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ORIGINAL ARTICLE

Two decades of accelerated deforestation in Peruvian forests: a national and regional analysis (2000–2020)

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Abstract

The global tree cover has kept reducing in the last two decades, mainly in tropical forests, despite the global efforts to conserve biodiversity and the ecosystem services that provides. Considering South America is the region that had the highest rate of net forest loss (2000–2020), it is crucial to understand the deforestation dynamics of each country and their regions for the evaluation of effective national conservation actions. Here, we carried out a spatiotemporal analysis of the deforestation rates from 2000 to 2020 on a national and regional scale, including the forest loss inside protected areas, in Peru. It was found that Peru lost 3.4 million ha of forest between 2000 and 2020, mainly in the Not Flooded Rainforest region. National deforestation rates accelerated, while within protected areas rates showed a very small increase. Regional deforestation rates followed the national pattern with one exception—the Coast region. Our results evidence the success of the national conservation strategy based on protected areas to avoid deforestation in all regions, except in the Andean. Moreover, the increment in deforestation rates is aligned with the growth in road infrastructure; increments in anthropic activities; and the more frequent and intense natural extreme events that vary according to the region. Therefore, it is urgent to differentiate the drivers of deforestation that operate at the national versus the regional scale, consider the inclusion of all forest types in the monitoring system, and the strengthening of policies related to land use change at all scales.

Keywords Tropical forest · Rate · Spatiotemporal analysis · Global Forest Change (GFC) · Protected areas · Peru

Introduction

Recent advances reveal that global forest extent decreased by 1 million km^2 (2.4% of the forest area since 2000) during the last two decades (Potapov et al. 2022). The highest deforestation occurred in tropical rainforests (32%) (Hansen et al. 2013), primarily in the Amazon, but also in the Congo basin, Indonesia, and other countries (Keenan et al. 2015; Potapov et al. 2022). Deforestation of tropical forests is an important global issue because these forests harbor a high percentage of land biodiversity and play a critical role in the global carbon and water cycles (Foley et al. 2007; Nobre et al. 2016; Vargas Zeppetello et al. 2020; Xu et al. 2022). Moreover, the conversion of tropical forests into other land uses contributes approximately to 20% of the world's greenhouse gas emissions (GHG), and thus, accelerating deforestation rates have dramatic impacts on global climate change (Achard et al. 2007; Vargas Zeppetello et al. 2020). South America is the region that had the highest rate of 2000–2020 net forest loss (5% of the year 2000 forest area or 0.44 million km^2) (Potapov et al. 2022). Concerning the different forest types,

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around 17% of the South American tropical humid forests have been lost in the last 50 years (Lovejoy and Nobre 2019). On the other hand, more than 50% of tropical dry forests deforestation occurs in South America (Miles et al. 2006), and 60% of South America's dry forest has already been converted to other land uses (Portillo-Quintero and Sánchez-Azofeifa 2010). Forests of the Andes mountains have been occupied for millennia and historically they have been greatly reduced in the past, but currently the deforestation process continues (Aide et al. 2019; Armenteras et al. 2011; Bax and Francesconi 2018).

Tropical deforestation is the result of many processes driven by multiple causes. Despite this complexity, many efforts have been made to explain the dynamics of tropical forest loss, its patterns, and variation across landscapes. Environmental factors play a crucial role in the dynamics of tropical forest cover loss (Aide et al. 2019; Bax and Francesconi 2018; Bax et al. 2016; Geist and Lambin 2002). Tropical deforestation is also associated to social, political, and economic changes that operate at multiple scales, differ among regions and forest types, and change over time (Armenteras et al. 2011, 2017; Geist and Lambin 2002; Rudel 2007; Rudel et al. 2009). In the effort to minimize the impact of tropical forest deforestation, the extent of protected areas has been expanding in the last 20 years (Baldi et al. 2019; FAO 2020b). Although some studies on the topic suggest that protected areas often have lower deforestation rates than unprotected areas (Blankespoor et al. 2017; Ford et al. 2020; Wade et al. 2020; Walker et al. 2020), there is still little information on whether the effect of protected areas may halt deforestation. Another mechanism to prevent deforestation through the conservation of forest carbon stocks, linked or not with protected areas, is the Reduced Emissions from Deforestation and Forest Degradation (REDD+) that have been developing since 2005 (UNFCCC 2016). However, the lack of historical national forest inventory data, the multiple forest classifications (overall and in each country), and the different methods for monitoring and ways for reporting deforestation (e.g., total deforestation annual rate, total rate, gross, net loss in hectares, among others) makes monitoring, comparison, and understanding of the dynamics of forest loss still more difficult (Armenteras et al. 2017; Puyravaud 2003).

Peru has the ninth largest forest area in the world (72 million ha in 2020; FAO 2020a). In the last 20 years, Peru has improved the performance of its economic and social indicators (e.g., total GDP has doubled since 1998, with an average annual growth rate of 4.5%; or extreme poverty has dropped from 16.8 to 3.8%) with the development of mining, agriculture, and other extractive activities, maintaining emissions per capita lower than the average of Latin America and the world (De La Torre Ugarte et al. 2021). However, despite the efforts of the Peruvian government to decrease deforestation rates toward net zero deforestation by 2021 (Che Piu and Menton 2014), including the increase in surface of protected areas (Aguirre et al. 2021), the rate of forest loss grew from 115,000 ha/year in 1990–2000 to 125,000 ha/year in 2000–2010, and to 172,000 ha/year in the last decade (FAO 2020b). However, forest loss is considered the primary source of carbon emissions in the country (MINAM 2016). Its evaluation has been focused on the Amazon area as a whole or locally (Asner and Tupayachi 2017; Bax and Francesconi 2018; Bax et al. 2016; Potapov et al. 2014; Sánchez et al. 2021). Moreover, Peruvian forest loss has also been evaluated as part of cross-national studies (Armenteras et al. 2017; Dávalos et al. 2016; Furumo and Aide 2017; Smith et al. 2021). In this study, we have carried out a spatiotemporal analysis of the deforestation rates in Peru from 2000 to 2020 on a national and regional scale, with particular attention to the deforestation rates of Peruvian protected areas during these decades. More specifically, we ask (1) Do national deforestation rates change over time between 2000 and 2020? Are there any differences between protected areas and unprotected areas? (2) Do these patterns change in the different regions of the country?

Materials and methods

Study area

The study was carried out in Peru (central-western South America), a tropical country located at 0°02′00″North, 18°21′03″South, 68°39′00″East, and 81°19′35″West. The total continental area of Peru is approximately 1.28 million km^2, within which 60% are tropical forests (FAO 2020a; IGN 2021). Furthermore, it is the fourth largest country in global tropical forest and second in Amazon rainforest after Brazil (FAO 2020b). Peru has highly heterogeneous climate, geomorphology, physiography, and edaphology, which results in a wide variety of vegetal covers, distributed in landscapes ranging from desert and semi-desert plains, as well as alluvial plains with rain forests, to hilly and mountainous landscapes (MINAM 2015). Here, we grouped the Peruvian forests in five regions according to MINAM (2019): coast (10% of whole area); Andean (30%); high rainforest (14%); and low rainforest or Amazon rainforest, further disaggregated into flooded (13%) and not flooded rainforest (33%) (Fig. 1a). The five regions considered here differ in their ecology and the spatial patterns of land use and human population distribution. The coast region is hot and dry, and extends from the sea level to approximately 1500 or 2000 m. It is the region that harbor more than half of the Peruvian population (58.0%; INEI 2018). The Andean region ranges from semi-warm arid to cold wet or cold dry, being wider and higher in the center and south. The Andean

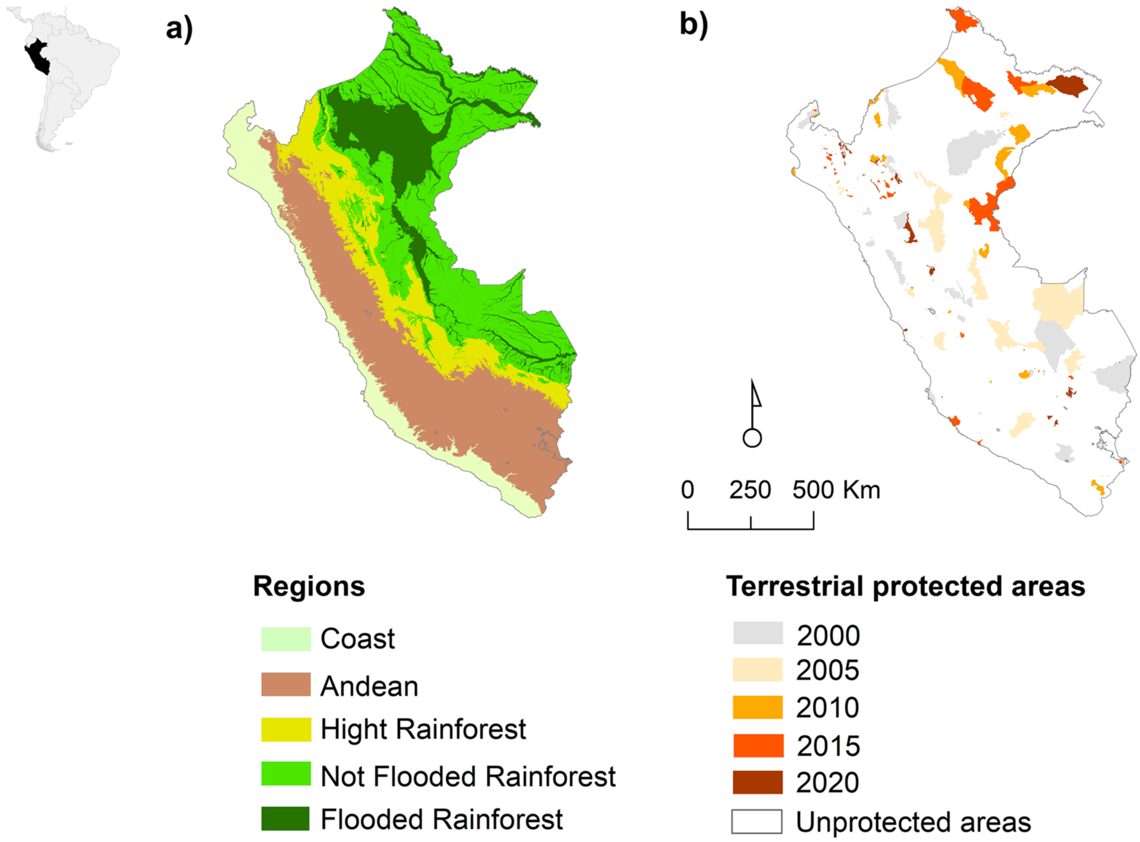

Fig. 1 Study area. **a** Peruvian regions. **b** Peruvian protected areas from 2000 to 2020

landscapes have highly transformed forest relicts with an estimated reduction of ten times its potential vegetation biomass (Miyamoto et al. 2018; Sylvester et al. 2017). The high rainforest region is on the eastern flank of the Andes Mountains, from 600 to approximately 3600 m. It is humid or subhumid, with permanent fog and strong slopes. This region is sparsely populated due to the highly sloped and arboreal landscape (INEI 2018). The flooded and not flooded rainforest regions are humid and rainy and they are in the Amazon basin. These regions contain the largest extent of forest in Peru and are sparsely populated, mainly near watercourses (13.9%; INEI 2018). The flooded rainforest region is mainly composed by floodplain alluvial forests (flooded several meters during the river crescent) and palm wetlands (permanently or nearly permanently water saturated). The not flooded rainforest region is mainly composed by hill and terrace forests. In this study, the terrestrial protected areas (Supplementary Table 1; SERNANP-MINAM 2021) have been considered as areas of interest (Fig. 1b).

Forest cover data

We obtained the forest cover maps (baseline: 2000; forest cover loss: 2001–2020) from the Global Forest Change (GFC) datasets of 30-m resolution- version 1.8 update to 2020 (). This allowed the analysis of the whole area of study with the longest time series available, in contrast to the official Peruvian national data, that only reports deforestation for the rainforest. We followed the forest definition of Hansen et al. (2013) that estimates the GFC using a decision tree approach based on the multitemporal profile of spectral metrics derived from Landsat satellite images. Our study area spanned five GFC tiles, which were clipped to match with the regional and country boundaries. In the GFC dataset, forest loss or deforestation was defined as the complete removal of pixel tree cover. Furthermore, forest gain areas were not considered, due to the annual exclusion of pixels after a deforestation event. Forest loss data are encoded as either 0 (no loss) or a value in the range 1–20, representing loss detected in the year 2001–2020, respectively (i.e., a pixel with value of 4 indicates that a forest loss event occurred in 2004) (GFC 2022).

Data analysis

We calculated the rate of deforestation (r; in $\%\cdot yr^{-1}$) of the unprotected areas and protected areas for the whole country and each region separately every 5 years from 2000 to

2020 (i.e., four periods: $r_1 = 2001–2005$; $r_2 = 2006–2010$; $r_3 = 2011–2015$; $r_4 = 2016–2020$), based on the cover forest maps (baseline and forest loss; GFC 2022) and protected areas surface (SERNANP-MINAM 2021) using ArcGIS 10.5 (ESRI 2016a) and R 4.1.0 software (R CoreTeam 2021). We used the standardized deforestation rate proposed by Puyravaud (2003), in order to ease comparisons of forest change:

$$Deforestation\ rate\left(r;\ \%\cdot yr^{-1}\right) = \frac{1}{(t2 - t1)}\ln\frac{A2}{A1}100$$

where A1 and A2 are the forest areas (in ha) in the years t1 and t2, respectively. In addition, we aggregated the new protected areas established in each period since terrestrial protected areas have increased from 37 protected areas (6.1% of national surface) in 2000 to 241 protected areas (17.7%) in 2020 (Fig. 1b; see Supplementary Table 2). Forest areas were calculated by converting the pixels (30 × 30 m) of forest cover maps into areas (unit: hectares; ha) within region or protected areas geometries using ArcGIS 10.5 (ESRI 2016a).

For the analysis, since the dependent variable was dichotomous (i.e., forest-1/no forest-0) and the independent variables were categorical, we elaborated a multiple contingency table for deforestation (dependent variable), period (1 = 2001–2005, 2 = 2006–2010, 3 = 2011–2015, and 4 = 2016–2020), status of protection (protected, not protected), and region (the five regions described above). Then, we evaluated the association between variables through log-lineal models using the log-likelihood ratio statistic (G^2). We carried out two different analyses: one for Peru as a whole (variables: deforestation, period, and protection), and another one adding regions (variables: deforestation, period, protection, and region). Statistical analyses were carried out using R 4.1.0 software (R CoreTeam 2021).

To detect the areas with the highest deforestation rate (deforestation hotspot), a Kernel density mapping with a radius of 15,000 m (ESRI 2016b; Silverman 1986) was performed using ArcGIS 10.5 (ESRI 2016a) for each period.

Results

Spatiotemporal changes in national deforestation rates

According to the forest cover maps, overall forest loss in Peru between 2001 and 2020 was 3,464,829 ha (4.4% of Peruvian forest cover at 2000) for the whole country and 114,220 ha in protected areas. The only acceptable model that fitted the data of deforestation in Peru (log linear model, $G^2 = 53{,}140$, $p < 0.05$) included the highest three-order interaction. Differences in deforestation increased progressively from the first to the last period considered, with a different pattern in unprotected areas and protected areas (Fig. 2; see Supplementary Table 3). Deforestation was higher in unprotected areas than in protected areas in all periods, but while deforestation rates increased in unprotected areas from 2001–2005 to 2016–2020, they showed a much smaller increase in protected areas (Fig. 2; see Supplementary Table 3).

Regional patterns of deforestation

Forest losses by regions from 2000 to 2020 were very different: 9299 ha in the coast region (2.2% of the region), 83,134 ha in the Andean region (4.4% of the region), 817,834 ha in the high rainforest region (4.9% of the region), 649,889 ha in the flooded rainforest region (4% of the region), and 1,904,673 ha in the not flooded region (4.5% of the region) (Fig. 3). The highest density of deforestation occurred in the unprotected areas of high, not flooded, and flooded rainforest regions, intensifying through periods (Fig. 4). The only acceptable model that fitted the regional data of deforestation (log linear model, $G^2 = 17{,}352$, $p < 0.05$) was again the full model including the highest four-order interaction. Differences in deforestation increased progressively from the first to the last period considered in all regions, except the Coast and Andean regions (Fig. 5; see Supplementary Table 3). In the coast region, the highest deforestation occurred in the third period while in the Andean region, there was a significant fluctuation from the first to the third period. Deforestation was higher in unprotected areas than in protected areas in all periods and regions (Fig. 5; see Supplementary Table 3). Moreover, regional deforestation rates in protected areas were

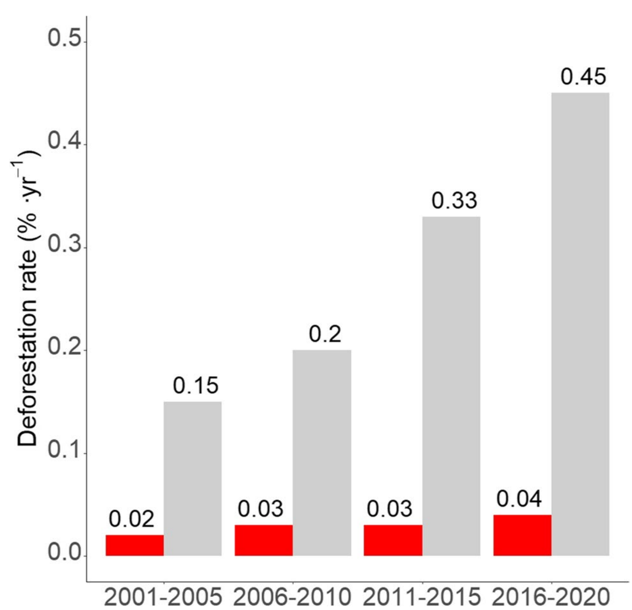

Fig. 2 National deforestation rates in Peru (|r|) (% · yr^{-1}) by periods between 2000 and 2020. Status: protected areas (red bars) and unprotected areas (gray bars)

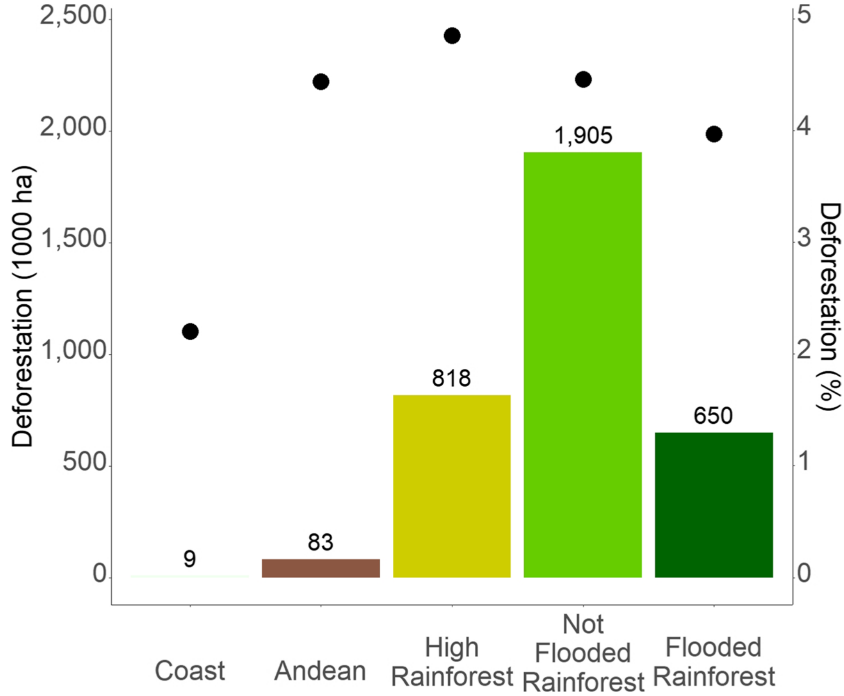

Fig. 3 Total forest loss in ha per region (bars) and percentage of each region deforested (dots) between 2001 and 2020

considerably lower than in unprotected areas in three regions, namely coast, high rainforest, and flooded rainforest, while deforestation rates in protected areas increased slightly in the not flooded rainforest and were particularly high in the Andean region in all periods, especially in the last one.

Discussion

Spatiotemporal deforestation rates trends

Deforestation in Peru from 2000 to 2020 (3.4 million ha; 4.4% of Peruvian forest cover at 2000) was lower in absolute and relative values than in other South American countries (see Supplementary Fig. 1). South America reduced to about half the annual rate of net forest loss in the decade 2010–2020 (2.6 million ha/year) than in the previous decade (4 million ha/year in 2000–2010) (FAO 2020b). However, deforestation in 2010–2020 was higher than in 2000–2010 in some countries, including Peru (FAO 2020b). Our analysis shows that deforestation in Peru increased over time (Fig. 2). We noticed that this increase in deforestation rate was aligned with the development and intensification of legal, informal, and illegal economic activities, such as agriculture or mining, depending on the region, that have transformed the landscape in the last twenty years. The development of these activities was exacerbated in the last two periods, which could be related to the almost doubling of the national road network during the second period of study (Aguirre et al. 2021). This is the case of the Interoceanic Highway (south national transversal axis; see Supplementary Fig. 2), that promoted deforestation of forests by expanding agricultural intensification, illegal gold mining, illegal crops, and illegal logging with an elevated social impact (Dourojeanni 2019; Gallice et al. 2019; Honorio Coronado et al. 2020).

Deforestation in Peru was considerably higher outside protected areas than inside. This pattern persisted over time (from about 8 times in the first period to 12 in the last; Fig. 2). This result is also consistent with other studies in tropical protected areas (Blankespoor et al. 2017; Ford et al. 2020; Wade et al. 2020; Walker et al. 2020) and other studies in Peru (Aguirre et al. 2021; Dourojeanni 2014; Miranda et al. 2015). Moreover, we noticed a very small increase in deforestation rates in protected areas over time (Fig. 2). This could be explained because most protected areas are still located in remote areas or areas of difficult access (see Supplementary Fig. 2). Thus, remoteness has a protective effect of protected areas at a national scale. Furthermore, there is evidence that awarding formal land titles to indigenous communities contributes to the reduction of deforestation in Peru (Blackman et al., 2017). However, indigenous people's land and resource rights in Peru are legally recognized but only partially, which fosters insecurity in a context of strong external pressure (Rodríguez et al., 2022; Lasheras et al., 2023). Moreover, studies alert that different anthropogenic activities such as the expansion of agricultural lands, agro-industrial plantations, cattle ranching, mining, and illicit coca cultivation have surpassed buffer zones, causing deforestation inside protected areas in the last decades (Asner and Tupayachi 2017; Dourojeanni 2018; Sánchez et al. 2021; UNDOC and DEVIDA 2018). This is

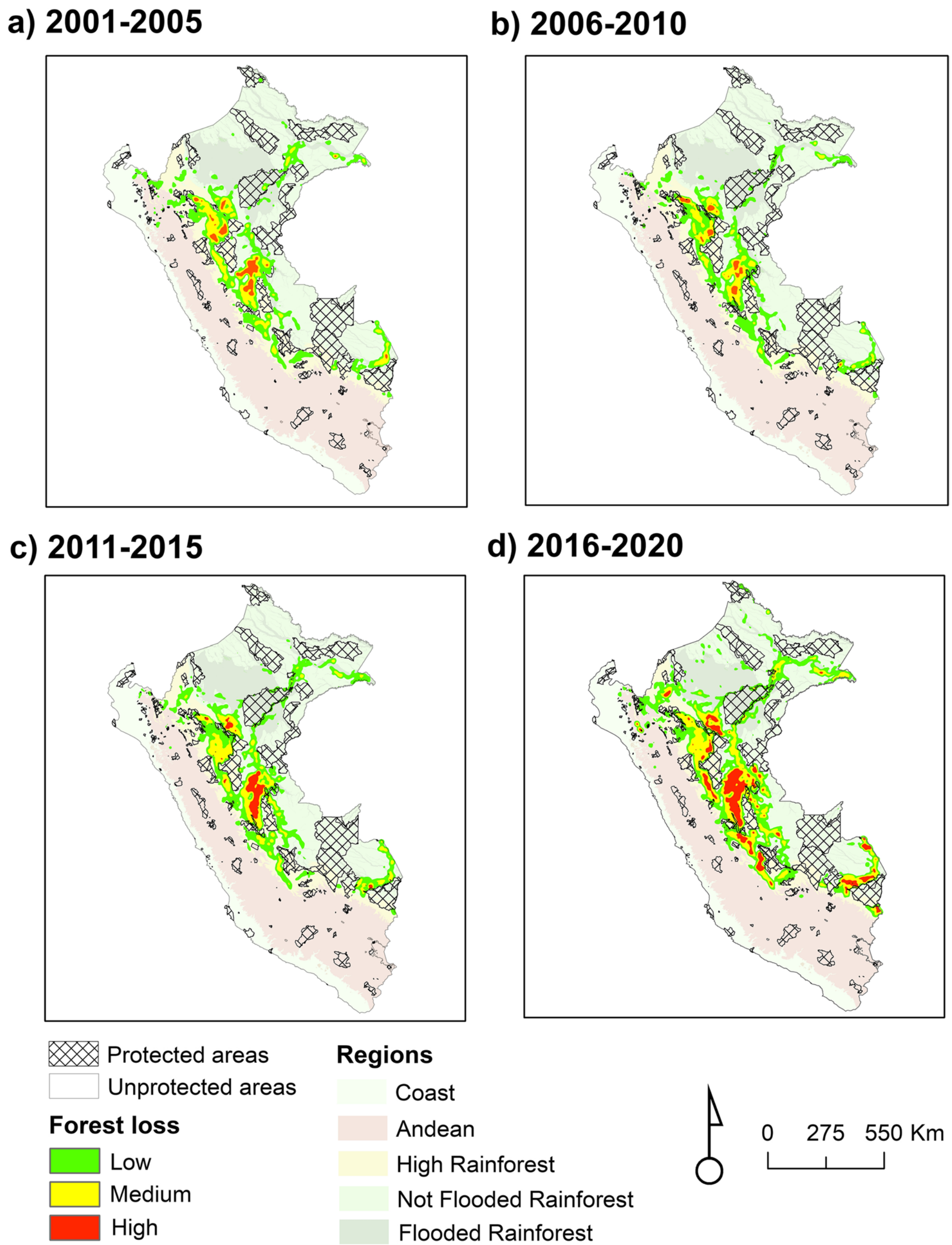

Fig. 4 Deforestation for each period: **a** 2001–2005; **b** 2006–2010; **c** 2011–2015, and **d** 2016–2020

again a result of the chaotic growth of road infrastructure that in some cases have dissected protected areas at various points (Aguirre et al. 2021). Moreover, although the legislation prohibits production activities inside intangible protected areas, the application of these laws is quite elastic (Dourojeanni 2015, 2018).

Understanding the changes in deforestation rates by regions

This study is probably the first spatiotemporal analysis of deforestation that includes a regional scale and protected areas from 2000 to 2020. Differences in deforestation by region (Fig. 3) are likely related to the environmental and climatic conditions that determine the extent of forest and land aptitude, as well as the process of occupation and land use of each region. In absolute terms, the not flooded region is the region with the most deforestation and the coast region with the lowest. In the not flooded rainforest region, the region with the most forest cover and with a recent accelerated proliferation of intensive and agro-industrial crops, occurred the 55% of deforestation of Peru (Ravikumar et al. 2017). High deforestation rates are also found in the high rainforest and flooded rainforest regions, where the increased access by the national road network or navigable rivers respectively has allowed disorderly rainforest penetration, disorganized

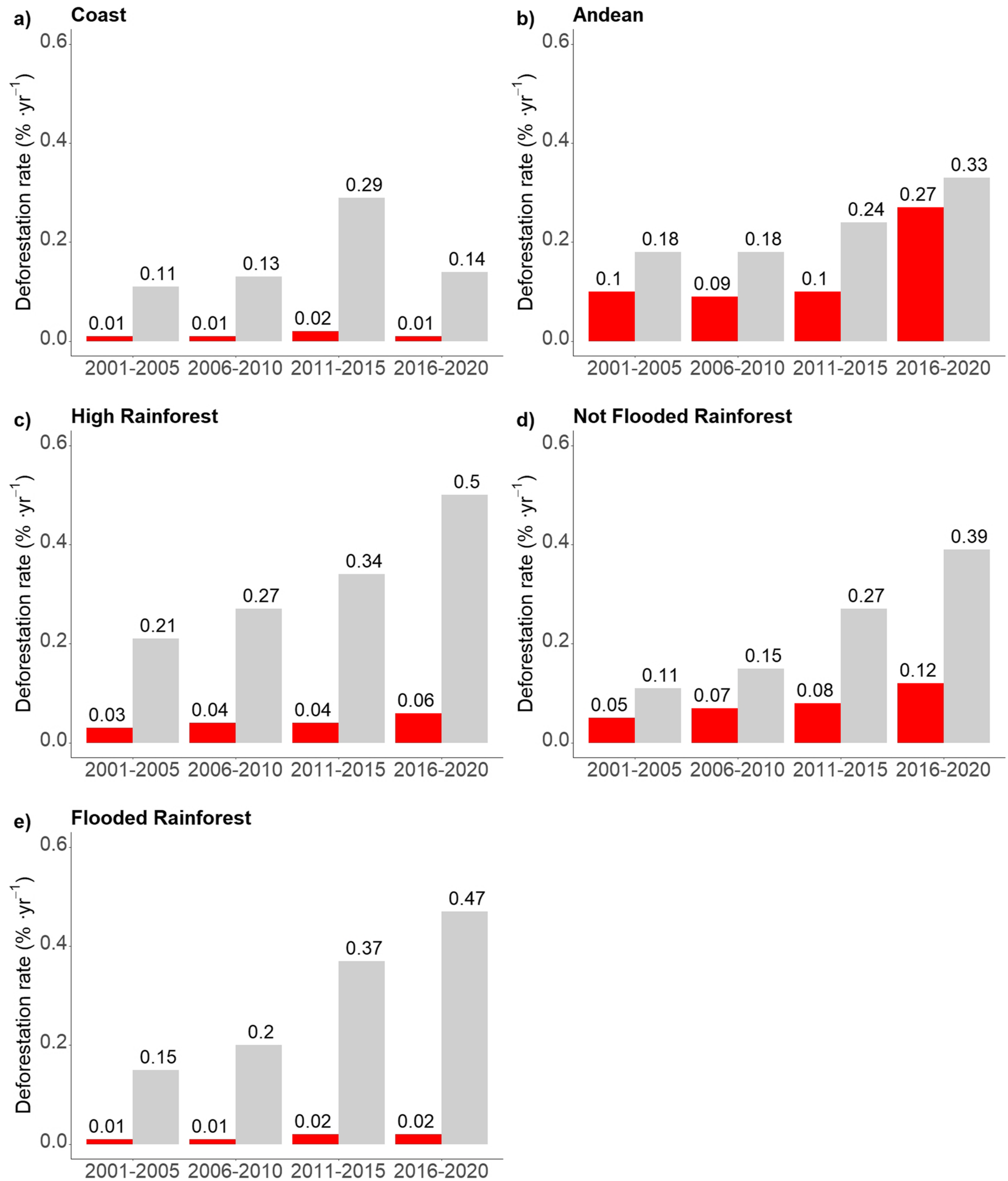

Fig. 5 Regional deforestation rates (|*r*|) ($\% \cdot yr^{-1}$) in protected areas and unprotected areas by periods between 2000 and 2020 and regions: **a** coast, **b** Andean, **c** high rainforest, **d** not flooded rainforest and **e** flooded rainforest. Status: protected areas (red bars) and unprotected areas (gray bars)

migrations and informal occupation of the land motivated by national policies from several decades ago (Dourojeanni 2019). Therefore, the deforestation focus is located along the national rainforest road network and navigable rainforest rivers (see Supplementary Fig. 2). In contrast, the coast and Andean regions had a lower deforestation rate (Fig. 3). These regions have less forest cover because of their long history of occupation and land use changes such as agriculture, livestock, and urban development (Portillo-Quintero and Sánchez-Azofeifa 2010; Sylvester et al. 2017). In the coast region, 95% of the potential Peruvian tropical dry forest has been already converted into other land uses, the highest percentage in Latin America, only remaining highly fragmented forest tracts (Portillo-Quintero and Sánchez-Azofeifa 2010). Likewise, in the Andean region, 90% of forest cover has been lost and only relict forests remain (Sylvester et al. 2017). Despite these differences in absolute values, our study shows that all regions lost between 2 and 5% of forest cover from 2000 to 2020 (Fig. 3). Moreover, the high rainforest and Andean regions had the highest forest cover loss relative to their cover in 2000. This result could be due to the presence of many roads established since 1940s, such as the "Carretera Marginal de la Selva" (1960s and 1970s) in the high rainforest region, which is strongly related to the deforestation process in the rainforest (Dourojeanni 2019; see Supplementary Fig. 2).

All regional deforestation rates had an accelerated growth following the national pattern with the coast region being the exception (Figs. 2 and 5). In this region, we observe a severe increment in the deforestation rate during the third period, followed by a considerable decrease in the last period. We relate this pattern to the influence of "El Niño" Southern Oscillation (ENSO) on the dynamics of regional forest cover. The Coastal "El Niño" Index (see Supplementary Fig. 3) maintained low during the periods one and two, increasing the fire risk from agricultural burning, which could have been increased due to national prohibition policies on the use of fire (Cuentas Romero and Salazar Toledo 2017; dos Reis et al. 2021). On the other hand, the reduction of the deforestation rate in the fourth period could be explained by the extreme "El Niño costero" (coastal) of 2017 (localized ENSO in the north of Peru, last documented in 1925; Ramírez and Briones 2017), which promoted a substantial increase of forest cover, reported by Rodríguez et al. (2018), altering the deforestation rates in the last period. The transition process between "El Niño" and "La Niña" in 2005, 2010, and 2016 in the central Pacific is related to the severe increase in the occurrence of forest fires in the Andean and High Rainforest regions (Zubieta et al. 2019). Therefore, in these regions the increase in deforestation rates (Fig. 5) could also be explained by the significant increase in fires resulting from agricultural burning practices that went out of control because of changes in precipitation and drought, and the national prohibition policies on the use of fire (Armenteras et al. 2020; Bax and Francesconi 2018; Zubieta et al. 2019, 2021).

For decades, the Government attributed the majority of rainforest forest cover loss (90%) to clearing for a small-scale, migratory, or subsistence agriculture (Ravikumar et al. 2017). However, there is an accelerated proliferation of agro-industrial crops and agroforestry, such as oil palm, mainly in not flooded rainforest; cocoa and coffee, mainly in high and not flooded rainforest; and fruits and other crops, in all rainforest regions, directly promoted by the rapid increase in global food and fuel demand (Castro-Nunez et al. 2021; Furumo and Aide 2017; Noble 2017; Ravikumar et al. 2017). Oil palm production has grown exponentially since the second period, reducing primary forests (Glinskis and Gutiérrez-Vélez 2019; Gutiérrez-Vélez et al. 2011; Vijay et al. 2018). In the same way, the increase in the deforestation rates of the last three decades, also in primary forests, was related to cocoa production increases (Finer and Mamani 2020; Noble 2017). Although there are more coffee cultivated areas than cocoa or oil palm in Peru (Castro-Nunez et al. 2021), there is surprisingly little information on the extent to which coffee is driving deforestation (Harvey et al. 2021). Moreover, in high and not flooded rainforest, oil palm, cocoa, and coffee production has been adopted by coca substitution programs to end its illicit cultivation (Castro-Nunez et al. 2021; Glinskis and Gutiérrez-Vélez 2019; Harvey et al. 2021). Although there is little evidence that coca increases deforestation rates (Dávalos et al. 2016), coca surface had a progressive increase during the first and second periods, decreased during the third period and increased again during the fourth period (see Supplementary Fig. 4).

The development of extractive activities, in particular mining and gas and oil extraction, in high, flooded, and not flooded rainforest regions also could explain the progressive increment in deforestation rates along the study periods (Fig. 5). After 2000, deforestation rates for gold mining grew every year, with an alarming increase at the end of the second period and remaining consistently high during the third and fourth periods (Espejo et al. 2018). These high deforestation rates have been related to the Interoceanic highway, the overcoming of the global economic recession (2008–2009), the large increase of gold price during 2005–2012, and national policies on mining legalization since 2012 (Dourojeanni 2015; Espejo et al. 2018). On the other hand, Peru had a new exploration boom in oil and gas blocks during the second period of study, as a consequence of national investment promoted policies (Finer and Orta-Martínez 2010). These blocks cover more than 70% of the Peruvian rainforest and their exploration and extraction could promote deforestation by facilitating access to previously remote primary forests. Although these activities are harmful, there is little information about them (Dourojeanni 2019).

Protected areas of all regions were outside the main deforestation focus through time (Fig. 4). Deforestation rates in the coast, high rainforest, and flooded rainforest protected areas had a very small increase along periods following the national pattern (Figs. 2 and 5). However, the protection effect of protected areas was not enough in the not flooded rainforest and, mainly, in the Andean region. In the not flooded rainforest, there are reports of anthropogenic activities, such as the expansion of agricultural lands, agroindustrial plantations; mining and the illicit coca cultivation, that had increased deforestation in protected areas (Asner and Tupayachi 2017; Dourojeanni 2018; Sánchez et al. 2021; UNDOC and DEVIDA 2018). On the other hand, the high deforestation rates in the Andean protected areas could be associated with the severe increase in fires due to droughts (Zubieta et al. 2021). The considerable increment in deforestation rate in the last period in the Andean region (Fig. 5) could be a consequence of the intense fire season at the end of 2016, before the 2017 "El Niño costero" that seriously affected protected areas in the coast and Andean regions in northern Peru (Novoa and Finer 2017). In 2017, 86.5% of the Andean deforestation was in the north of the country (departments of Piura, Lambayeque, Cajamarca, and La Libertad) and 93.6% was within seven Andean protected areas (see Supplementary Fig. 5).

Final remarks

Although our analysis shows that deforestation in Peru from 2000 to 2020 was lower than in other neighboring countries, national and regional deforestation rates were increasing, especially for 2011–2020, except for the coast region. However, the national conservation strategy based on protected areas succeeded in avoiding deforestation in all regions, except in the Andean region. It is important to note (1) the reports of anthropogenic activities that surpassed buffer zones causing deforestation inside protected areas have been more frequent in the last decade; (2) the episodes of drought and ENSO have been more frequent and intense in recent decades because of climate change; (3) forest fires are increasing in last years, but Peru is not prepared to face new and more intense fire risks (Dourojeanni 2016); (4) the development of road infrastructures near the protected areas increases the rates of deforestation and partially cancels the protective effects (Aguirre et al. 2021); and (5) we noticed that the increment in deforestation rates could be related to variations in environmental and climatic conditions, intensification of climatic events that influenced disturbed forest cover, increase in accessibility of forests. It also could be aligned with the increment in anthropic activities, which vary according to the region, and were promoted by subjacent causes (although we did not analyze these factors; supplementary Table 4). Therefore, it is urgent to differentiate the drivers of deforestation that operate at the national versus the regional scale and that all forest types are to be considered in the monitoring system and to strengthen the policies related to land use to change at all scales.

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Data availability As we indicated in forest cover data, the data utilized in our analysis originates from the publicly available Global Forest Change (GFC) version 1.8 dataset.

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