions (Vergara-Asenjo and Potvin, 2014). Such studies rarely involve visits to the research site for ground verification (Bennett and Sierra, 2014), and even fewer broach in-situ exploration of historical socio-economic dynamics with local people themselves (Fox, 2002; Vuohelainen et al., 2012; Finer et al., 2018). Rather, causal modeling is often employed instead (de Espindola et al., 2012; Ferretti-Gallon et al., 2014). Whilst these studies make a valuable contribution, the lack of engagement at the community level is an information shortfall for science and policy, as it ignores the contours of local realities that influence land-use management and that may explain the fluctuations in forest change observed by satellites over time and space, and their policy implications. Such engagement could help improve the econometric models that try to connect the socio-economic with the

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spatial (Caviglia-Harris and Harris, 2008) and include the voices of often marginalized and important local stakeholders in the generation of data and the interpretation of research results (Bohensky and Maru, 2011; Hill et al., 2020).

Additionally, longitudinal studies on forest dynamics beyond ten years are rare (but see: Arroyo-Mora et al., 2005; Dávalos et al., 2011; Toomey et al., 2013). This dramatically reduces the capacity of science to show the dynamism of forest loss and gain on any type of lands, much less understand at a meaningful level what is happening on the ground to influence the changes seen in satellite images (Davis and Wali, 1994).

Most deforestation analyses are based on *accumulated* loss of *new* deforestation events, which overlook analyses of dynamic natural and human-generated forest regrowth or reforestation metrics (Chazdon, 2014; Cook-Patton et al., 2020). The methodological approach of deforestation science can have profound political implications from local to global scales. This is because how decision-makers understand the dynamics of forests and forest peoples greatly influences their understanding of the problem and thus how successfully (or not) they confront environmental challenges (Espinosa Llanos and Feather, 2011; Ravikumar et al., 2017).

For example, Peru's Ministry of the Environment (MINAM) used data referring to the *frequency* (rather than area) of small deforestation events (CDI/INDUFOR, 2012) to determine that "90% of the logging and burning of Peru's Amazon forests occurs at the hands of peasants living in poverty who practice subsistence agriculture" (MINAM, 2014) (translation by (Ravikumar et al., 2017). Yet, MINAM put ICLs as the land category with the highest *rate (area)* of deforestation. Later, a collaborative effort between MINAM, The Ministry of Agriculture and Irrigation (MINAGRI), and the Observation Centre- Amazon Cooperation Treaty Organization (SdO–OTCA) developed a methodology to analyze satellite images and standardize data on the Amazon forests at the national level. Through this methodology they concluded that ICLs were the land tenure category with the second-highest *accumulated* deforestation during the study period 2000–2011 (MINAM, MINAGRI, 2014). This concurs with findings of Celis-Llanos *et al.* (2019) in their investigation on the same topic between 2001 and 2016 (2021). Conversely, some researchers that found that Peruvian indigenous lands tend to prevent forest loss as much as or more than protected areas did not use accumulated values (Blackman et al., 2017). Thus, there is a seeming contradiction in the human categories ranked as deforesters because of differential and sometimes rather unhelpful evaluation metrics.

We recognize that 'Net deforestation' is a contested scientific metric for measuring deforestation as it does not account for forest quality. Additionally the provision of "net" deforestation statistics to political and private spheres such as businesses in forest-related supply chains, BINGOS (Lambin et al., 2018), and large political summits involving diverse decision makers can be problematic for reasons we discuss in section 3. However, it is increasingly the metric these actors prefer to use. For instance Norway has provided millions of dollars to its commitment to support Peru's net zero deforestation pledge, implemented in collaboration with global and regional NGOs such as the World Wide Fund for Nature (WWF) and indigenous federations (Humphreys et al., 2016; King et al., 2016). Nevertheless, this controversy does not invalidate the importance of recognizing how forests can and do regenerate on human-managed landscapes.

We chose to apply our methodological approach to ICLs in Peru for this study. We have done so for four main reasons. First, there has been a flurry of research investigating the relationship between ICs, ICLs, land tenure and avoided deforestation in Latin America (Ricketts et al., 2010; Vergara-Asenjo and Potvin, 2014; Finer, 2021). Second, there is increasing socio-political and academic interest in the theme of the territorial category of ICLs related to conservation. Third, it is important to highlight how a methodological approach that excludes forest regeneration, may result in placing unmerited 'culpability' on a marginalized and historically brutalized group of people that have the right to manage their land as they wish. Fourth, research suggests that approximately 80 percent of the world's biodiversity inhabits the lands of 370 million indigenous peoples (<five percent of the global human population) that occupy 25–33 percent of the world's land surface (AMPB et al., 2015; Garnett et al., 2018), making it a particularly interesting human-managed Territorial Category to analyze with relation to the environment.

It is already well known that there are no one-size fits all outcomes for any territorial category, including ICLs (Blackman and Veit, 2018). For example, Blackman and Veit (2018) analyse what they call *pathways* between internal governance (within ICs), and external governance (outside ICLs including conservation and development initiatives and the state). They explain that under proper conditions and incentives, local communities have the capacity to sustainably manage forests, but that they may also favor agriculture, forest extraction activities or other environmentally degradational practices for their own valid reasons. Furthermore, external interactions alter livelihood strategies, including forest management, land use and indigenous cosmovisions. We highlight Blackman and Veit́s paper as a segue into our historical political ecology research in our study sites on the nuances and endogeneity of IC land-use decision making. This is a heuristic that can be used for any territorial category or land user. For example, the increasing exposure of some ICs to external processes has profound implications for land management options and decision making. The state supports many programs that influence this such as infrastructure expansion, natural resource extraction and development or conservation programs and the consessioning of land to private companies and new kinds of settlers such as Mennonite colonies (Hecht and Cockburn, 2010; Mongabay, 2020). This often results in overlapping land rights and related conflicts.

A mixed methods approach is essential to the measurement of forest dynamics. Specifically, it provides a more accurate understanding of fluctuations and thus better grounds for appropriately targeted policy or project solutions. Although the emphasis of policy questions has been on whether ICLs are reliable as a pro-environment[1] land category in the global effort to halt deforestation and forest degradation, a more meaningful angle is to understand that a disposition to conserve or not, is not static in space, time or culture. Indeed, we show that deforestation and reforestation events at different points in time demonstrate a plasticity and dynamism that is visible from space, but understandable only by including other methods, such as engagement with communities.

This paper reports findings from the CIFOR-UNALM research project *Securing Tenure Rights for Forest-Dependent Communities: a global comparative study of design and implementation of tenure reform*. It asks the following questions:

1. How much net deforestation has taken place on the studieś ICLs since 1970?
2. Why is ground verification and engagement with local people critical for studies that use Large-Scale Earth Observation methodologies to monitor deforestation?
3. What are the implications of net, rather than accumulated, values of deforestation for the Global agenda for examining which territorial categories, including ICLs, may benefit most from green funding?

The paper addresses these questions by:

[1] In this paper pro-environment or pro-forest refers to a land category or land management approach that facilitates more nature to survive and even thrive than one that does not. As the paper describes, there are categories such as gold mining concessions that clearly have very negative and often irreversible impacts on nature and the environment and would by this definition be classified as the opposite of pro-environment, pro-nature or pro-forest.

a) Quantifying deforestation and reforestation in the ICLs of Madre de Dios at 5-year intervals between 1975 and 2016 overall, by time period and by community, using remote sensing.
b) Verifying remote sensing results with field and random verification.
c) Qualitatively investigating the historical political ecologies of case study communities to explore connections between forest loss and gain and socio-political factors within and outside ICLs.

2. Study area and case study Sites:

2.1. Indigenous land and governance in Peru

Over the past half-century, more than 1,300 ICs in the Peruvian Amazon have obtained title to more than 12 million hectares of land—about 17% of the country's forest area. The allocations have come through a sequence of regulatory reforms that have resulted in both progress and obstacles for indigenous communities (Gebara, 2018; Monterroso and Larson, 2018). Progress has been possible due to various reforms that recognized indigenous rights to collective lands, however implementation continues in a context that is conflictive, complex and slow, such that many ICs are waiting for formalization of their claim to territories. This is partly due to the enormity of the job for regional government offices to traverse these large expansive lands and negotiate allocating title where there are often overlapping land rights or other territorial conflicts. It is also because of state relations with indigenous and rural peoples (Biffi, 2021), where titling can often be arbitrary, affected by previous relations between the state office or individuals within it and the communities, rent seeking behaviors and land trafficking interests (ibid). There were 2268 recognized native communities in January 2020, but only 887 titled and registered in public records – thus 1381 (61%) recognized ICs remained without legal title (SPDA, 2019).

Aside from state governance and its land allocation methodology, there is a strong formal indigenous governance system in Peru. Thus, the context of the relationship between the state and indigenous people in Peru, and the indigenous movement is politically complex and rapidly evolving (Biffi, 2021). Peru has seven main formal indigenous federations, of which The Interethnic Association for the Development of the Peruvian Rainforest (AIDESEP), and itś regional factions are the most powerful. The federations are actively involved in the titling process from the level of negotiations with donors, central government, regional government and in communities. They have been important in driving the process and assuring some level of coordination across multiple sectors. However, after paying high administrative costs at the national level, and allegedly losing money through corruption both on the part of the State, and that of federations, benefits from funds often reach only a few communities.

2.2. Madre de Dios and indigenous community case studies

The Madre de Dios region is one of four Peruvian departments making up the Peruvian portion of the Amazon (Fig. 1). It represents 6.6% of the national territory and hosts 12% of the countrýs forests (of which 60% are in protected areas). 3.2% of the population are indigenous peoples, occupying 34 recognized ICLs which cover approximately five percent of Madre de Dios (Sanchez Espinoza, 2015; INEI, 2018).

The climate is warm, humid and with abundant rainfall except for June to August. Temperatures range between 38 °C and 8 °C. Water systems comprised of a set of rivers and streams that cross the department from west to east provide food and transport for local people. The predominant classification of vegetation in Madre de Dios is that of tropical humid forest, which covers almost all the provinces of Tambopata and Manu. There is however some differentiation in biophysical characteristics across the department. For example, to the north there is a lower elevation, which is even lower to the east, and it is hotter. Whereas to the south the region elevates into the mountainous area towards Cusco, there is more frequent change in the weather and precipitation is higher. Meanwhile to the east there are stronger wind speeds. The supplementary materials (SM3) show maps of these characteristics (created by Zachary Posnik for this study), and although they

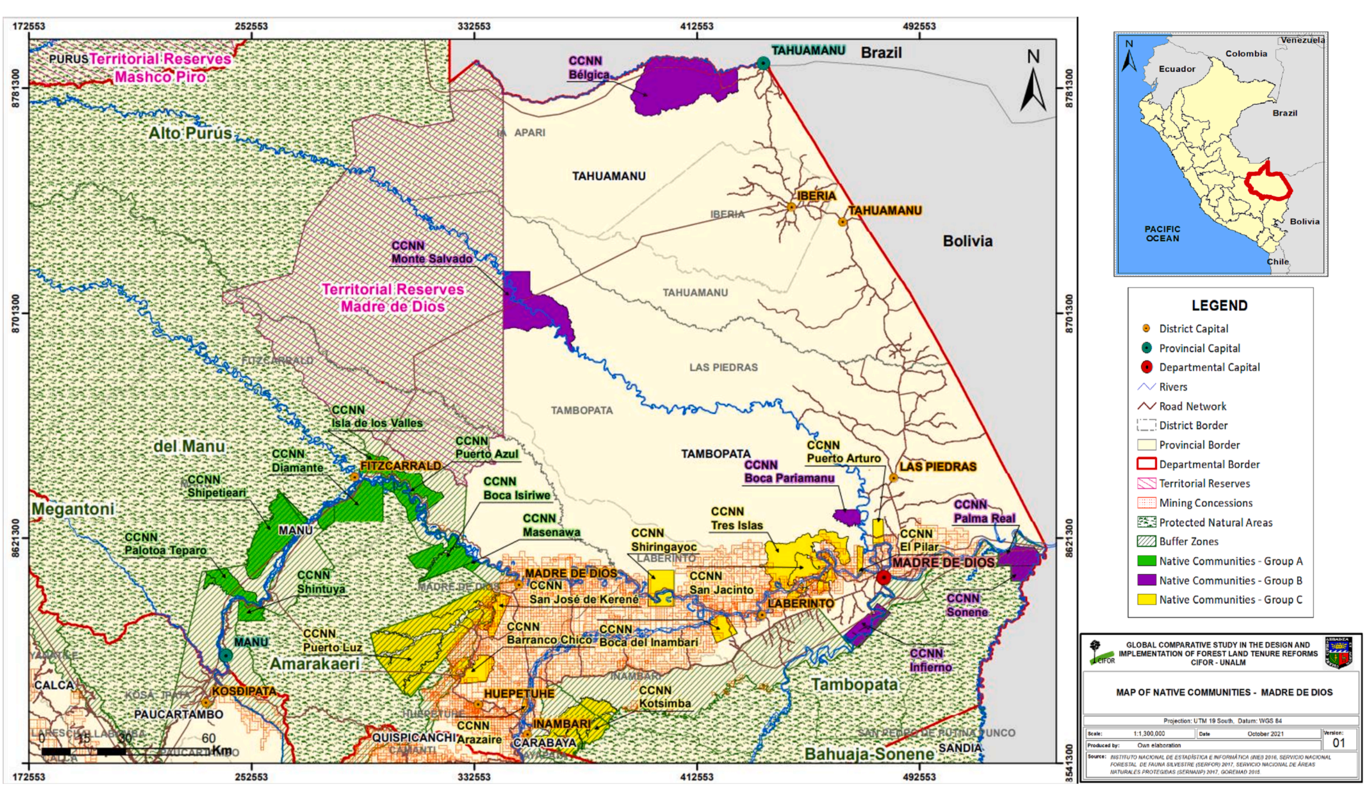

Fig. 1. Map of indigenous communities in madre de dios in groups (colour).

are not the focus of this study, they are an important component to consider in deforestation and reforestation discussions because not all forest change is due to anthropogenic activity. This is another reason why field visits are such a critical component for understanding deforestation events.

This paper is focused within the confines of the ICLs and on ICs, but the department it is a vibrant, diverse and fascinating place full of many different actors, activities, interests and human and non-human life aside from ICs. The *peri*-urban and rural landscape is a mosaic of ICs, protected areas, ribereño villages, road-side mestizo villages, smallholder agricultural farms, large agricultural plantations and timber and mining concessions. It has abandoned lands, young and old second-growth forests, and expanses of mature forest. Space constraints limit further descriptions of dwellers neighboring the communities, who are mainly discussed with relation to our internal and external pathways theoretical framing.

To date deforestation on ICLs in Madre de Dios has been relatively low, nevertheless, deforestation – including in its ICLs - is on the rise. For example, MINAM showed that an average of 5% of forest cover was lost per year from 2000 to 2014 (MINAM, 2020), with losses in the second half of that time almost twice the losses in the first half (82,118 ha and 45,600 ha, respectively). In 2017 and 2019, the region lost more than 20,000 and 21,378 ha of old growth forest, respectively (Rodriguez-Ward, Larson and Ruesta, 2018; MINAM, 2020). Drivers of forest loss change rapidly and extremely depending on markets ranging from legal and illegal timber and gold to ecotourism (which, for example disappeared during COVID-19), as well as offers of incentive-based conservation or development projects. Socio-political change also has a significant impact on forest loss and gain. At the micro level this could be the change of an Apu (chief), disputes or alliances within or between communities and migration and other issues. At the macro level activities such as national structural political change, shifting laws that incentivize or sanction forest exploitation and land rights and state presence (or lack thereof) are examples of such impacts. Finally, the building of roads, or the change of course of rivers or natural fires impact how humans interact with their lands and resources (Susanna B. Hecht and Alexander Cockburn, 2010; Chirif et al., 2019).

It is estimated that gold mining activities account for almost 96,000 ha of deforestation in the region since the mid 1980′s, approximately 41,000 of which has occurred between 2013 and 2018 (RAISG, 2018). Taken together these numbers show unprecedented rapid increase in deforestation.Much of these deforestation activities - and the social conflicts that are rooted in skirmish over the rights to land and to extract above and below ground natural "resources" such as timber, oil and gold - take place in and around ICLs (Acuña Villavicencio, 2019; Nicolau et al., 2019).

In an effort to protect the region's biodiversity rich ecosystems, the government has created six national protected areas, covering 44% (3,762,942 has) of the region. It is also promoting its eco-economy, for example through ecotourism (MINETCUR, 2019).

There is much socio-ecological and political-historical heterogeneity amongst ICs. There are large differences in size, a wide range of linguistic families (and hence cultures), different types and levels of exposure to development interventions, and diverse affects from environmental changes, such as shifting river trajectories, floods, fires and droughts. Nevertheless, to facilitate the organisation of the results, we have divided the communities into groups:

Group A are communities from the more remote *alto* Madre de Dios area. In this group there are eight communities, which are located on the banks of the upper part of the Madre de Dios River. These are difficult to access from the closest city, Puerto Maldonado. They are also surrounded by reserve areas such as the Manu National Park, the Amarakaeri Communal Reserve, the ACCA Conservation Concession and the Madre de Dios Territorial Reserve.

Group B are six communities from Tambopata and Tahuamanu. This group is located on the east side of the department of Madre de Dios, outside of the mining corridor. In general, they are relatively isolated, and access to the nearest cities is an effort (except for the community of Infierno, which improved its access road, discussed later.

Group C (eleven communities) comprise communities close to and/or overlapping the mining corridor (Fig. 2). All communities in this group (except Puerto Arturo) have legal mining concessions on their territories.

3. Methods and results

3.1. Methods

Our study spans over 415,749 ha of land and includes 25 of the 33 ICLs that are recognized, registered in the government land registry and have georeferenced polygons.

We used quantitative and qualitative approaches, which we describe next.

3.2. Remote sensing and ground verification

The remote sensing (RS) analysis is based on the official 2016 polygons of formally titled ICLs created by the Regional Directorate of Agriculture (office of physical and legal sanitation of rural property) of Madre de Dios (DRAM). Available Landsat images were analysed at five-year intervals from 1975 to 2016, and five images were downloaded per year. Each mosaic image was classified into the following categories: hydrography, forest no forest (deforested/forest loss areas). Natural reforestation/regeneration is identified where forest cover is found in classification years subsequent to the no-forest classification, tree plantations were excluded.

Ground verification was undertaken in four ICLs at the end of 2016. We were able to verify 160 of 178 of the intended points. Ground verification was done using visual inspection, in which a local field guide helped our ecologist to confirm topographical features such as agricultural plots, recent or old secondary forest, old growth forest, flood forests and species often not picked up by RS such as *pacal* (a type of fibrous bamboo), which could be confused as deforestation or no forest areas in RS if not ground verified. Additionally, the field guide provided information about the ecological status of the few points we were unable to reach.

In addition to the field points taken in the four ICs described above, a shapefile was built with 200 random points distributed within the 25 Native Communities in the study. These points were visually interpreted from the Sentinel satellite image and Google Earth. The field data together with random data were used to evaluate the accuracy[2] of the map classifications, through quantitative evaluation metrics: the confusion matrix, the kappa index (KI), and the percentage correctly classified (PCC).

Further details on RS and validation analysis are provided in the Supplementary Material.

3.3. Historical political ecology

Our Political Ecology research is primarily based on our parallel work in the same communities in CIFOR's Global Comparative Study on Tenure Reform (GCS Tenure 2014–2018) (Cruz Burga et al 2017). Flexibility was central to the study's iterative and multi-method approach. For example, this included combining the knowledge of local people with that of technical experts and decisions to help them envision scenarios based on their own context, in-person. This took place within ICLs, or a location of their choice, adjusting as needed and forging critical links with local partners. The main methodology was four key person interviews, 25 household interviews and one workshop in each community. Gender balance was controlled for in all activities. Through this methodology, socio-economic, demographic, and – more importantly – perspectives and historical information was collected. The

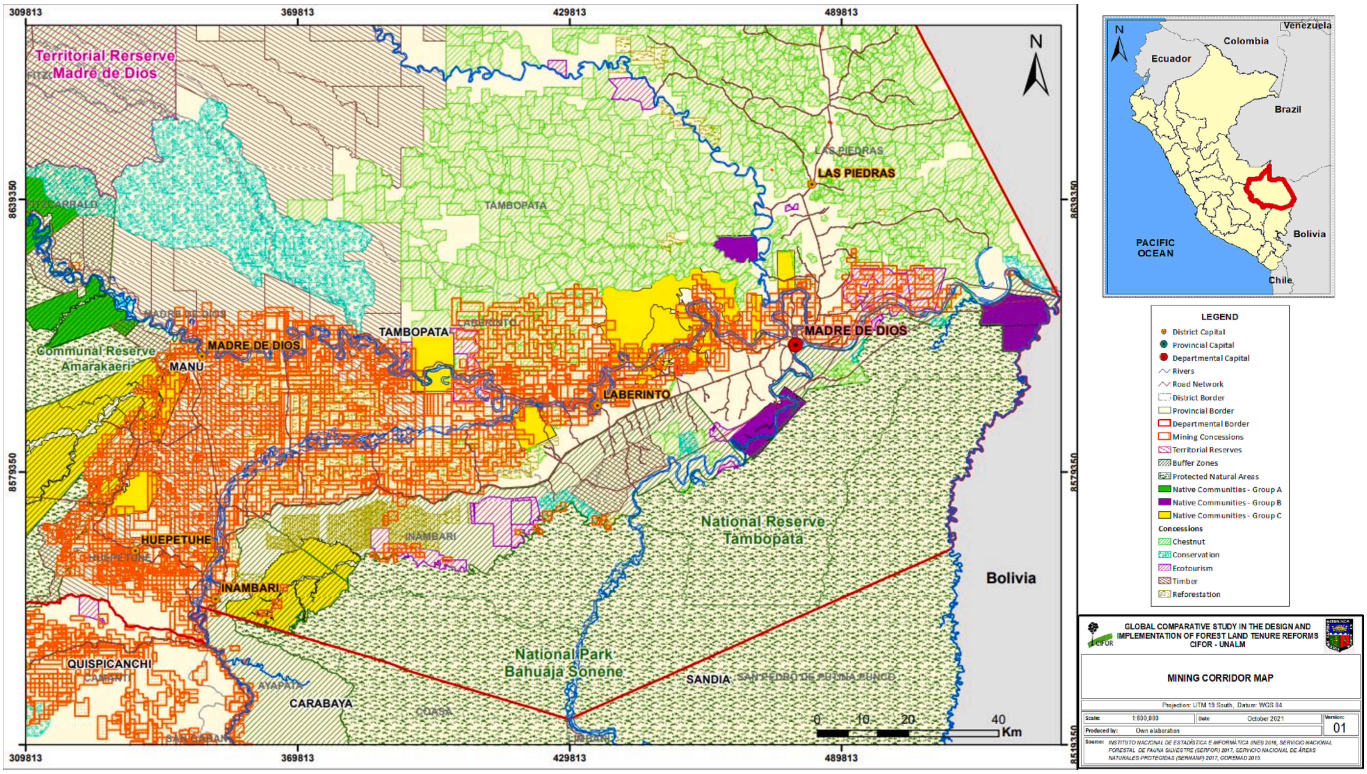

Fig. 2. Map of mining corridor (colour).

team undertook ten social studies in the 25 communities analyzed in this paper (Supplementary materials SM1).

3.4. Results

3.4.1. Validation results

Overall, our classification maps are highly accurate (Table 1). The kappa index indicators are 0.88, an almost perfect concordance force. The percentage correctly classified (PCC) has a highly precise: 0.94. The confusion matrix corresponding to the classification of deforestation analysis in the ICLs an indicator of overall map precision also calculated a high value of 0.94. Separating the validation accuracy[2] scores between the random and field data, the accuracy remains high for both. Although the overall precision of both random and field verification is high, a hydrography score of 100 is expected, and since hydrography represents 1/3 of our classification, this inevitably increases the overall accuracy.

Comparing the matrices (Table 2), the field validation scores for forest/no forest are 88.2 and 96.3 respectively, whilst the random (remote) validations for the same categories are 98.3 and 56.3 respectively. This suggests that the remote algorithm for random verification is stronger in identifying forest, but weaker in identifying non-forest. Since so few studies make it to the field to grounds test their RS analyses, this discrepancy of accuracy has important implications for our methodological contribution, discussed in section 4.

Table 1
Validation indicators.

	IK (%)	PCC (%)	Overall precision of the classification maps
Overall	0.88	0.94	0.94
Random points	0.71	0.95	0.95
Field points	0.86	0.94	0.94

Where: IK = Kappa Index, PCC = Correctly Classified Percentage.

3.4.2. Disaggregating long-term dynamic deforestation rates

3.4.2.1. Overall deforestation and reforestation results. Results showed a very low annual and accumulated deforestation but a steady increase in forest loss overall from 539 ha in 1975 to 7,460 in 2016 and an accumulated overall deforestation of almost 22,000 ha, or 5% of the total land area analysed (Fig. 3).

However, when the forest regeneration values were added to the accumulated values to decipher a *net* deforestation, there was a marked change in the forest-loss areas. Net deforestation per year dramatically reduced deforestation totals even in the year of 2016, the highest deforestation year recorded, where the total decreased by more than 2000 ha. In other years, for example 2006, the area reduced from almost 800 ha gross to only 12 ha net. Meanwhile, the overall accumulated net deforestation reduces from 20,000 ha (5%) to just below 15,000, or 3.5% of the total land area (Fig. 4).

3.4.2.2. Deforestation and reforestation rates according to group and community. In the previous section, we saw some overall numbers for a large area of land under the governance of 25 very dispersed dynamic communities pertaining to various tribes and ethnicities. These communities are different from each other in many ways. Thus, overall deforestation and reforestation numbers serve only to highlight the variance in results according to analysis strategy (accumulated versus net deforestation). However, it tells us little about where the main deforestation is happening and why. We next narrow the focus to look at the land cover change at the group and community levels.

Group C – the group near to and overlapping the mining corridor – is

[2] 'Accuracy' is defined as the agreement between the real value and the result of the observations or estimates of a characteristic on the map, *and* the level of agreement between repeated measurements of the same characteristic. It is represented as a narrow grouping of results from the sampling points. Accuracy is inversely proportional to error.

Table 2
Confusion matrix comparison of random and field verifications.

	Forest	No Forest	Hydrography	Total	Precision (%)	E. Omission
A: Confusion Matrix random points						
Forest	177	0	3	180	98.3	1.7
No Forest	6	9	1	16	56.3	43.8
Hydrography	0	0	4	4	100	0
Total	183	9	8	200	**Overall map precision**	**0.95**
Precision	96.7	100	50			
E. Omission	3.3	0.0	50.0			
B: Confusion matrix field verification						
Forest	45	6	0	51	88.2	11.8
No Forest	4	104	0	108	96.3	3.7
Hydrography	0	0	1	1	100	0
Total	49	110	1	160	**Overall map precision**	**0.94**
Precision	91.8	94.5	100			
E. Omission	8.2	5.5	0.0			

Group	Community	Language family	Area (hectares) Year title	Connectivity	Population People/ families	Interviews	External intervention level
A	Shintuya	Harakmbut	5670 has 1979	Two hours by road to the city of Salvación, (capital of Manu district)	206/48	key informants = 3 workshops = 21 people Surveys = 29 households	Medium
B	Infierno	Tacano	11,896 has 2013	Less than one hour to the city of Puerto Maldonado	2345/87	key informants = 4 workshops = 22 people Surveys = 25 households	High
C	Tres Islas	Shipibo Conibo and Ese'Eja	31, 423,71 1994	Less than one hour to the city of Puerto Maldonado	223/103	Key informants = 5 Workshops = 17 people Surveys = 25 households	Low

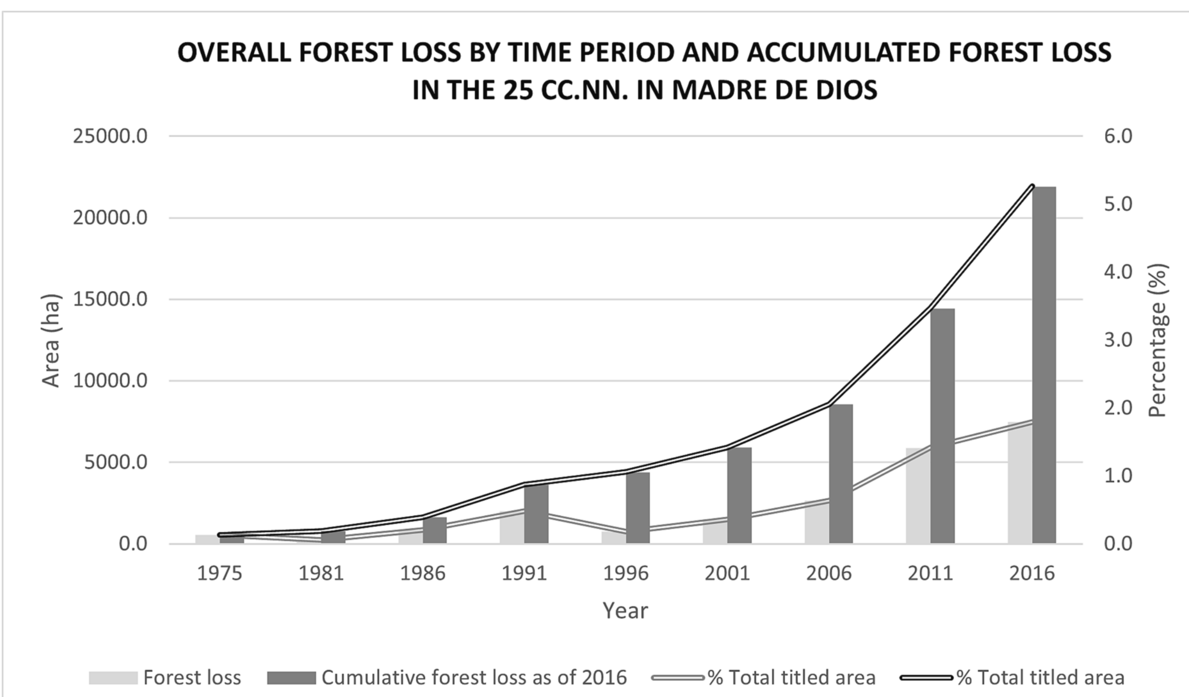

Fig. 3. Overall forest loss by year and accumulated in the 25 indigenous communitites in madre de dios.

consistently the highest net deforesting group throughout the entire period studied, with a steep increase in deforestation between 2006 and 2011, and again in 2011–2016 (Fig. 5). The second highest (but comparatively much lower) deforesting group is group B. However, unlike group C, the dynamics of group B do not increase incrementally in steep jumps in time periods. Rather it fluctuates between small losses and small increases. This type of differential pattern is an important part of this analysis as it highlights different use and management. Indeed, management is itself related to the variation of conditions the communities live and act within, for example community-specific combinations of historical political ecology, location, size, biophysical landscape and state governance and the community relation to it, as we discussed previously.

Finally, group A – the most remote – has both the lowest overall and periodic deforestation; furthermore, it is the only group to have four periods of net *gain* (1996, 2006, 2011 and 2016). Including

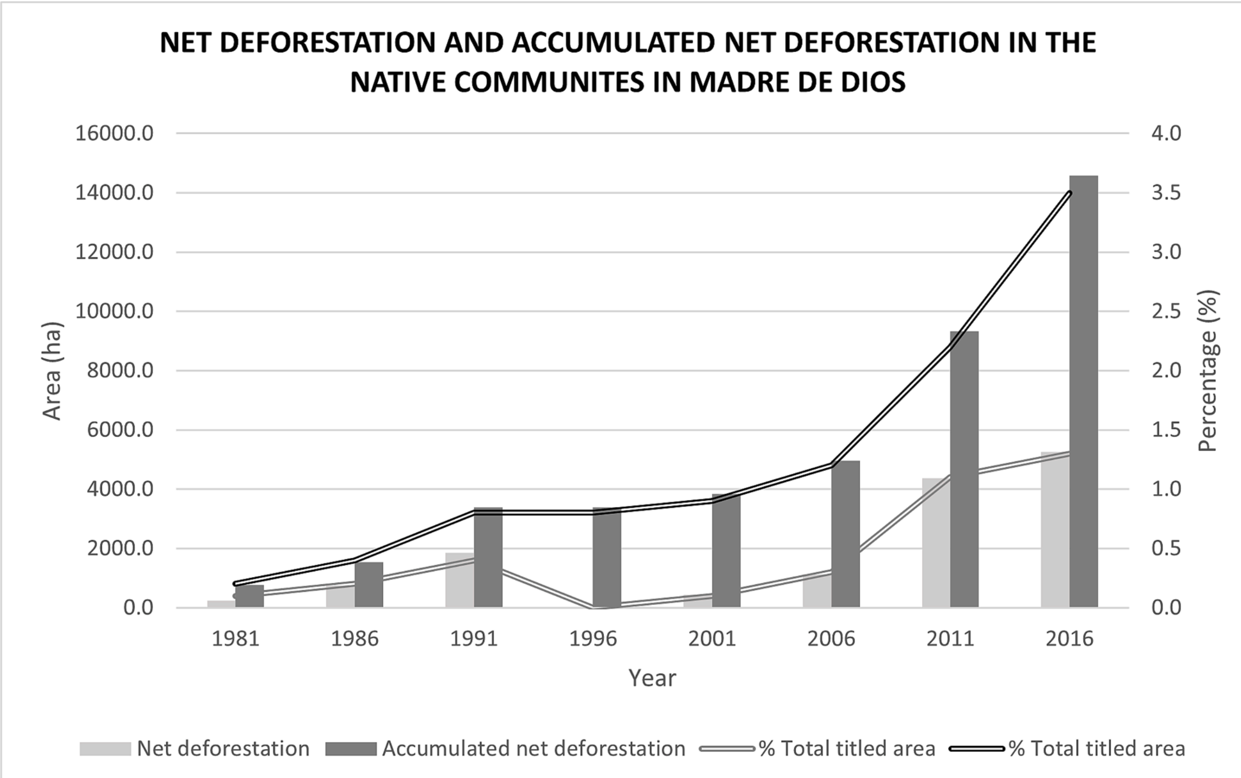

Fig. 4. Net deforestation by year and accumulated in the native communities of madre de dios.

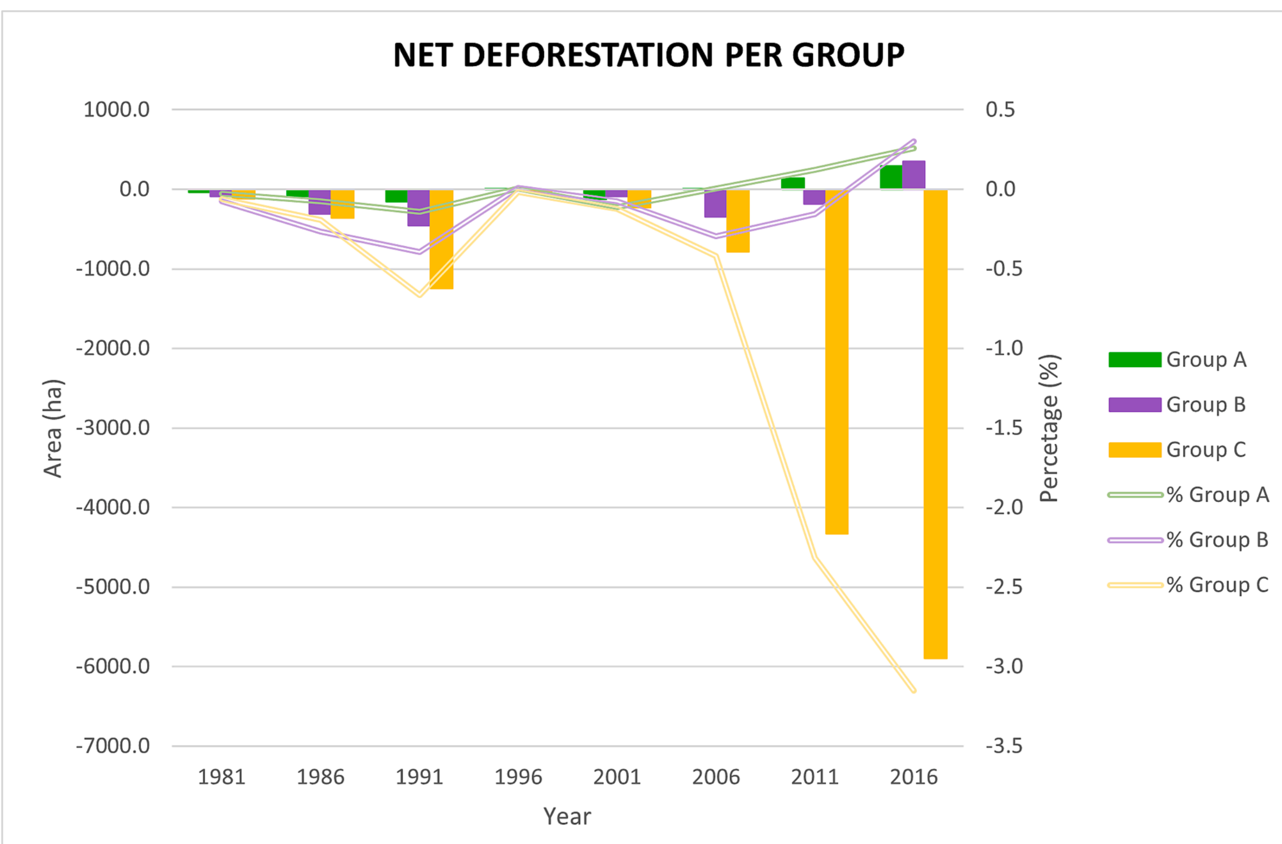

Fig. 5. Net Deforestation Per Group.

regeneration, group A maintained 99% of its forest lands over time. We have also indicated the *percentage* of area lost, which is important due to the discrepancy in size of groups and communities. For example, group C has eleven of the 25 communities and hosts 45% of the total land area of the study, therefore describing their loss and gain metrics in area and percentage provides for a fairer picture.

All groups deforested the least (almost nothing) between 1991 and 1996. In fact, during this period both group A and group B had a small net increase in forest cover, which happened again between 2011 and 2016.

Further heterogeneity in the loss and gain dynamics is evident within the groups (Fig. 6). For example, whilst the individual ICLs in group A are generally much smaller than those of group C, relative percentage can vary. For example, San José de Karene (Group C) accumulated a lot more hectares of deforestation when compared with other communities, yet the relative percentage area of deforestation is less. Nevertheless, Group C and its composite communities are the forerunners in deforestation whatever way it is analysed. Fig. 7 shows what accumulated deforestation looks like (red), versus accumulated deforestation and reforestation (red and green). The reduction of overall on the ICL is stark and shows the importance of this approach in scientific deforestation reporting.

Fig. 8 shows how much of each ICL was deforested in 5-year time periods. It also indicates how much reforestation has occurred in ICLs during the same period. The figure shows the highly dynamic and unique nature of the deforestation and reforestation history of each ICL. This graph series highlights heterogeneity between communities and the changes in forest cover at different points in time within them. It also shows the outcomes of different methodological approaches for looking at deforestation. Finally, we brought loss and gain matrices together to offer a net value. The patterns are dramatic. For example, in the case of IC Shintuya (group A), there are two peaks and troughs in their forest cover, including a 100-hectare deforestation peak (1% of their lands). Nevertheless, the regeneration graphs concurrently show exponential reforestation on an ongoing basis from 1986, resulting in several periods of net forest gain. The ICLs with the greatest deforestation in Group B are Infierno and Bélgica, though both also have high rates of regeneration so that by the end of the study both were close to zero net. Thus, ICs show differentiated deforestation levels in different years: for example, IC Kotzimba (group C) gained almost 50 ha in 2006, to later deforest 1500 ha in 2016 alone.

There are some patterns - such as the marked change from overall loss to net gain in 2006 and 2016 - that may indicate a more macro driver of change such as new policy or development scenarios.

3.4.3. *Linkages to the historical political ecology*

3.4.3.1. Macro-level observations: Political change. At the macro level there was a steep drop in deforestation and an increase in regeneration in almost all communities during the period 1991–1996. This observation warrants a short (albeit hypothetical) discussion, as it serves as a potential example of macro external pathways impacting forest management in ICLs.

The early nineties saw the end of high economic instability in Peru, as well as the quashing of a long-term terrorist campaign that had shaken the country. The communities do not mention this era in their historical timelines according the CIFOR reports, so we looked at different socio-economic dynamics that might suggest possible reasons for the decline in deforestation, This included the commerce of gold, new international collaborations, and new environmental regulations, for example.

Gold prices were stable during this time and as such metal market dynamics are an unlikely explanation for the decline in deforestation. However, in the early nineties the Peruvian government generated other sectoral regulatory changes to recover the economically and socially stricken country that may at least partially explain this steep drop in deforestation. For example, The Environment and Natural Resources Code (Legislative Decree No. 613) was published in 1990, introducing

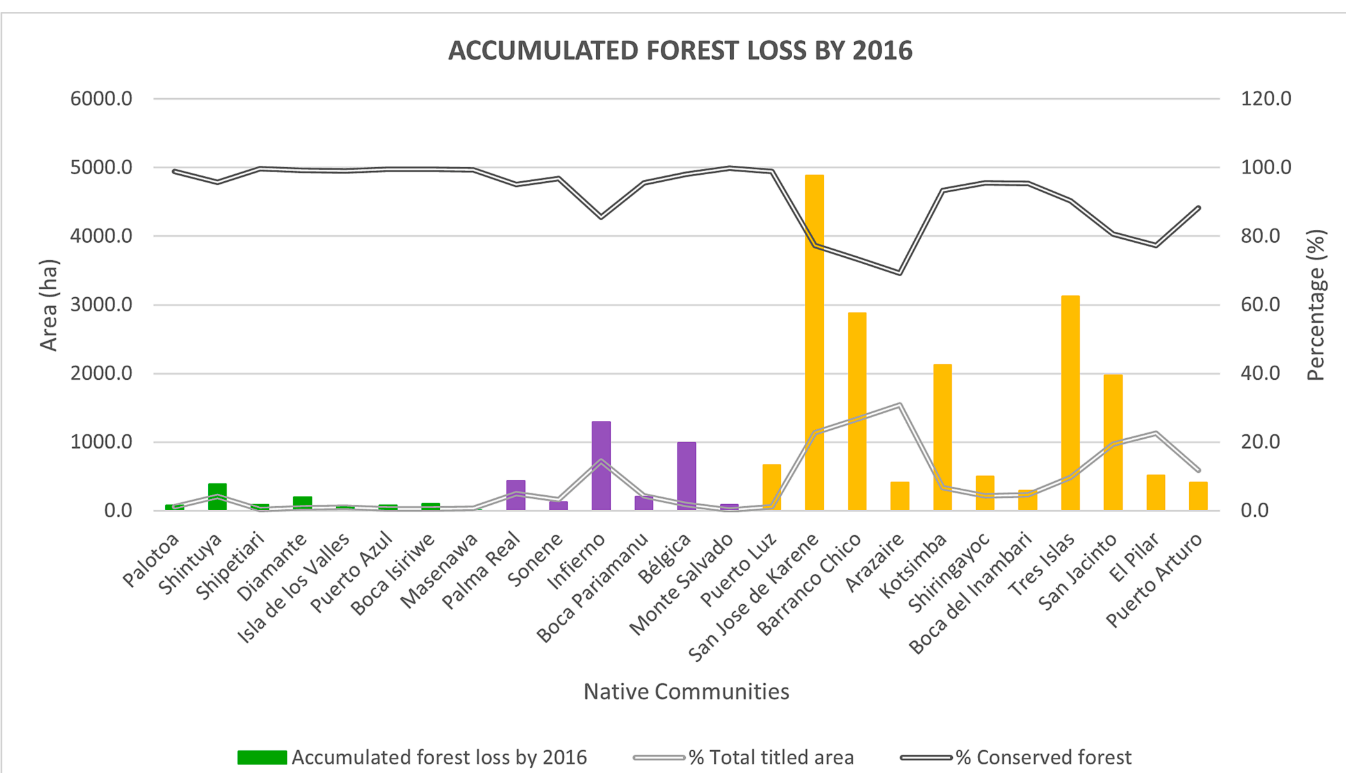

Fig. 6. Accumulated forest loss per community by 2016.

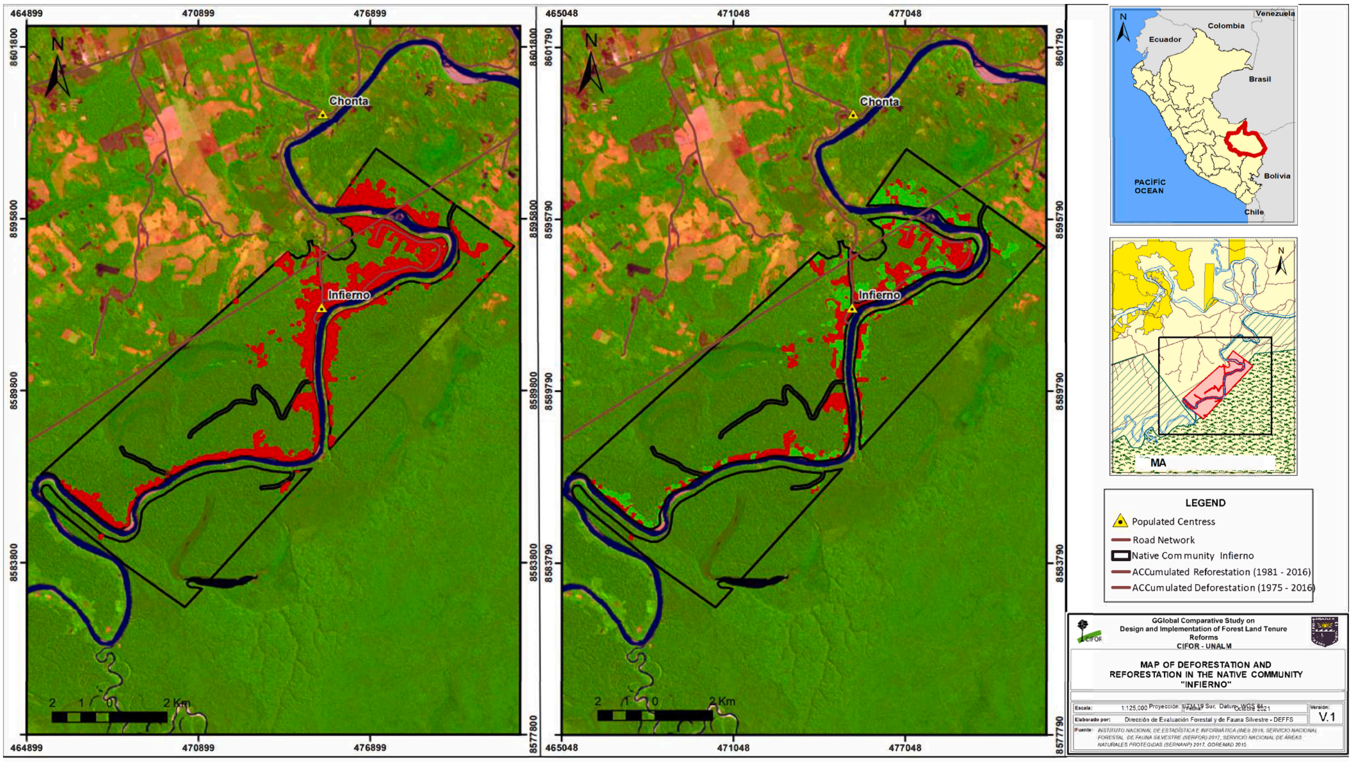

Fig. 7. Comparison of accumulated deforestation and net deforestation in native community infierno.

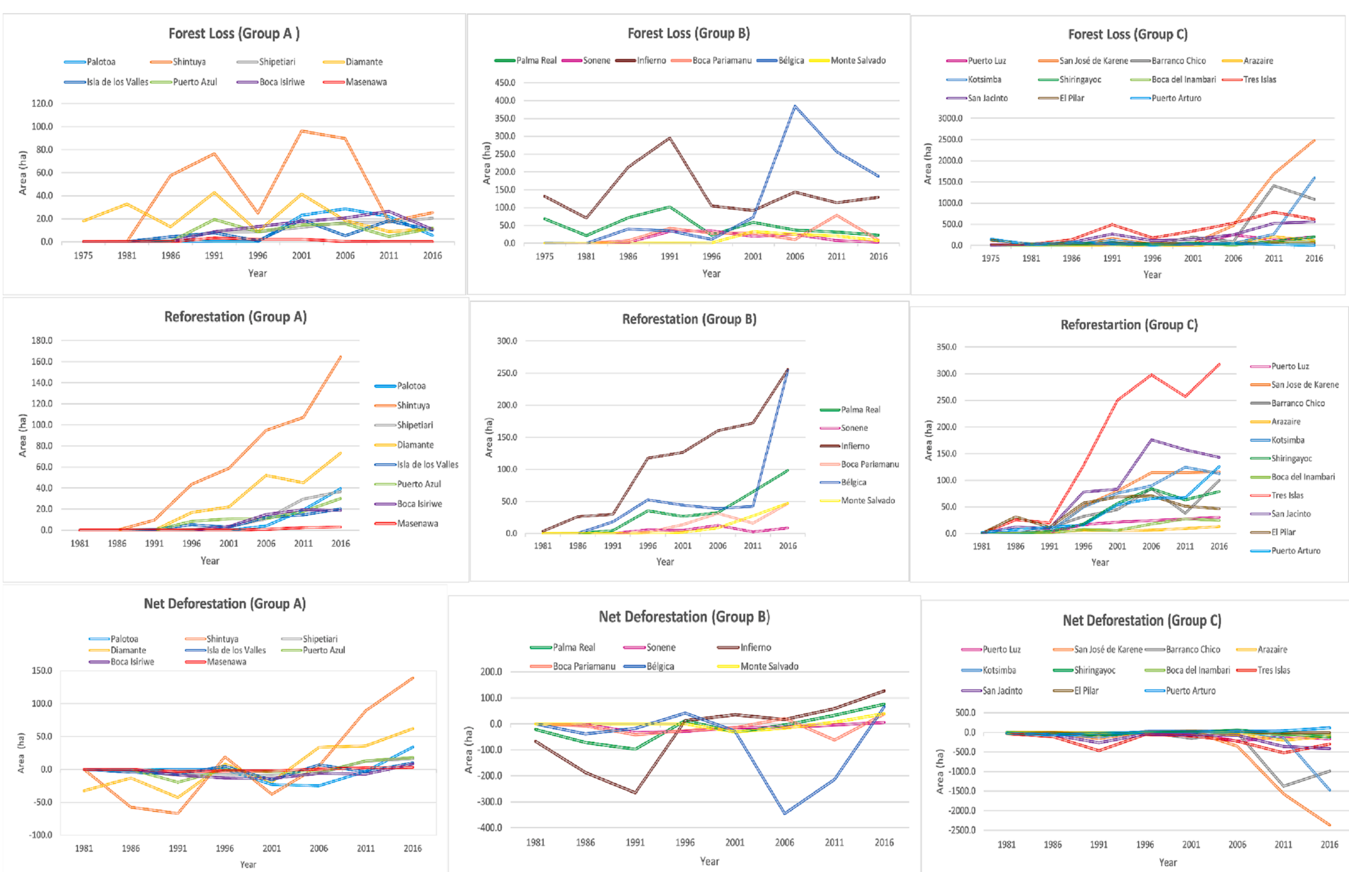

Fig. 8. Figure series community level forest loss, reforestation and net deforestation.

new environmental principles and management tools (Buntaine, Hamilton and Millones, 2015). Additionally, the National Institute of Natural Resources (INRENA) was created, which provided a more active government presence in environmental policy, monitoring and sanctioning. The granting of contracts for forest extraction in National Forests was suspended (Supreme Decree No. 051-92-AG). This, together with a new decree that forest extraction contracts in concessions would only be granted for one year may have made timber extraction less attractive.

In 1994 a new intersectoral coordination process of agreement on policies, standards, deadlines and goals with a view to promoting sustainable development was created (CONAM), and 1995 a trust fund was created to channel financial resources for the National System of Natural Areas Protected by the State (SINANPE). This increased the presence of the state to control activities carried out in the buffer zones of protected areas, which includes some of the ICLs in this study.

However, in April 1995 the ban on contracts for forest extraction in National Forests and Free Availability Forests as well as those in ICLs was lifted. This heralded the end of the period of macro-level forest loss drop (1991–1996), and deforestation increases once again in the region (Fig. 3).

3.4.3.2. Micro (community)-level observations: External and internal governance and pathways through quality-of-life plans. To explore the socio-ecological dynamics at the community level, we selected one community from each group that has interesting deforestation and regeneration patterns. We demonstrate socio-political heterogeneity and explore links between territorial organization and land use with reference to internal/external governance and pathways (Blackman and Veit, 2018), and observed forest change. Inclusion of such data in deforestation analyses is rare, but it is critical to include the voices of the ICs involved in these environmental conundrums as an ethical standard and to highlight the relevance of heterogeneity between communities when discussing themes related to conservation and development practice and policy. Table 2 offers a brief summary of the communities; additional information about the communities is in supplementary materials (SM2).

All three communities received formal recognition as native community territories before getting legal title. Nevertheless in all cases the majority of the 'zoning' or territorial organization that we discuss in this section was implemented through a process called 'quality of life plans'. In theory these quality-of-life plans are developed from the bottom up, preserving the governance, traditional community membership structures, land uses and development desires of the IC. However, this claim about the plans is not always shared by ICs and other stakeholders. Furthermore, state or NGO bureaucrats that arrive to communities to co-create quality-of-life plans often have limited training capacity, little desire to be in a rural community and unreasonable time-constraints. Furthermore, once the plan is put in place, even when the community complies, rent seeking behaviors or even corruption or fraud can occur. For example, one community the first author works with had been involved in a carbon offsetting credit scheme. After 2 years complying with the quality-of-life plan agreement, the bureaucrat told the community that there would be no payout because the carbon had "gone moldy". The outcomes of projects and the room for manoeuvre these ICs actually have to decide over their forest futures can be greatly affected by political state-IC relationships, alliances or tensions between communities and particular factions or individuals of regional government offices or NGOs (Biffi, 2021).

The first community we discuss is Shintuya (Group A) Fig. 9. Agricultural and timber extraction activities increased after receiving title in 1979 especially during two periods (1986–1991 and 2001–2006) when deforestation rates increased (Fig. 8). According to our multi-source data this appears to be due to population settlement of migrants of different kinds including outsiders and members of the same linguistic and/or blood families, and highway construction. Nevertheless, it was through the quality of life plans that the community entered into agreement with an oil extraction company to identify and zone areas apt for fruit tree reforestation, planting and harvesting of timber species and the identification and zoning of ecotourism areas (1980). This zoning in turn changed and the formal distribution of land-management and use

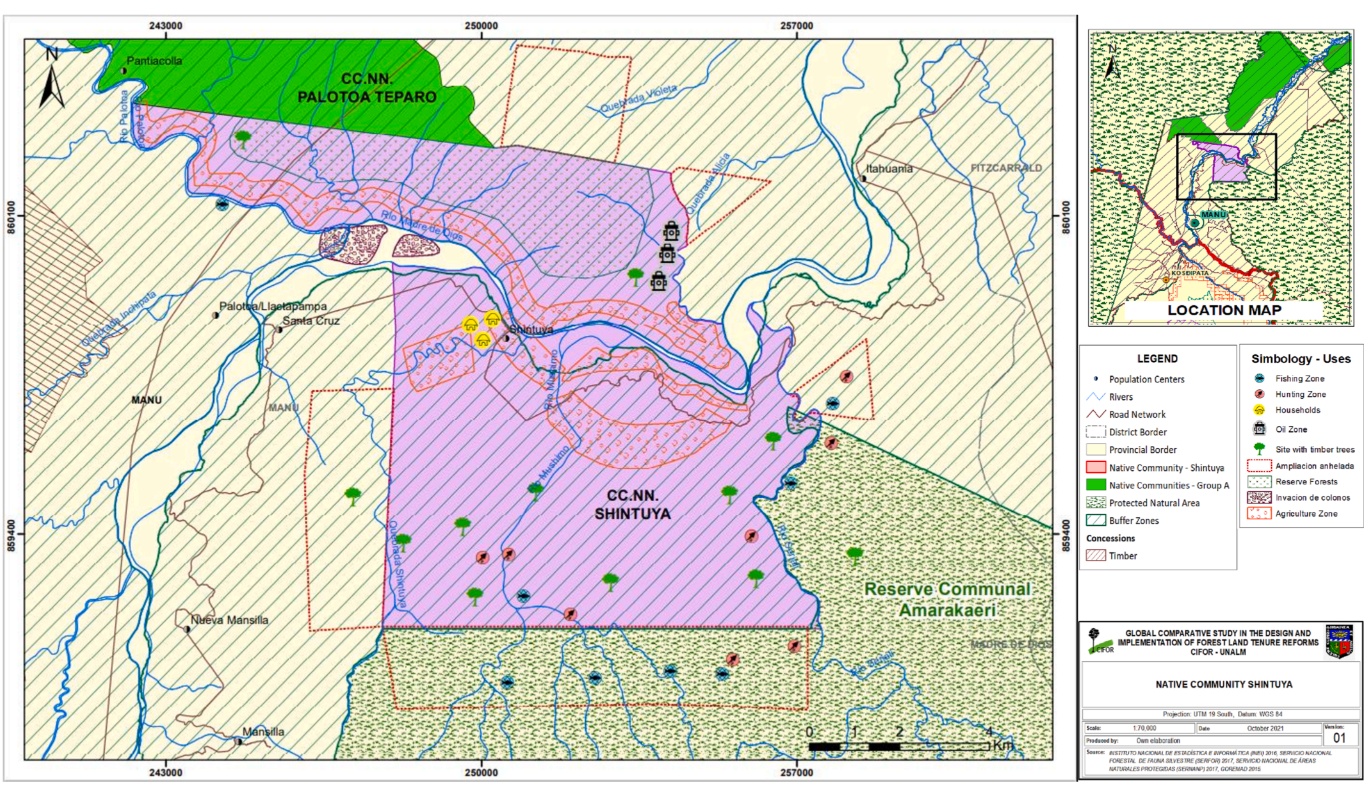

Fig. 9. Map of native community shintuya.

rights within-community and permitted the company to explore the ICL for oil (2007). Through the creation of these zones and the corresponding rights to their use and management, new 'communal statutes' – or governance structures – were created. The latter included processes such as writing management plans and regulations for each zone. These continue to be drawn up in the traditional way, through a community assembly but always guided by outside actors and formalized with external binding structures such as statutes and agreements or state legal documents. Through these processes the community also established a communal reserve (a type of protected area) in 2002. By 2011 the IC decided to cancel many of the ICL wood extraction contracts with outsiders, going on in 2014 to start planting trees as part of a reforestation initiative. Correspondingly the community experienced exponential net forest gain between 2003 and 2016 inferring a link between these internal-external interactions and decision making and forest regeneration dynamics (Fig. 8).

The Community of Tres Islas (Group C) (Fig. 10) is the fourth largest in the region; 14.3% of its lands are deforested, 45.9% of which is due to mining in the south of the ICL. Community members say that although mining has been practiced since the 70 s, the arrival of a new type of motor from China[3] in the early-90 s facilitated large-scale mining deep in the forest, beyond the riparian forest and riverbanks where the laborious and slow process of artisanal mining takes place. However, the peak in deforestation around 1991 is attributed by the community (and corroborated by satellite images) to agriculture and human settlement (Fig. 8).

A similar process of quality-of-life plans (mainly drawn up between the community and NGOs) began in Tres Islas from 1994 (the same year it received legal title). The plans aimed to zone the community according to land uses such as forest extraction areas, forest reserve, agriculture, and later mining. Over time this process has also led to the division of parts of the ICL into family plots. This individualistic allotment is a territorial and governance organization far removed from the traditional communal governance the community described in their histories, which was previously organized by communal responsibilities, values, tasks and decision making. This parcelling of communal land gave way to the allotting of gold mining plots to families and allies, governed by a 'gold mining association' – a sub-section of the community formalized by outside governance norms, mandates, and pathways in 2010. The governance structure of the non-kin based ́ associatioń meant that external pathways were having a direct impact on socio-ecological dynamics, which bodes a highly uncertain future for forests and people in this community. Although the formation of the pro-mining association corresponds both to an increase in deforestation and a decrease in forest generation the year of and a few years after its establishment, these trends soon reverse when the committee falls apart (Fig. 8).

In 2011 a conflict within Tres Islas and between Tres Islas and other communities over territorial delineation corresponds with an increase in deforestation and a sharp decrease in forest regeneration in Tres Islas (Fig. 8). Territorial conflict (including the state making decisions about their land without their agreement), along with illegal logging, were cited by the community as one of their principal concerns for a sustainable future.

The Native Community of Infierno (group B) (Fig. 11), experienced the highest rates of loss before 1991. However, between 1991 and 1997 the community dramatically reduced their deforestation reaching net zero (Fig. 8). These dates coincide with the establishment of the Tambopata Reserve (1991) and agreements with Rainforest Alliance through quality-of-life plans focused on new economies of ecotourism and reforestation projects (1996–2019). Deforestation since then has been low and remains stable (around 25 ha/ year) and forest regeneration increased exponentially. Drawing on the experience gained through the coalition with Rainforest Alliance, the community currently manages two eco lodges. Because ecotourism is the main economic activity, there is strong policy to avoid the conversion of the forest to other uses in certain areas, so most of the deforestation is concentrated in the northeast area (adjacent to the city). Our multi- methods datasets suggest that population growth of the community due to proximity to, and interaction with, nearby towns may be an important factor for land use change. Finally, the community history is a barrage of conflict since 1990 over a strip of land on the Tambopata reserve, which has implications for ́ sustainable developmenť, which we discuss in section 4.

4. Discussion

4.1. *Remote sensing, and net deforestation: Limitations for analysing dynamic community forests*

Our RS – like many other deforestation studies – is limited by the failure to address the *quality* of the forest under investigation. The ostensible contribution any land category makes to global efforts on carbon sequestration and the slowing of biodiversity loss through forest management by ICs is significantly reduced when vegetation biomass is maintained but forest quality decreases (Walker et al., 2020). This is a critical question for further investigation for nature conservation initiatives and policy, meeting biodiversity targets, and supporting indigenous livelihoods long-term.

Furthermore, the concept of ́ Zero-net deforestatioń is not without valid critique as we mentioned in our introduction. The ́ neť metric can lead to false understanding that degraded forests and even non-woody vegetation can be an effective substitute for old growth forest. Where the idea is to conserve biodiversity and ecosystem health and reduce carbon emissions, net deforestation definitions are currently ambiguous at best, and dangerous at worst. For example, using the FAO-FRA methodology, low or even negative net deforestation may be reported even when there are tremendous losses of native forests if those losses are offset by increases in young forests or tree plantations with inferior carbon, biodiversity, and other ecosystem service values (Brown and Zarin, 2013; Humphries et al., 2013; Watch, 2021). For this reason, UNFCCC, many nations, and most researchers (including the authors of this paper) exclude plantations from their reforestation definitions. However, this only partially tackles the issues of zero-net deforestation methodologies, and the implications of their use.

Nevertheless, we argue that to use accumulated values of deforestation in a tropical forest region is to assume a static state of existence that simply does not reflect the dynamic Amazonian Forest ecology and its peoples. As such we present the net values whilst recognizing the problems inherent in doing so. Our approach is novel, and even with its limitations offers a different perspective on deforestation as studied on ICLs. This is especially relevant as our study is over a very long period; many of the long-term regenerated forests in the dataset are highly ecologically valuable. The rapid advancement of RS technology, and the capacity to report degradation, forest type, age and condition might facilitate the process both of defining zero net deforestation, and monitoring and reporting actual forest state more easily in the not-too-distant future. Right now, increased practice of ground verification with RS research would contribute to tackling this issue. Even with this limitation, our contribution is significant in its combining of longitudinal data, inclusion of reforestation, ground verification and in-community social research.

4.1.1. *The importance of ground verification*

Our ground and random verification processes showed our RS analyses to have produced highly accurate quantitative information about

[3] Law 24,507 del 16–05-1986 approved the Peru - China Commercial Agreement and its Additional Protocol. During 1990 and 2000, Chinese machinery began to become popular in the country, mainly due to its lower price compared to competition. By the 2000s, Chinese machinery held a large part of the market captive, due to price, quality and availability of spare parts.

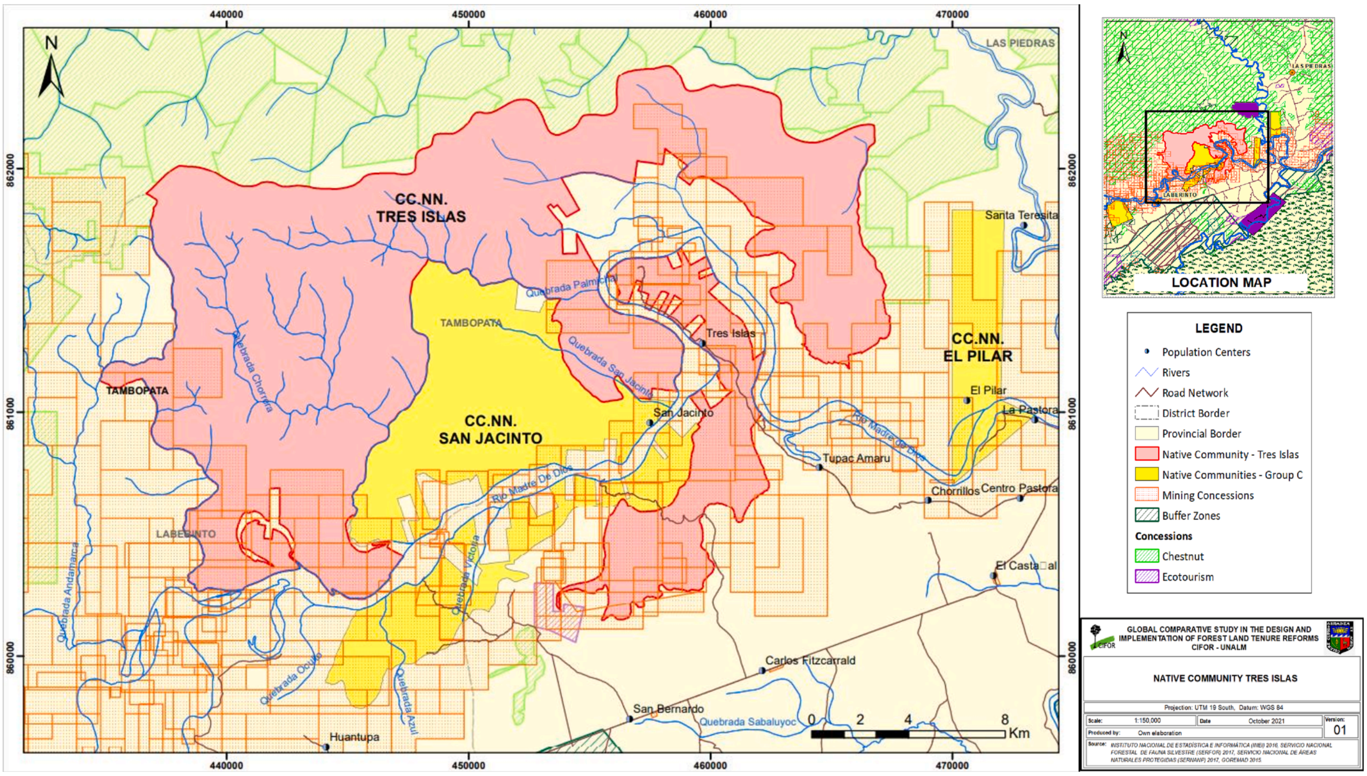

Fig. 10. Map of Native Community Tres Islas.

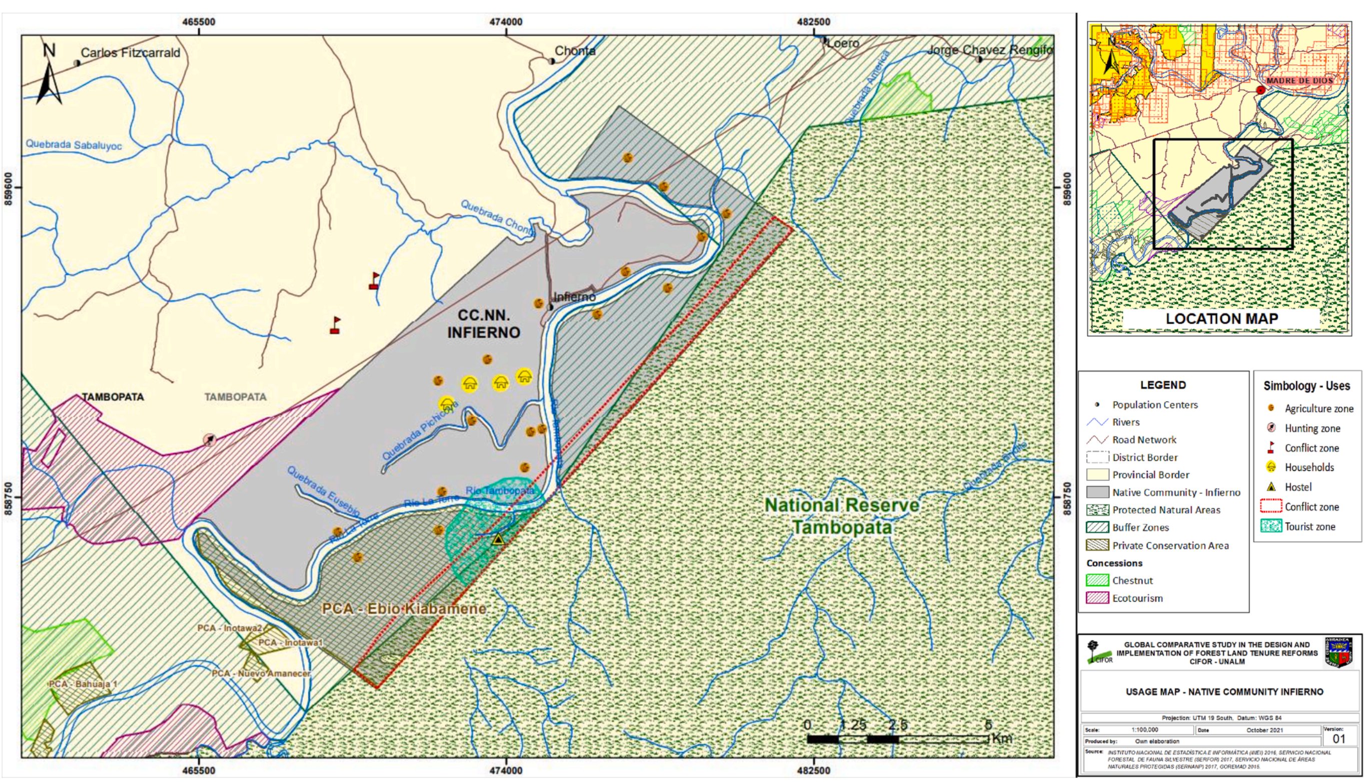

Fig. 11. Map of native community infierno.

the historical deforestation rates of each community every five years from 1975 to 2016. We verified our results using both random verification points and ground verification in-situ. The overall accuracy of both verification approaches was almost the same at 94% and 95% precision for the field verification and random points respectively (Table 1). However, it is interesting that the percentage precision for the no forest indicator is 56% in the random sample, and 93% in the human-based field validation. Whilst this could be related to the number of observations, it may also point towards the limitations of satellite images (for example cloud presence or classification mistakes in the algorithm), which can generate confusion in the results. On the other hand, the trained human eye (whilst also having its limitations) does not share these problems. It is possible that these results are because of the benefits of *in-situ* validation. More RS researchers might be encouraged to invest in ground validation as part of their methodologies.

When taken alone, deforestation results showed a very low but mostly steady increase in deforestation per period overall. However, peaks and troughs were also evident in the overall trends at all scales of analysis, indicating macro and micro drivers and influences. For example, there was a drop in deforestation rates in all communities just after the terrorist period came to an end, together with the launch of a new political regime, new monetary system, new socio- environmental and development policies and projects, increased state presence for environmental protection in rural areas, and new international accords. Although we explored this dynamic with a hypothetical approach, our results shed light on how infrequently researchers link fascinating and important political history to environmental change in ICLs. Further interdisciplinary research on this would contribute to knowledge about the macro and micro scale impacts of socio-political change in and around ICs, particularly when they are the result of external processes (Humphreys, 1996; Fjeldså et al., 2005; Kuusela and Amacher, 2016).

When analysing deforestation, first we quantified annual and accumulated deforestation based on *new* forest loss at specific intervals of time, as is the more common way of reporting deforestation - including by the Peruvian Government. This gave us an overall deforestation value of only 5%. However, when the regeneration values were taken away from the accumulated values to decipher a *net* deforestation, deforestation per year was reduced from 5% to 3.5% overall. This is a significant difference considering the small quantity to begin with.

On a regional scale, and on par with other studies, we find that the lowest rates of deforestation are in more remote communities and communities that border on protected areas (mainly Group A). Greater levels of deforestation are found in communities that are well connected by road and commerce to cities (mainly Group B). Meanwhile, the highest rates of deforestation are consistently in the mining corridor (mainly group C) (Scullion et al., 2014; Asner and Tupayachi, 2017; Espejo et al., 2018; Garnett et al., 2018). Many communities have progressed their 1950′s artisanal mining practices to mechanized extraction after Peru-China agreements facilitated the introduction of more powerful machines that allowed mining to migrate from rivers and streams deeper into the forest (Torres, 2010). This political and technical change has led to formal allocation of mining concessions both to members of the community and other actors that ICs choose to work with (or are unsuccessful in excluding). Although mining was not a focus of our paper, our results support other studies and initiatives that cry out for political action related to gold mining in the Peruvian Amazon, including areas around ICLs (Asner and Tupayachi, 2017; Finer, 2021; Finer et al., 2021).

4.1.2. Regeneration and forest management on ICLs and other land categories

We hold that the inclusion of regeneration (and assisted reforestation) in deforestation analyses is a critical component of science as this science may be used to guide the designation of lands for a specific use or purpose. Research has suggested that legally titled areas for protected areas, ICLs or other land categories often have lower levels of land conversion than untitled areas (Scullion et al., 2014). This research indicates that land designation can be an important factor influencing land conservation outcomes, but also that designation is only one factor among many that determines the efficacy of conservation or titling policies (Vuohelainen et al., 2012; Scullion et al., 2014; Blackman et al., 2017). In this sense our paper engages with literature that uses the variable of "exclusion" to evaluate whether titling ICLs could have positive outcomes for forests (Buntaine, Hamilton and Millones, 2015; Yin et al., 2016). Several authors have argued that ́designatioń- or in this case holding title- increases the land managers ́ capacity to exclude invaders. This would mean that opportunity for regeneration might be increased despite difficulties communities may have excluding invasions or the state in reality. Finally, designation and title also facilitate development projects which can be detrimental for forests – suggesting that outcomes can be opposed.

Our study suggests, however, that this discussion misses the most important variable: what happens to degraded or deforested areas? On the one hand, state policies often redesignate ́ degraded ́ forest from forest to farming land – never to be forest again. On the other hand, it is commonplace for small farmers - with the government's permission - to take possession of such areas (EIA, 2015; Reátegui and Arce, 2016). A title means that although there may be deforestation within designated lands such as ICLs (Fig. 7), these sites often recover and regenerate when no longer in use. This would happen infrequently in undesignated forest areas where cleared areas are quickly converted to small or large-scale farming and populated centres form, spreading deforestation. We argue that when reforestation is considered in discussions on exclusion for designated areas, it could greatly change the assumptions made by the government about specific actors, such as ICs.

4.1.3. Community diversity

Finer temporal and geographic scale analyes, studying at the community level, and including forest gain in the analysis draws out nuances that are key to identifying successful pathways towards healthy futures for nature and people. For example, when comparing accumulated deforestation to net deforestation over the entire time period, losses in the community of Tres Islas drop from 3125 ha (15% of their lands) to 1828 ha (Fig. 8). In contrast, San José de Karene shows almost no difference when analysed as total or net loss. This information – visible from RS data – likely signposts different community forest and land management approaches often in response to the pathways discussed in this paper. These are worthy of investigation at the local level, as they might affect the specific needs and priorities for conservation or sustainable development funding and livelihoods. Our RS and political ecology analyses also showed that deforestation and reforestation events on an annual or per period basis at the community level give more precise information about where, how and why land use changes happen at different points in time. Working directly with the communities to understand these processes is an effective way to understand problems and develop appropriate solutions. This challenges the notion that accumulated loss over time is the best way of measuring deforestation in communities.

Finally, analysing deforestation rates in this way alleviates some of the confusion caused by differing methodologies and their resultant reports, especially by scientists and policy makers. It also helps avoid the negative implications of data dissemination about specific land users such as IC's and smallholding farmers (Ravikumar et al., 2017; SERFOR, 2021). Many ICs are connected to and influenced by external and international commodity markets, styles of land-use or organization that are not traditional to the community or local area. Thus, there is often a consequent change to traditional production strategies, livelihood options and land-use decision making. The zoning of land uses and allocation of land parcels to specific families for specific uses is a shift from communal territorial management to a more individualistic approach. Our case study community 'Tres Islas' (group C) is an example of this. It also serves to highlight that whilst the RS deforestation and reforestation data are highly dynamic, so too are the socio-economic processes that drive them. These changing dynamics have potential implications for pro-conservation arguments linked to IC titling, since the de jure titled communal IC polygon may be de facto individualized smallholder plots, where decisions about land-use are no longer taken as a community. The case studies also showed some very positive outcomes of appropriate external interventions, such as the growing eco-tourism in IC Infierno.

Our introduction referred to Blackman and Veit's (2018) pathways and management types to highlight the range of scenarios that can affect the on-the-ground reality of ICLs as a segue to our argument that it is important to understand some of the multi-level nuances when proclaiming specific land tenure types, territorial categories or land managers as pro or anti-environment.

Indeed, Indigenous Peoples have a wide range of legitimate political, cultural and economic aspirations for their lands that are dynamic and changeable over time and, as a result, conservation priorities and regulations often differ or even clash with them (Kohler and Brondizio, 2017; Schreckenberg et al., 2018). Shintuya, and most of the communities in the mining corridor (group C), who choose to mine to the detriment of the environmental health of their lands, could be an example of this. Nevertheless, Indigenous or local-led approaches, often together with governmental or non-governmental allies have developed innovative ways to design conservation reserves, environmental policy instruments, wildlife monitoring and management programs (Raymond et al., 2010; Sears et al., 2018). For example, Shintuya sought outside support to create and formalize a communal protected area, and Tres Islas has a thriving ecotourism business. Thus, the blanket view that ICs *necessarily* manage ICLs sustainably, or do so more than other land users, is unhelpful both for environmental outcomes and for indigenous autonomy in livelihoods and politics. Hence a nuanced understanding of ICs through engagement with them is necessary to consider how donors, projects or governments should support ICs, as well as recognizing the right of ICs *not* to engage in such projects based on their own long term vision, and the use of mechanisms such as quality of life plans (Etchart, 2017).

Finally, irrespective of whether legal title leads to improved environmental health, there remains the socio-political importance and responsibility of guaranteeing the security of ICLs to ICs in the wake of many years of oppression and systemic violence. Section 2 described how indigenous communities continue to fight for formalized communal rights to their ancestral lands and our supplementary materials (SM2) show that this has been identified as a threat to IC security on various levels, and many scholars see it as a barrier to both equitable land allocation and pro-environmental outcomes (Monterroso et al., 2017; Cronkleton et al., 2019).

5. Conclusions

Together, our quantitative RS findings and qualitative research show that a mixed methodological approach like this provides a more rigorous and ethical analysis of specific territorial categories and their land managers, and the dynamics surrounding land use change.

We find that overall net deforestation rates on ICLs are extremely low: 3.5% over 40 years is undeniably minimal. The results here permit a deepening of the discussion on whether placing land under indigenous control through mechanisms such as bestowing formal tenure can be an effective approach to better forest conservation. Furthermore, we posit that it is likely that forest regeneration in these areas was permitted at least in part because the IC title prevented or discouraged outsiders from taking possession, quickly and usually legally, of cleared areas for agriculture. This is a key point when discussing the people-nature dynamics of regeneration and land-use politics. Our methodological approach would be useful for better understanding any territorial category, but the results produced for ICLs are particularly important, because of the increasing political interest around conservation, carbon sequestration and the titling of indigenous territories.

Finally, the heterogeneous patterns of both forest dynamics and socio-economic and cultural change call for closer attention to nuance and detailed local contexts, to inform better fund flow decision making for people and nature, and especially in supporting ICs to define the future of their territories.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2023.102695.

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