Deforestation Dynamics in Peru

A Comprehensive Review of Land Use, Food Systems, and Socio-Economic Drivers

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ABSTRACT

The drivers of deforestation and land use change in the Peruvian Amazon and Andes are complex and interconnected, shaped by various factors, including agricultural expansion, wood extraction, mining, infrastructure development, climate change, and socio-economic factors. This review highlights the multifaceted nature of these drivers and their impacts on the environment and local communities. Addressing these issues requires a comprehensive approach that accounts for both direct and underlying drivers and the unique context of each region. Effective management strategies must consider the ecological, social, and economic dimensions of these challenges. Promoting sustainable agricultural practices, improving forest governance, empowering local communities, and fostering collaboration between stakeholders are crucial steps to protecting Peru's natural resources. These measures can help balance economic development with environmental conservation, ensuring the sustainable use of land and resources. Equally important is addressing the underlying social and economic factors that drive land use change, including poverty, population growth, and migration. These factors often exacerbate environmental degradation and need to be integrated into broader development and conservation strategies.

A holistic approach that acknowledges the distinct challenges faced by the Amazon and Andean regions, can contribute to face deforestation as well as ensure the well-being of local communities, biodiversity conservation, and contribute to the effort to mitigate climate change. Such an approach requires coordinated efforts from government, non-governmental organizations, local communities, and international partners to create effective and sustainable solutions.

1 INTRODUCTION

Peru is highly vulnerable to the impacts of climate change due to its unique geographical location and socioeconomic conditions (Oliver-Smith, 2014). The country is particularly susceptible to climate change effects, such as increased frequency of extreme weather events, enhanced glacier retreat, loss of biodiversity, increased soil erosion risk, among others (Correa et al., 2016; Heikkinen, 2017; Zevallos and Lavado-Casimiro, 2022). Smallholder farmers face significant challenges adapting to these changes, as their livelihoods are closely tied to natural resources (Heikkinen, 2017; Lennox, 2015). Moreover, socioeconomic factors, such as poverty, food insecurity, poor health, and marginalization, exacerbate these vulnerabilities and make it difficult for communities to adapt (Heikkinen, 2021; Oliver-Smith, 2014).

In Peru, climate change has intensified hydrometeorological hazards, such as torrential rainfalls, floods, and glacier retreat, leading to migration within the country (Bergmann et al., 2021). The country's geographic, economic, developmental, social, demographic, and environmental characteristics vary between its regions, making them vulnerable to different levels of climate change impacts (Hoffman and Grigera, 2013).

The climate hazards are exacerbated in the Peruvian Andes and Amazon because of the high levels of poverty and inequality, with major deficiencies in basic services and threats related to environmental degradation, climate change, and pressure on water sources in the coastal and Andean areas, resulting in social tension and violence centered on the environmental impacts of extractive industries and large infrastructure projects. Also, melting glaciers are shrinking dry-season water supplies, disrupting rural highland society, and sparking migration (Hoffman and Grigera, 2013).

Climate hazards among other factors have push migration from the Andes highlands to the Amazon, together with aspiration of access new land (Ichikawa et al., 2014). Immigrants from the Andes often move to the Amazon for better opportunities and resource access, contributing to deforestation and environmental degradation in the region (Menton and Cronkleton, 2019).

In turn, deforestation affects the carbon stock by releasing carbon stored in trees and soils, contributing to greenhouse gas emissions and climate change (Achard et al., 2014). Loss of forest cover also reduces the capacity of forests to absorb carbon dioxide from the atmosphere through photosynthesis. According to the IPCC Special Report on Climate Change and Land 2019 (IPCC, 2019a), the agriculture, forestry, and other land use sector is the second largest contributor to global greenhouse gas emissions, second only to burning fossil fuels. During 2007-2016, land use and land-use change are estimated to have generated net CO2 emissions of 5.2 ± 2.6 GtCO2 yr-1 (IPCC, 2019b). Deforestation was the main cause of net CO2 emissions, as well as soil cultivation and oxidation of wood products, among others. In the western Amazon, specifically in the Madre de Dios region, forest loss was at an annual rate of -0.21% between 1999 and 2018 (Alarcón et al., 2021). In addition, Asner et al. (2010) reported that over 4.3 million ha of the Peruvian Amazon between 1999 and 2009, emissions from land use totaled 1.1% of the standing carbon and forest degradation increased regional carbon emissions by 47% over deforestation alone, while secondary regrowth provided an 18% offset against total gross emissions.

Peru is among the nations that have ratified the Paris Agreement. Through its Nationally Determined Contributions (NDCs), Peru has committed to reducing its annual GHG emissions by 30% in 2030 compared to a business-as-usual scenario. An established target in these NDCs is to reduce greenhouse gas (GHG) emissions associated with the forestry sector and land-use changes (LUCs) by 43.1 MtCO2eq by 2030, which represents more than the 50% of the total reduction committed by that year (MINAM, 2019). In contrast, deforestation rates increased by 58% in 2009-2016 compared to 2001-2008 (MINAM, 2016; Vázquez-Rowe et al., 2019). In this sense, identifying and addressing the direct and underlying drivers of deforestation and land use change is essential for effective national strategies. This study aims to analyze these main drivers, particularly focusing on the interconnected regions of the Andes and the Amazon.

Some studies have been done to predict deforestation across the Peruvian Amazon, such as applying machine learning algorithms or other related tools. Using such methods could help improve strategies for reducing future deforestation and preserving carbon stocks in Peru and other forest regions (Rojas et al., 2021). Additionally, high spatial resolution monitoring of aboveground carbon density (ACD) and emissions (ACE) in Peru revealed a total of 7.138 Pg C estimated for the country, with an annual ACE of 20.08 Tg C between the third quarters of 2017 and 2018 (Csillik and Asner, 2020a). This finding underscores the need for enhanced forest carbon management at scale to mitigate climate change.

Understanding the impact of land management practices on soil carbon dynamics in Peruvian ecosystems is essential for implementing effective conservation and restoration policies. Oliver et al. (2017) found that grazing and burning increased soil CO2 fluxes and decomposition rates in Peruvian montane grasslands. Still, long-term carbon storage in occluded light fractions and heavy fractions was not negatively impacted. This is useful for designing appropriate land-use management strategies that do not compromise the carbon storage capacity of these ecosystems.

This document focuses on the Andes and Amazon conditions where climate hazards affect a large number of smallholders and produce the largest amount of greenhouse gas emissions in the country. The insights gained from this study are crucial for informing policy decisions and conservation efforts, not only in Peru but also in other regions facing similar challenges.

2 CLIMATE CONDITIONS AND VULNERABILITY IN THE ANDES AND AMAZON

2.1 NATURAL CAPITAL AND CLIMATE CONSEQUENCES OF DEFORESTATION IN THE AMAZON AND ANDES

The Amazon rainforest, a vital ecosystem for global carbon regulation and a significant reservoir of natural capital, is critical in mitigating climate change and preserving biodiversity (Azevedo et al., 2020; Gatti et al., 2021). The interplay between the Andean and Amazonian ecosystems is crucial for regional climate regulation, underscoring the need for integrated conservation strategies that consider the dynamics of both regions. Coe et al. (2017) noted that tropical forests play a direct role in maintaining low surface temperatures and high precipitation. Indigenous and local communities play a vital role in preserving the natural capital of these regions. Recognizing and integrating their traditional knowledge and practices is essential for effective and sustainable management of these ecosystems.

On the other hand, forest degradation from selective logging and understory fires contributes to carbon emissions, potentially accounting for up to 40% of carbon loss in the region (Berenguer et al., 2014). In this sense, some authors point out that addressing deforestation and degradation requires implementing policies that consider aspects such as reducing forest fires and increasing the area of secondary forests while avoiding further removal of primary forests (Aragão et al., 2014; Azevedo et al., 2020). Incentives for better forest management and integrating local, regional, national, and international policies are also noted as necessary to adapt to and mitigate climate change (Azevedo et al., 2020). For instance, a study by Barua et al. (2012) found that carbon payments could effectively reduce forest clearing and pointed out that an effective policy to combat tropical deforestation should jointly consider the forestry and cash-crop sectors. Some authors point out that policies and programs like Reducing Emissions from Deforestation and Forest Degradation (REDD+) should support existing efforts towards forest sustainability and balance economic development with the protection of natural capital to ensure the long-term viability of these critical ecosystems (Bottazzi et al., 2014; Galford et al., 2011).

In 2016, Aguiar et al. noted a decrease in deforestation rates in the Brazilian Amazon, stabilizing around 6,000 km^2 yr^{-1} in the previous five years of their study. They stated that while a combination of factors contributed to the decreased deforestation rates in the Brazilian Amazon, including creating protected areas, effective monitoring systems, and credit restriction mechanisms, several threats remained, such as rapidly expanding global markets for agricultural commodities, large-scale transportation and energy infrastructure projects, and weak institutions (Aguiar et al., 2016). In contrast, Murugasan et al. (2019), modeling deforestation scenarios, concluded that the

Amazon Basin is at risk of significant deforestation, with the forested area predicted to be reduced by about half by 2050 under the Business-as-Usual scenario and if the current rate of deforestation continues, the world´s forests could dissolve within the next 100 years.

On the other hand, the high Andes region is home to diverse ecosystems crucial in carbon sequestration and climate regulation, such as paramo grasslands, montane cloud forests, and high-altitude wetlands (Peña et al., 2011). Andean forests act as strong sinks for aboveground carbon and have a high potential to serve as future carbon refuges (Duque et al., 2021). As climate change continues to impact these regions, adaptive management strategies that can respond to evolving environmental conditions are crucial for the sustainability of these ecosystems and the communities that depend on them. For instance, montane cloud forests in the high Andes, such as those in Manu National Park, Peru, are also significant carbon stores. Improved management of these ecosystems can generate additional income for rural communities by commercializing carbon credits (Gibbon et al., 2010). Also, Andean peatlands are essential for carbon and nitrogen accumulation. Understanding the factors affecting the accumulation of these elements in peatlands is crucial for assessing the impacts of climate change on these ecosystems (León and Oliván, 2014). In addition, the Andean plateau contains significant soil organic carbon (SOC) reservoirs, which are vulnerable to climate change and anthropogenic activities, such as changes in land use and water management (Muñoz et al., 2015).

The region faces numerous challenges, including land use change, deforestation, and climate change, which affect carbon storage and the livelihoods of local communities (Barrera et al., 2012). Although several projects have been implemented to promote environmentally friendly farming practices and soil and water conservation techniques, economic development in the Andean region is often hampered by extreme poverty, low agricultural productivity, and limited off-farm opportunities. Exploring sustainable economic opportunities, such as ecotourism and sustainable harvesting of non-timber forest products, could provide alternative income sources for local communities while contributing to conservation efforts.

Deforestation and land-use change have been significant sources of anthropogenic CO_2 emissions in South America, with pasture expansion, commercial cropland, and infrastructure development often noted as some of the main drivers (De Sy et al., 2015). While there are policies in place aimed at protecting these ecosystems, challenges in implementation and enforcement remain significant. Strengthening governance and institutional capacities is crucial for the effective management of these regions. In the Andean community countries, there is a bidirectional relationship between economic growth, consumption of energy, and CO_2 emissions (Koengkan et al., 2018). To ensure the sustainable development and protection of these ecosystems, it is essential to implement effective land use policies, promote environmentally friendly practices, and address the economic and social challenges local communities face.

2.1.1 Amazon ecosystems with a high accumulation of carbon

The Amazon is a critical carbon sink in the global carbon cycle and climate change mitigation. Its ecosystems, including the rainforest, peatlands, mangroves, and transitional forests, store substantial carbon. These ecosystems are essential for optimizing conservation efforts and maintaining global climate stability.

The Amazon rainforest has been a long-term net biomass sink, although the rate of carbon accumulation has decreased over recent decades (Brienen et al., 2015). Rödig et al. (2018) found that the Amazon rainforest gains 0.56 GtC per year, driven by a mean gross primary productivity (GPP) of 25.1 tC ha^{-1} a^{-1} and a mean woody aboveground net primary productivity (wANPP) of 4.2 tC ha^{-1} a^{-1}. The study also found that forest structure and successional states are essential factors in the relationship between productivity and biomass, highlighting the need for forest management strategies that consider these aspects.

Tropical rainforests store enormous amounts of carbon, but human disturbances, such as selective logging, understory fires, and habitat fragmentation, affect carbon stocks and emissions. Disturbed forests store 40% less aboveground carbon on average compared to undisturbed forests and are structurally similar to secondary forests. Carbon emissions from these disturbances are significant and could represent up to 40% of the carbon loss from deforestation in the Amazon (Berenguer et al., 2014).

Mangroves are ecologically and economically important forests in the tropics, contributing disproportionately to the carbon sequestration (Alongi, 2014). The Brazilian Amazon has one of the largest areas of mangroves in the world, storing substantial amounts of carbon. The mean ecosystem carbon stocks of mangroves east of the Amazon River ranged from 361 to 746 Mg C ha^{-1}, with the Amazon mangroves storing over twice the amount of carbon than upland evergreen forests and almost ten times the amount found in tropical dry forests (Kauffman et al., 2018). However, potential carbon losses due to deforestation are of immediate concern, with rates greater than these ecosystems' carbon storage (Alongi, 2014).

The dry transitional forests in southern Amazonia have received less attention but represent important carbon-cycling ecosystems (Araujo-Murakami et al., 2013). These forests exhibit higher leaf photosynthesis and total GPP due to drier soil conditions favoring dry deciduous tree species. Carbon allocation patterns are similar to those in wetter humid forests, with the dry forests of southern Amazonia acting as a scaled-down version of their humid counterparts (Araujo-Murakami et al., 2013).

Amazonian peatlands store significant amounts of carbon, with tropical peatlands accounting for about half of the global peatland emitted carbon (Ribeiro et al., 2021). For instance, the Amazon's Pastaza-Marañón Foreland Basin (PMFB) is among the largest known intact tropical peatland landscapes globally and is considered highly threatened due to human activities such as deforestation and agricultural expansion (Roucoux et al., 2017). Peatlands in Amazonian Peru cover 35,600 ± 2133 km^2 and contain 3.14 (0.44-8.15) Pg C. Peatland pole forests, in particular, are identified as the most carbon-dense ecosystem in Amazonia (1391 ± 710 Mg C ha^{-1}) (Draper et al., 2014). Swindles (2018) reported that the Aucayacu peatland in the PMFB is the oldest peatland in Amazonia, accumulating peat up to 7.5 meters deep in approximately 8,900 years.

These ecosystems face various threats, including deforestation, agricultural expansion, and climate change. The preservation of these ecosystems is not only crucial for carbon sequestration but also for maintaining biodiversity and supporting local communities. It is crucial to protect these ecosystems and support their role as carbon sinks to maintain global climate stability and ensure the success of the Paris Climate Agreement (Walker et al., 2020).

Peruvian amazon has several concrete examples of ecosystems that play a key role in mitigating climate change by acting as carbon sinks such as palm swamp peatlands and high-altitude grasslands. Understanding their carbon storage and dynamics is essential for developing effective conservation and restoration policies (Guerrero-Palomino et al., 2022; Hastie et al., 2022; Muñoz et al., 2015).

Amazon palm swamp peatlands are major carbon sinks and reservoirs, storing significant amounts of carbon alongside Andean forests with a strong carbon sink capacity (0.67 ± 0.08 Mg C ha^{-1} y^{-1}) (Dezzeo et al., 2021; Duque et al., 2021). However, these ecosystems are threatened due to deforestation and land-use changes, with the Peruvian Amazon losing around 190,000 hectares of forest in 2020 alone (Dourojeanni, 2022). The ongoing degradation of these ecosystems can potentially disrupt peat accretion and reduce carbon stocks, emphasizing the need for sustainable management and protection (Dezzeo et al., 2021; Duque et al., 2021).

2.1.2 Andean ecosystems with a high accumulation of carbon

The High Andean ecosystems, such as wetlands, forests, grasslands, and the paramo, puna, and southern Andean steppe habitats, are characterized by unique environmental conditions and diverse flora and fauna that contribute to various ecosystem services, including carbon accumulation and sequestration (Alvis-Ccoropuna et al., 2021; Arroyo and Cavieres, 2013). These ecosystems play a critical role in mitigating climate change by storing significant amounts of carbon in aboveground biomass, belowground biomass, and organic soil (Gibbon et al., 2010; Segnini et al., 2011).

High Andean wetlands, forests, grasslands, and other habitats are known for their substantial carbon storage capacity due to their low decomposition rates, which result from flooded soils, low temperatures, and low soil pH (Alvis-Ccoropuna et al., 2021; Muñoz et al., 2015; Oliveras et al., 2014). Research has shown that these ecosystems store significant amounts of carbon in aboveground and belowground biomass, as well as in organic soil, with the latter accounting for the highest carbon storage (Alvis-Ccoropuna et al., 2021; Girardin et al., 2014; Vásquez et al., 2014). In a study centered on the cloud forest-grassland transition of the high Andes in Manu National Park, Peru, Gibbon et al. (2010) found that the puna grasslands stored 7.5 ± 0.7 Mg C ha^{-1} in aboveground biomass, while the forest near the treeline contained 63.4 ± 5.2 Mg C ha^{-1} aboveground and an additional 13.9 ± 2.8 Mg C ha^{-1} in the coarse roots.

The unique environmental conditions of the High Andean ecosystems, such as cold and wet climate, low atmospheric pressure, and low soil pH, contribute to the accumulation of organic matter and carbon storage (Muñoz et al., 2015, 2013). Organic matter decomposes very slowly in these conditions, and its content increases with altitude. Approximately 40-60% of the soil organic carbon (OC) exists within the top 20-cm layer, with a high C/N ratio in the Andean highlands indicating intense humification (Muñoz et al., 2015). Segnini et al. (2011) determined carbon contents and carbon stocks in five Peruvian agroecologies along a 1,000 km transect and found that soils in the tropical highland rainforest site had the highest carbon contents (134 g kg $^{-1}$ [13.4%]) and that diversified production systems with crops and livestock were more stable for carbon stocks.

Human activities, such as grazing, burning, and land use changes, can negatively impact the carbon storage capacity of high Andean ecosystems and their biodiversity (Muñoz et al., 2013; Oliveras et al., 2014; Tovar et al., 2013). These disturbances can reduce the net primary productivity (NPP) of the puna grasslands and result in the loss of grasslands and montane forests due to agriculture and other land use changes (Oliveras et al., 2014; Tovar et al., 2013). Consequently, it is essential to implement strategies to protect these ecosystems and their essential functions, including their roles as stable carbon reservoirs and habitats for threatened species.

The tropical montane forest ecosystems of the Peruvian Andes are under threat from climate change, which is expected to have a high potential impact on 58% of all montane forests, particularly in the elevation range between 800 and 1200 m.a.s.l (Bax et al., 2021). Moreover, about 64% of montane forests in protected areas will be exposed to high potential impact. Enhancing the adaptive capacity of these ecosystems through restorative and preventive conservation measures, such as improving forest functions and mitigating deforestation and forest degradation pressures, is crucial for their survival (Bax et al., 2021).

Andean peatlands, particularly those formed by cushion plants, and high-altitude grasslands in the Andean plateau, such as the puna, are vital carbon sinks in Peru. These peatlands and grasslands are influenced by climate change and human activities, such as grazing, ditching, and unsuitable water management, which alter hydrologic conditions and degrade these essential carbon reservoirs (Muñoz et al., 2015; Planas-Clarke et al., 2020). Hydrologic restoration, such as rewetting of moderately drained peatlands, could help moderate climate change's impacts on Andean peatlands and increase their ability to store carbon (Planas-Clarke et al., 2020)

2.2 Vulnerability to climate change in Peru

Climate change poses significant risks to Peru, making the country highly vulnerable to food insecurity, floods, landslides, water scarcity, vector-borne diseases, coastal risks, and systemic failures due to cascading impacts of hazards and epidemics, among others (Hagen et al., 2022). Inequities in water governance and changes in the hydrology of Peru due to glacial retreat are magnifying vulnerabilities in communities, food producers, and poor urban neighbourhoods (Lynch, 2012). These challenges underscore the need for comprehensive and inclusive approaches to water management and climate adaptation strategies. Various adaptation measures have been identified to address these risks, but the low adaptive capacity and climate change may limit their effectiveness (Hagen et al., 2022). Furthermore, there is a need for increased investment in building adaptive capacities at local and national levels to enhance resilience against climate change. Additionally, adaptation strategies have limited attention, which is insufficient for the country (Takahashi and Meisner, 2012).

Climate change affects the food systems in Peru, with implications for agricultural production, food security, and the livelihoods of smallholder farmers (Lozano-Povis et al., 2021; Tito et al., 2018). The Andean region is highly vulnerable to climate change, with increased rainfall intensity, soil erosion, retreat of glaciers, and loss of vegetation cover, all impacting crop dynamics. Innovative agricultural practices and technologies, such as climate-smart agriculture, are essential to adapt to these changing conditions. In this regard, Peru's food production and crop yields are also negatively affected, especially for crops such as quinoa, potatoes, and tarwi (Lozano-Povis et al., 2021).

One of the primary challenges to Peru's food systems is ensuring adequate food production and security in the face of climate change. Rising temperatures can lead to declining crop yields, forcing farmers to change cultivation practices or relocate their crops to higher elevations. However, such changes may also result in the introduction of novel pests and a decline in crop quality and value, leading to severe economic losses for local farmers and food insecurity (Tito et al., 2018).

2.2.1 Climate-related hazard for the Andes and Amazon

The climate-related hazards in Peru pose significant threats to the diverse environments, ranging from coastal deserts to high Andean mountains and humid Amazon lowlands (Young and León, 2009). Population growth and urban expansion increase the vulnerability of communities to these hazards, which include floods, landslides, glacial retreat, and extreme weather events (Oliver-Smith, 2014; Vilímek et al., 2005).

El Niño events are one of the primary climate-related hazards in Peru, causing intense rainfall, ponding water, flash floods, and landslides, leading to significant damage to society (Brill et al., 2020). Damage modelling based on data-mining methods and remote sensing products, are some tools used in risk assessments. The integration of these advanced technologies with traditional knowledge systems can enhance the accuracy and relevance of risk assessments. Also, the topographic wetness index and the slope length and steepness factor are crucial features in classifying damage from compound natural hazards like El Niño events (Brill et al., 2020).

On the other hand, glacier retreat in the Cordillera Blanca mountain range has led to the formation of glacial lakes, posing a risk of glacial lake outburst floods (GLOFs) (Vilímek et al., 2014). GLOFs are closely connected with dynamic slope movements, such as ice- and rock-falls and landslides of steep moraine slopes, accounting for around 80% of GLOFs in the region. These outburst floods can lead to highly hazardous debris and mudflows, significantly impacting the high mountainous environment (Vilímek et al., 2014). Despite efforts by a Peruvian glaciology and lakes security office, glacier disasters killed nearly 30,000 people in five glacier-related disasters in Peru´s Cordillera Blanca from 1941 to 1970 (Carey, 2005). A lack of trust between local communities and government officials has exacerbated the problem, where many residents live in hazard zones.

Andean populations are vulnerable to climate change and disasters due to poverty, food insecurity, poor health, and marginalization. According to Oliver-Smith (2014), to address these vulnerabilities, adaptation policies must integrate measures to reduce specific hazards with programs aimed at reducing systemic vulnerabilities and societal inequality. This approach should include empowering local communities and ensuring their active participation in decision-making processes.

Addressing climate-related hazards in Peru requires a better understanding and integration of scientific knowledge and local expertise (Salzmann et al., 2009). For example, physically-based numerical models can help simulate complex cascades of mass movement processes, informing the development of hazard maps and guidelines for debris flows (Schneider et al., 2014). Integrating earth science research and social science insights is crucial in understanding the processes and mechanics of hazard occurrence and impact and exploring the causes of human vulnerability to hazards. Building on this research can contribute to more inclusive and unified disaster mitigation strategies at the local, national, and international levels (Degg and Chester, 2005).

Furthermore, investing in early warning systems and hazard monitoring, such as developing hazard maps and guidelines for debris flows (Schneider et al., 2014), can improve preparedness and reduce the impacts of natural disasters on communities. These efforts should be combined with targeted education and awareness programs to help communities better understand the risks associated with climate-related hazards and implement appropriate adaptation and mitigation measures.

Apart from this, indigenous communities in the Andes have a long history of effectively responding to water threats. Developing better communication and trust between local people, scientists, and policymakers is essential in reducing vulnerability to natural disasters (Carey, 2005). By incorporating local knowledge and expertise into hazard management strategies, communities can better adapt to the changing environment and mitigate the adverse effects of climate-related hazards (Postigo, 2021; Salzmann et al., 2009). For instance, indigenous pastoralist communities have adapted by creating wetlands and moving livestock, supported by dynamic and flexible institutions that facilitate access to alternate grazing areas and the necessary labor force (Postigo, 2021). However, climate change and increasing water demand maintain the water threats as serious hazards to the communities.

Lastly, addressing the underlying social factors that amplify vulnerability to natural hazards, such as poverty and disconnection between scientific predictions and people's actions, is crucial (Young and León, 2009). Enhancing community resilience through education, infrastructure development, and equitable resource distribution is vital for long-term hazard mitigation.

2.2.2 Climate risk in Peru

Climate risks in Peru are a significant concern as the country is highly vulnerable to the adverse effects of climate change, such as glacier recession, water scarcity, soil erosion, and river overflow (Correa et al., 2016; Mark et al., 2017; Nieto-Chaupis, 2018; Oliver-Smith, 2014). These issues impact not only the environment but also the socioeconomic well-being of the Peruvian population.

One major climate risk in Peru is the rapid recession of glaciers due to global climate change. The accelerated glacier retreat in the Peruvian Andes significantly impacts the hydrologic cycle and water resources (Mark et al., 2017). As glaciers continue to melt, the timing and variability of hydrologic changes and their impacts on water availability become uncertain. These changes affect water access, and hydro-social risks across various sectors and water uses, with implications for environmental sustainability, agricultural activities, and water rights and governance (Mark et al., 2017). Incorporating climate change projections into water management planning is essential to ensure long-term water security.

Water resources are crucial for Peru's socioeconomic development, and their estimation is vital for adequate water management in the future (Andres et al., 2014). Changes in precipitation patterns due to climate change may negatively impact the siltation of Andean storage reservoirs, such as river catchments (Rosas et al., 2020). The vulnerability of these reservoirs to climate change highlights the need for improved strategies to mitigate the risks associated with climate-induced changes in key ecosystem processes (Scholze et al., 2006).

Soil erosion is another significant climate risk in Peru, particularly in the Andes region, where steep slopes, sparse vegetation cover, and high-intensity rainfall exacerbate soil degradation (Correa et al., 2016). Climate change may further increase soil erosion risk, threatening environmental sustainability and agricultural activities in the Mantaro River basin and other vulnerable areas (Correa et al., 2016; Trasmonte et al., 2008). Furthermore, the El Niño phenomenon can exacerbate the risk of river overflow in coastal areas of Peru, highlighting the importance of disaster anticipation and risk management (Nieto-Chaupis, 2018).

Oliver-Smith (2014) argues that the policies should integrate measures to address specific hazards with programs that reduce systemic vulnerabilities and societal inequality. Furthermore, there is a need for improved scientific baseline and integrative concepts to deal with the adverse effects of climate change in mountain regions like the Peruvian Andes (Salzmann et al., 2009).

2.2.3 Vulnerability to Climate change in Andean-Amazon ecosystems

Peru's vulnerability to climate change is exacerbated by its complex topography, diverse ecosystems, and agricultural dependence (Vidal Merino et al., 2019). Rural populations, in particular, face significant challenges as their livelihoods depend on natural resources increasingly affected by climate change (Diaz et al., 2011).

The Andean-Amazon foothills region is one of the most biodiverse ecoregions on Earth. Its rich ecosystems are threatened by climate change and unsustainable agricultural practices, such as extensive livestock farming (Beltrán-Tolosa et al., 2022). These practices not only contribute to environmental degradation but also reduce rural farming diversification, making households more vulnerable to climate change.. The study conducted by Beltrán-Tolosa et al. (2022) revealed that households with higher rural livelihood diversification are less vulnerable to climate change, emphasizing the importance of promoting diversified farming practices to enhance resilience in the face of climate change.

Farm households in the Central Andes of Peru face various climate-related hazards such as frost and droughts. Their capacity to adapt is influenced by farm areas, agroecological zones, irrigation, off-farm employment, and climate-related damages (Vidal Merino et al., 2019). It is essential to tailor adaptation strategies to these diverse conditions to effectively increase the adaptive capacity of farm households.

Some authors highlight the need for integrated local assessments to better understand the vulnerability and adaptation to climate change (Martínez et al., 2006). Such assessments can help inform future interventions to decrease the sensitivity of Andean households and strengthen their adaptive capacity to climate change (Beltrán-Tolosa et al., 2022).

Additionally, climate change can impact the frequency and severity of El Niño Southern Oscillation (ENSO) events, which have been associated with increased cases of diseases such as cholera, malaria, and dengue in Peru. Climate change can also exacerbate existing environmental risk factors, such as water and air pollution, further endangering the health and livelihoods of the Peruvian population (Gonzales et al., 2014).

The vulnerability of Peru to climate change is a multifaceted issue that requires concerted efforts to enhance the resilience of communities, particularly those in rural areas. Developing and implementing comprehensive climate change adaptation and mitigation strategies, which include community participation and consider local socio-economic and environmental contexts, is vital for building resilience in these vulnerable regions.

3 LAND USE CHANGE IN THE PERUVIAN AMAZON

Land use changes are caused by a variety of direct factors in the Andes and Amazon. We identified through an extensive literature review, the most relevant ones in this chapter.

3.1 Amazonian land use

Deforestation in the Peruvian Amazon has become a significant environmental concern, with numerous direct causes contributing to the rapid loss of forest cover. One prominent direct cause of deforestation in the region is agricultural expansion, particularly the conversion of forested land to smallholder farming and cattle ranching (Arce-Nazario, 2007; Chávez et al., 2014). Agricultural activities have been driven by various factors, such as increasing demand for food and land and migration from the Andean highlands to the lowland Amazon basin (Perz et al., 2005; Serra-Vega, 1990). The need for sustainable agricultural practices that balance environmental conservation with economic development is therefore critical. Establishing new settlements and infrastructure development, including roads, further exacerbate deforestation by providing easier access to previously remote forest areas (Armenteras et al., 2017).

Another direct cause of deforestation in the Peruvian Amazon is the extraction of timber and non-timber forest products (Bax et al., 2016). Illegal logging and unsustainable harvesting of forest resources have contributed to the degradation of the region's forests, affecting the ecological balance and biodiversity (Rojas Briceño et al., 2020; Sánchez-Cuervo et al., 2020). Implementing effective forest management and monitoring systems is essential to combat these practices.

Moreover, expanding mining activities, particularly gold mining, has led to significant forest loss and environmental degradation in the Peruvian Amazon (Rojas et al., 2021). Mining operations often involve clearing large forest areas and using hazardous chemicals, such as mercury, which can contaminate water sources and impact the health of local communities (Espinoza-Guillen et al., 2022). Deforestation in the Peruvian Amazon is a multifaceted issue driven by various direct causes. This section presents multiple studies that examine each of these drivers, highlighting the complexity of the issue and the need for integrated solutions.

3.1.1 Extractive causes

A. Agricultural expansion

Deforestation in the Amazon region of Peru has been a major environmental problem for several decades, and the causes of this phenomenon have been the subject of intense debate. Arce-Nazario (2007) analyzed aerial photographs and satellite images of the Peruvian Amazon for a long-term study to reconstruct spatial transformations. He found that the highland region was used for agriculture in 1948, and farms encroached on primary forests. However, in 1965, 49% of the upland agricultural area was converted to secondary forest. Farmers left upland farms fallow and moved to the floodplains to grow crops promoted through agricultural credit programs. Between 1965 and 1977, river channel migration affected the riparian landscape, causing flooding throughout the Amazon River, and many farmers migrated to the city. During the 1980s, credits granted to small farmers increased, resulting in the highest density of farms in the landscape in 1993. The disappearance of these credits is reflected in the reduction of agricultural activity and the increase in charcoal production. However, according to Ravikumar et al. (2017), a predominant narrative in Peru has been that small-scale or shifting agriculture is the main cause of deforestation. However, the authors argue that this narrative is based on remote sensing data that do not necessarily distinguish between various forms of land use, including sustainable fallow management and agroforestry, which could have positive environmental outcomes.

Andrieu et al. (2019) analyzed the link between food security and deforestation in mestizo communities in Ucayali, one of the regions with the highest deforestation rates in the Peruvian Amazon. The study reported that the most diversified farming households had the lowest trade-offs between food security and forest conservation, as they are the most likely to preserve the forest while ensuring their food security. In addition, according to Blundo-Canto et al. (2020), based on a survey of 53 households in Ucayali in 2000 and 2015, there is an emerging trend toward less diversified food access, along with a loss of forest cover and a reduction in agricultural biodiversity. The authors indicated that agricultural production systems are becoming increasingly specialized, with a shift towards cash crops, and the years of increased deforestation appear to be related to incentives for agricultural expansion.

To address the problem of deforestation in Peru, the Forestry Law provides for Agroforestry Concessions. The objective is to integrate small landowners encroaching on public forest lands into the formal economy, strengthen local livelihoods and stimulate land restoration. According to Pokorny et al. (2021), based on a study conducted in three districts of Ucayali and San Martin, cocoa farmers have conflicting views on the potential of agroforestry and land tenure security to create economically and environmentally sound livelihoods. In the study, less than 20% achieved economically sound livelihoods. Although farm size, specialization, and participation in associations contributed to household economics, these had little effect on the quality of natural resource management and forest conservation capacity. So, it is argued that although sustainable land use practices are an important step, a broader holistic approach is required. This suggests that while agroforestry is a promising approach, it needs to be part of a broader, more holistic strategy that includes economic, social, and environmental considerations.

Van Straaten et al. (2015) in a comparative study that included data from Peru (Ucayali region), Indonesia and Cameroon, quantified the impact of forest conversion to agroforestry plantations of oil palm, rubber, and cocoa on soil organic carbon (SOC) stocks at 3 m depth in deeply weathered mineral soils. Their study showed that deforestation for tree plantations reduced SOC stocks by up to 50%. This finding highlights the need for careful consideration of the ecological impacts of agroforestry practices. Deforestation for commercial tree crop plantations causes significant alterations in SOC dynamics, highlighting the need for land-use management policies that protect natural forests on carbon-rich mineral soils to minimize SOC losses.

A frequent practice in the Peruvian Amazon is shifting cultivation, in which small-scale farmers clear and cultivate a plot of land for a while before abandoning it and moving to another plot. Coomes et al. (2021) conducted a study along three major rivers in the Peruvian Amazon in 138 communities to identify factors influencing the choice of fields for this practice. Among their results, they found that old-growth forest clearance rates were low and that these lands quickly returned to secondary forest cover. They also identified contextual, historical, and household factors influencing the decision to clear upland forests. They found that access to lowlands in floodplains was associated with lower rates of old growth clearing, and conversely, increased clearing was associated with higher educational attainment of the household head. Similarly, farm size, the degree of upland orientation, and the number and age of fallows when the logging decision was made were important factors in logging upland forests. Also, Coomes et al. (2022) found that while customary shifting cultivation created a zone of secondary forest, orchards, and crop fields around communities in what was once old-growth terra firme forest along the Napo and Amazon Rivers in the Peruvian Amazon, the area and rate of expansion into old-growth forests were modest when compared to forest conversion in Peru for colonization and plantation development. This indicates that shifting cultivation, when practiced sustainably, may not be as detrimental to forest conservation as often perceived. So, the study challenged the notion that smallholder agriculture along rivers was a significant threat to terra firme forests in Amazonia and emphasized the relevance of protecting forests from loggers, and colonists, among other outsiders.

In this regard, Coomes et al. (2011) reported some insides of the relationship between poverty and land cover change in an Amazonian village in northeastern Peru (San Jose). They examined how the dynamic links in shifting cultivation systems among asset poverty, land use, and land cover affect the persistence of poverty and the transformation of primary forests into secondary forests, orchards, and croplands based on aerial photographs and satellite imagery from 1965 to 2007 to assess land cover change and household and plot-level data to track land holding, portfolios, and use, as well as the land cover over the past 30 years. They identified two types of "land-use" poverty traps: a "subsistence crop" trap and a "short fallow" trap. In this case, they suggested that insufficient initial land holdings induce land use patterns that trap households in low agricultural productivity.

Apart from this, cattle ranching also contributes to the problem in the region. Cattle ranching is considered an essential economic activity in many parts of the Amazon. As demand for beef and other cattle products increases, more land is cleared for pasture, leading to deforestation (Hosonuma et al., 2012). Moreover, the expansion of cattle ranching is often facilitated by weak land-use policies and regulations and the construction of new roads and infrastructure projects that enable the industry to expand further into previously untouched forests (Plekhov et al., 2021).

One of the key challenges in addressing deforestation due to cattle ranching is the limited ability of extrinsic motivators, such as material incentives and protective laws, to reduce deforestation behaviors (Chambers et al., 2020). This is because local people's motivations for cattle ranching often stem from broader economic drivers, such as the need to generate income and secure their livelihoods. As such, conservation projects that rely on external design and fail to engage with local communities in co-designing governance approaches are often unable to achieve their intended outcomes (Chambers et al., 2020).

B. Wood extraction

Wood extraction is a major cause of deforestation in Peru, particularly in the Amazonian forests. In this regard, illegal logging is of concern because of its economic, environmental, social, and political impacts. At the same time, it can lead to the degradation of forest ecosystems, loss of biodiversity, and, indirectly, deforestation and the expansion of agricultural activity in some developing countries. It is estimated that between 2% and 4% of globally traded softwood lumber and plywood, and between 23% and 30% of globally traded hardwood and plywood, could originate from illegal logging activities (Sheikh, 2010).

Finer et al. (2014) indicated that Peru's legal logging concession system is not effective in ensuring sustainable logging practices, and several concessions are suspected of significant violations. Permits associated with legal concessions are sometimes used for logging trees in unauthorized areas, posing a threat to all forested areas. Furthermore, Anderson et al. (2019) reported that fines for illegal deforestation did not correspond with lower deforestation rates. This suggests a need for stronger enforcement and monitoring mechanisms within the legal framework.

According to Fitts et al. (2022), the forest is often crucial to the economic, social and cultural well-being of Peru's indigenous communities due to their long-standing connection to it. However, when communities partner with external institutions for timber exploitation, forest degradation, internal and external conflicts, and disinterest in new timber management projects have sometimes been reported. For example, the authors reported that in the Sinchi Roca I native community in Peru, locals partnered with a company for logging, resulting in negative perceptions of the activity and internal and external conflicts due to the company's presence. In addition, Salo et al. (2011) analyzed the allocation of logging rights using a case study from Loreto in the Peruvian Amazon, where millions of hectares of rainforest were offered for concession in a competitive bidding process that addressed locality-related issues. The study found that the allocation process left many forest areas under the management of small and local actors, making their participation a component for considering the implementation of sustainable forestry practices and reducing the negative impact of logging.

On the other hand, Goodman et al. (2019) evaluated carbon emissions from selective logging in certified and non-certified concessions in Madre de Dios, Peru. They found that emissions estimates did not differ by certification status. Still, certified concessions had higher log recovery and damaged fewer commercial species during felling, which should increase their current and future timber yields. They found that total carbon emissions from selective logging were low per hectare due to low logging intensities, and emissions per volume and per ton of carbon in the harvested wood were also relatively low. Emissions were dominated by the harvested tree itself, while transport infrastructure contributed comparatively little.

Also, Rico-Straffon et al. (2023) analyzed the impact of logging concessions and eco-certifications on deforestation in Peru. The researchers estimated the effects of logging concessions and their eco-certifications on forests in the

Peruvian Amazon between 2002 and 2018. The results suggest that logging concessions did not increase forest loss and could even reduce it slightly by avoiding spikes in deforestation pressure. However, in this study, eco-certifications did not significantly impact forest loss, which may indicate that, although eco-certifications are designed to promote sustainable forestry practices, more is needed to address the root causes of deforestation in Peru.

Apart from this, wood extraction for charcoal production is a significant driver of deforestation in Peru, especially in the Amazon region, where it is an important source of fuel (Bennett et al., 2018). Charcoal is mainly used in urban areas to fuel industries and households. For example, charcoal production in the urban area of Pucallpa, Ucayali, is estimated to be much higher than official figures, with most of it being used to supply chicken rotisseries in Lima (Bennett-Curry et al., 2013). Amazonian commercial charcoal is mainly produced from sawmill by-products and is not considered a direct threat to the rainforest. However, according to Bennet-Curry et al. (2013), the lack of availability of the preferred species, shihuahuaco, is of concern as it suggests overexploitation of the species in the region. One of the main challenges in addressing the issue of charcoal production and deforestation in Peru is the informal nature of the charcoal supply chain. Charcoal production is often undertaken by rural populations, who depend on it for their livelihoods. The decentralization process has institutional barriers to formalizing charcoal supply chains at different levels, perpetuating inequity (Bennett et al., 2018).

The impact of charcoal production is not limited to the Amazon region alone. Jameson and Ramsay (2007) reported that the high-altitude Polylepis forests of the Andes, which are an essential habitat for endemic species and provide natural resources to people, are also threatened by overexploitation and land management practices. For example, in the Vilcanota Cordillera, firewood collection for charcoal production and livestock grazing activities have decreased canopy density and tree size, negatively affecting forest dynamics, associated biodiversity, and ecological function and ecosystem services (Jameson and Ramsay, 2007).

However, there is a discussion about developing a more sustainable supply chain for charcoal. Labarta et al. (2008) analyzed the impact of incorporating charcoal production by pioneer farmers in the Peruvian Amazon rainforest on household net returns and the rate of deforestation at the early stage of forest colonization. The study found that charcoal production diverts scarce dry-season labor from land clearing for agriculture, resulting in slower deforestation rates. Furthermore, incorporating charcoal production into the livelihoods of pioneer farmers resulted in higher net income and a less forested area cleared, providing a potential alternative to unsustainable land use practices (Labarta et al., 2008).

Overall, these studies highlight the need for policies to combat illegal deforestation and promote sustainable logging practices in the Peruvian Amazon. Effective management and regulation of the timber industry, along with community engagement and sustainable livelihood alternatives, are crucial in addressing the challenges posed by wood extraction.

C. Illicit crops

Illicit crops influence drivers of deforestation in various regions of South America (Bradley and Millington, 2008; Dávalos et al., 2011; Negret et al., 2019; Quiroga Angel et al., 2022; Viña et al., 2004). Illicit crop cultivation, specifically coca cultivation, has also been identified as a driver of deforestation in the Peruvian Amazon and a constraint on biodiversity conservation (Bax and Francesconi, 2018; Fjeldså et al., 2005; Gardner, 2012). Since the 1970s, coca cultivation has increased significantly and contributed to deforestation in the Peruvian Amazon (Garcia-Yi, 2014). This trend underscores the need for integrated strategies that address both the environmental and socio-economic aspects of illicit crop cultivation.

For example, Young (1996), studying threats to biological diversity from deforestation due to coca cultivation in the Huallaga Valley, reported that forest destruction due to coca cultivation and cocaine production occurs mainly in the premontane tropical forest belt, specifically between 500 and 2000 meters altitude. Land dedicated to upland agriculture, most of which was devoted to coca cultivation, occupied more than 223,000 hectares. Thus, the extent of deforestation caused by coca/cocaine production was probably much larger than previously estimated in this study. In addition, Paredes and Manrique (2021) indicate that the Peruvian Amazon experienced significant deforestation between 1950 and 1980, coinciding with the State's colonization policies in the Upper Huallaga region, especially from the 1950s onwards. Also, Garland (2016) argues that various factors influence the pace of deforestation in the VRAE region, including the farmers' dependence on the forest for survival, their financial views of the forest, and the amount of available land. Groups representing coca farmers prioritize the protection and expansion of coca cultivation over preserving the forest, which is not considered a fundamental aspect of their platform. Currently, there is increasing access to information to determine how much forest has been converted to coca cultivation in Peru (Dávalos, 2018), e.g., studies conducted by institutions like UNODC and Peru's Ministry of Environment (2011).

While some studies have shown a positive correlation between coca cultivation and deforestation (Oxford Analytica, 2019), others suggest that coca production does not cause damage on the same scale as other activities (Dávalos et al., 2016; Oxford Analytica, 2023). Some mention that although deforestation is, to a certain extent, due to the illicit cultivation of coca brush, its impact is relatively lower than other agricultural practices, with 2 percent less in Peru according to UNODC (2022).

In addition, illegal crop cultivation can encourage deforestation by providing the means to expand settlements and other agricultural practices and using the profits to finance cattle ranching and other land-intensive activities (UNODC, 2022).

Some efforts have been made to counteract this trend, such as shade coffee cultivation which avoids conversion to non-forest land uses (Aerts et al., 2011). Promoting alternative and sustainable agricultural practices like shade coffee cultivation can be an effective strategy in reducing the impact of illicit crops on deforestation.

D. Mining

Mining (both large-scale and artisanal) is a driver of deforestation (Romet, 2022). Hosonuma (2012) stated that it accounted for approximately 7% of global tree cover loss. In Peru, illegal mining is a primary cause of forest loss (Luque-Ramos, 2021). Asner et al. (2013) assessed the effects of mining in the Madre de Dios region of the Peruvian Amazon between 1999 and 2012. During this period, the geographic area affected by gold mining increased by 400%, and the annual rate of deforestation due to gold mining tripled in 2008 in response to the global economic recession and rising gold prices. More than half of the gold mining operations in the region are small-scale clandestine operations. In another study, Asner and Tupayachi (2017) evaluated annual changes in gold mining extent from 1999 to 2016 in the Madre de Dios region, including the Tambopata National Reserve and buffer zone known for its rich biodiversity. Their results indicate that an average of 4,437 hectares of forest were lost annually due to gold mining and the total estimated area of gold mining in the region increased by approximately 40% between 2012 and 2016. This highlights the urgent need for effective regulation and monitoring of mining activities to protect these critical ecosystems.

Furthermore, Nicolau et al. (2019) applied spectral mixture analysis (SMA) on a cloud-computing platform to create a map of forest loss both inside and outside indigenous territories, protected areas, mining concessions, and reforestation concessions in the Madre de Dios Region of Peru, especially on the western areas of the Tambopata National Reserve and the vicinity of the Malinowski River, where significant forest loss was observed. They found large forest loss areas, particularly within the buffer zones of protected areas. Additionally, they found that gold mining activities might not be limited to legal mining concession areas, as almost half (49%) of the forest loss occurred outside these areas.

Artisanal-scale gold mining (ASGM) is a large cause of this deforestation and brings extensive environmental, social, governance, and public health impacts, including large carbon emissions and mercury pollution (Espejo et al., 2018). Diringer et al. (2019) discussed the impact of artisanal and small-scale gold mining on deforestation and mercury mobilization in Madre de Dios, Peru. They estimated that deforestation had increased soil mobilization by a factor of two in the Colorado River watershed during the 18 years and by 4-fold in the Puquiri subwatershed. They showed that the deforestation caused by artisanal and small-scale gold mining (ASGM) contributes to the transfer of naturally occurring and human-made mercury from land to water. This process might result in mercury accumulation in fish and increased exposure to downstream communities. Also, Swenson et al. (2011) discussed how the global demand for gold was linked with deforestation in the Peruvian Amazon. It found that gold price was linked with exponential increases in Peruvian national mercury imports over time and that virtually all of Peru's mercury imports were used in artisanal gold mining. Implementing sustainable mining practices and reducing mercury use are critical to mitigating these environmental and health impacts.

Moreover, Álvarez-Berríos et al. (2021) analyzed the environmental outcomes of initiatives aimed at formalizing artisanal gold mining in a gold-rich region of the Peruvian Amazon. They found that mining significantly expanded and caused the clearance of approximately 40,000 hectares of forest. Following the declaration of the mining corridor and enhanced enforcement, there was a rise in new mining sites within titled regions and the corridor compared to other areas. The formalization of ASM (Artisanal and Small-scale Mining) may lead to ecological damage without proper enforcement, coordination among agencies, and consideration of competing land claims.

In addition, alluvial gold mining is a major cause of land degradation and deforestation in the Amazon, particularly in the Madre de Dios region (Luque-Ramos, 2021; Ramirez et al., 2014). For instance, Alarcon et al. (2016) reported an area of 55,426 hectares was deforested, resulting in an annual change rate of -0.22% and an average yearly deforestation of 3,246 hectares. The authors attribute the primary cause of deforestation to the expansion of alluvial gold mining, which has been influenced by the construction of the interoceanic road and the increase in gold prices. Also, according to Muñoz (2020), the tropical forests in Huepetuhe, Cachee, Delta Uno, and Río Inambari (which include the Reserva bionatural del Manu and Reserva del Bahuja Sonene) have been affected by illegal gold extraction through the use of heavy machinery, excavators, front loaders, and dump trucks, resulting in disturbance of approximately 7,000 hectares over the past 17 years in the department of Madre de Dios.

Mining projects have the potential to be a significant threat to biodiversity and it is considered in different conservation narratives in Peru (Zinngrebe, 2016). Weisse and Naughton-Treves (2016) examined the effectiveness of 13 buffer zones in the Peruvian Amazon in preventing deforestation and limiting the extent of mining concessions from 2007 to 2012. Their results showed that buffer zones prevented the loss of 320 km^2 of forest and 1739 km^2 of mining concessions between 2007 and 2012. However, upon further examination of the buffer zone surrounding the Tambopata National Reserve, it becomes evident that controlling illegal and informal activities is a challenging task. The proposal to create more profitable livelihoods that are also sustainable and environmentally friendly is to increase the value of alternative products derived from the forest. Strengthening governance and community-based conservation initiatives is essential to protect these areas effectively.

A study of Fisher et al. (2018) conducted in the buffer zone of Tambopata National Reserve in Peru concluded that activities such as Brazil nut harvesting and fish farming could be as or more profitable than artisanal gold mining. Promoting alternative livelihoods that are both sustainable and economically viable is crucial for reducing the reliance on mining.

In a different approach, Csillik and Asner (2020b) used deep learning models, satellite remote sensing and airborne LiDAR to produce high-resolution, spatially explicit estimates of aboveground carbon stocks and emissions from gold mining in 2017 and 2018. They found an alarming emission of 1.12 Tg C in just one year, affecting 23,613 hectares, including protected zones and their ecological buffers. This highlights the significant carbon footprint of mining activities and the need for carbon accounting in environmental impact assessments.

3.1.2 Other direct causes

A. Infrastructure and investment projects

Road construction and proximity to infrastructure in Peru are key drivers of deforestation (Alvarez and Naughton-Treves, 2003; Mäki et al., 2001; Marcus et al., 2020; Mendoza et al., 2007; Perz et al., 2013; Rudel and Roper, 1997; Southworth et al., 2011). The possibility of infrastructure facilitating market connections and mobility is appealing to certain segments of local communities, as exemplified by the proposed Hidrovía Amazónica in Northeastern Peru (Bebbington et al., 2020). Although enhanced accessibility is commonly seen as beneficial for activities such as trade, communication, and social interactions, it can lead to unfavorable environmental outcomes (Salonen et al., 2012). This is especially true in tropical regions where easily accessible areas are often subject to high levels of land use and resource pressure, resulting in increased deforestation (Alvarez and Naughton-Treves, 2003; Imbernon, 1999; Oliveira et al., 2007).

Some authors have emphasized the tendency of road construction to facilitate land invasion and, subsequently, deforestation (Marcus et al., 2020). Indeed, road building has historically closely followed deforestation in Peru (Tollefson, 2011), and push and pull factors such as policies and road construction underlie demographic shifts that contribute to deforestation (Marcus et al., 2020). Baralotto et al. (2015) studied the effects of road infrastructure on forest degradation based on forest value metrics across a tri-national Amazonian frontier. They found that plots in communities in Madre de Dios, where settlements and unpaved portions of the Inter-Oceanic Highway have existed for decades, were more degraded. Also, Larrea-Gallegos et al. (2017) utilized a life cycle assessment to conduct an environmental sustainability analysis of the construction, traffic, and maintenance of an unpaved tropical road in Peru. Their results revealed that deforestation was the primary environmental hotspot regarding climate change resulting from direct land use changes.

Recently, Rojas et al. (2021) used the Maxent machine learning algorithm to forecast deforestation in the Peruvian Amazon. Their findings revealed that proximity to roads and agricultural land were the predictor variables with the most significant contribution to the final model. The model classified 73.2% of the early alerts in 2020 as high or very high-risk areas.

Furthermore, Larrea-Gallegos and Vázquez-Rowe (2022) generated a deforestation prediction model for specific time frames (2002-2017 and 2010-2017) utilizing machine learning algorithms (neural networks and random forest). The purpose was to estimate the potential carbon emissions linked to various anthropogenic factors in the Peruvian Amazon. They reported that using a random forest algorithm was a more efficient and straightforward approach to modelling the system, particularly because there is no need for additional data processing during the prediction and modelling stages. Their predicted results suggested that the projected expansion of roads could lead to significant carbon emissions in the future, which were particularly relevant considering the mitigation efforts undertaken by Peru as part of the Paris Agreement.

Implementing roads and rural roads in connection with mining and logging activities has also been linked to accelerated erosion and landslides (Hernandez et al., 2022).

On the other hand, Aguirre et al. (2021) argued that the creation of protected areas could reduce the deforestation rate. They examined the efficacy of protected natural areas (PNA) in mitigating deforestation amidst road infrastructure. The results indicated that the expansion of the road network has contributed to an escalation in deforestation rates in the Peruvian Amazon. However, they reported that creating protected areas had partially mitigated this effect, reducing deforestation rates by 6.5 km^2 per 400 km^2. They emphasized the effectiveness of protected areas in preserving forests, even in the presence of roads. In addition, Gallice et al. (2019), assessing the expansion of roads in the buffer zones of Manu National Park and Amarakaeri Communal Reserve, argued that to promote economic development and improved mobility in this context, there are several alternatives to further road expansion, including intensified agriculture, enhanced land-use planning, and less intrusive transportation infrastructure.

B. Environmental causes

Although anthropogenic factors are the most frequently reported drivers of deforestation and forest degradation, environmental variables also affect Amazon forests. For instance, Bax and Francesconi (2018) analyzed the influence of climate conditions and biophysical landscape characteristics on deforestation in Peru's tropical Andes. Applying Random Forest regression models, they found that soil type and precipitation were the primary predictors of deforestation throughout the tropical Andes region. Deforestation caused by mining activities was associated with the distance to rivers, whereas deforestation in coca cultivation areas was linked to elevation and temperature.

Another deforestation driver listed in the literature is fire. Fires, most often linked to deforestation, are exacerbated by climate change, forest fragmentation, and land use changes (Aragão et al., 2007; Armenteras et al., 2017; Bax, 2018; Gutiérrez-Velez et al., 2014; McMichael et al., 2013; Uriarte et al., 2012). Fires are used both directly and indirectly in the Amazon to spread deforestation and increase forest accessibility, which contributes to forest fragmentation (Armenteras et al., 2017). Forest fragmentation is also attributed to the occurrence of fires in the tropics. The spread of fires to flammable forests could lead to significant changes in the biome if droughts become more frequent (Armenteras et al., 2017).

In the Peruvian Amazon and tropical Andes regions, forest fires are most prevalent in the departments of Ucayali/Huánuco and San Martín. The use of fires is a principal method for converting tropical forest ecosystems into other land uses (Bax, 2018). Fire risk in these areas can be reduced through land-use planning that minimizes the contribution of road expansion and subsequent access to Amazonian natural resources (Armenteras et al., 2017).

According to Gutiérrez-Velez et al. (2014), fire is becoming a pervasive driver of environmental change in the Amazon, and its influence is expected to intensify due to projected reductions in precipitation and forest cover. Post-deforestation land-cover changes, such as vegetation regrowth and oil palm expansion, significantly correlate with fire occurrence. Drought severity has the greatest influence on fire occurrence, which may negate the effectiveness of secondary forests in reducing fire occurrence in very dry years.

Moreover, McMichael et al. (2013) analyze that recurrent fire does not appear to be the driving mechanism behind the current distribution of bamboo-dominated forests in western Amazonia. However, increasing human activity, including fire and deforestation, combined with predicted Amazonian drought, may allow bamboo to expand from its current distribution and replace typical Amazonian closed-canopy forests. This could have important implications for carbon storage, as Amazonian forests are currently the largest terrestrial carbon sink globally (McMichael et al., 2013).

In the Peruvian Amazon, Uriarte et al. (2012) indicate that the factors associated with fire frequency from 2000 to 2010 include drought, proximity to roads, and decreases in rural populations. The increased burn scar frequency and size reflect the increased flammability of emptying rural landscapes and reduced capacity to control fire. To reduce damage from fire, initiatives should focus on warning systems targeting high-risk locations, coordinated firefighting efforts, and promoting options for people to remain in rural landscapes (Uriarte et al., 2012). Addressing this problem requires a multifaceted approach, including land-use planning that minimizes road expansion, encourages natural regeneration and perennial crops on cleared land, and implements warning systems for high-risk sites (Armenteras et al., 2017; Gutiérrez-Velez et al., 2014; Uriarte et al., 2012).

3.2 Direct drivers affecting Andean land use

The High Andes of Peru, a region characterized by its diverse ecosystems, plays a critical role in the environmental and socio-economic well-being of the country. However, the region has experienced significant land use changes over the years, altering its landscape and ecological balance. These changes have far-reaching implications for both the environment and the local communities that depend on these ecosystems. Furthermore, the high-altitude grasslands have been subjected to considerable land use changes, with potential consequences for the ecosystems they support (Tovar et al., 2013).

Agricultural expansion is one of the primary factors contributing to land use change in this region. The cultivation of crops such as quinoa has experienced rapid growth in recent years, leading to alterations in traditional land use patterns and posing implications for land use management (Bedoya-Perales et al., 2018a). This expansion underscores the need for sustainable agricultural practices that balance productivity with environmental conservation. Furthermore, the expansion of agricultural activities has been linked to changes in soil fertility and nutrient cycling, which can have significant long-term impacts on the sustainability of the land (Chevallier et al., 2010; Rolando et al., 2018).

Climate change has also substantially driven land use change in the High Andes of Peru. The retreat of glaciers and shifts in precipitation patterns have altered water resources, affecting the livelihoods of small-scale farmers and leading to changes in agricultural practices and land use (Chevallier et al., 2010; Mark et al., 2017). Adapting to these changes requires innovative water management strategies and the development of climate-resilient agricultural systems. Additionally, changes in temperature and precipitation have been shown to impact the distribution of ecosystems along the Andes-to-Amazon elevation gradient, with potential consequences for biodiversity and ecosystem services (Asner et al., 2014).

Urbanization and rural-to-urban migration have further contributed to land use change in the High Andes. As populations in urban centers grow, the demand for land increases, leading to the expansion of peri-urban areas and the conversion of agricultural and natural lands into built-up areas (Haller, 2014, 2012). This urban expansion highlights the need for integrated urban planning that considers the preservation of agricultural lands and natural habitats. This process can result in the loss of valuable agricultural land and the fragmentation and degradation of ecosystems (Tovar et al., 2013).

3.2.1 Degradation of Grasslands and peatlands

Land use change in the grasslands and peatlands of the Peruvian Andes has significant implications for ecosystem services, biodiversity, and local communities. The causes of these changes can be attributed to a combination of environmental and human factors, such as soil degradation, water resource challenges, climate change, agricultural expansion, livestock grazing, and afforestation (De Valença et al., 2017; Tovar et al., 2013).

Soil degradation is a primary concern for the sustainability of farming communities in the Andes. Land use intensification, including conversion from forests or pastures to croplands, has led to significant soil degradation and a loss in soil-based ecosystem services and biodiversity. This degradation highlights the need for sustainable land management practices that maintain soil health and productivity. The management systems within low-mid elevation zones have demonstrated important differences in soil biological communities, with less-disturbed forest and pasture systems supporting more diverse soil communities than the more intensively managed croplands (De Valença et al., 2017).

Agricultural expansion is another leading factor contributing to land use change in the Andean region, driven by climate change and agricultural intensification (Rolando et al., 2018). The conversion of native grasslands and forests to agricultural lands, particularly in densely occupied provinces, has led to a decline in pasture and forest extent (Madrigal-Martinez and Miralles García, 2019). This expansion has resulted in a loss of native Jalca grasslands, montane forests, and shrubland habitats, as well as increased fragmentation of these habitats (Tovar et al., 2013). Moreover, agricultural activities have contributed to soil erosion and degradation in the long term, especially after land abandonment (Rolando et al., 2017).

Livestock grazing is a significant factor in land use change, with variable impacts on catchment hydrological regulation (Ochoa-Tocachi et al., 2016). Overgrazing in native grasslands can lead to net economic losses at the national level, as the resulting degradation of ecosystem services, particularly water provision, outweighs the financial returns to landowners. Adopting sustainable grazing practices is crucial to mitigate these impacts. The impacts of grazing are more pronounced in areas where grassland productivity is low, and proximity to the village is high (Raboin and Posner, 2012).

Water resource challenges, particularly in the context of global change, pose additional threats to grasslands and peatlands in the Peruvian Andes. Climate change, glacier shrinkage, and socioeconomic forces related to demographics, agroindustrial development, and hydroelectricity generation impact the hydroclimatic and socioeconomic drivers of water availability and allocation (Drenkhan et al., 2015). Effective water management policies are essential to address these challenges. In the context of peatlands, the hydrologic regime of these ecosystems has been found to be primarily supported by hillslope groundwater discharge rather than stream water. It may not be as vulnerable to glacial decline as previously thought. Nevertheless, glaciers and peatlands are susceptible to changing thermal and precipitation regimes that could affect their persistence (Cooper et al., 2019).

Climate change is another significant factor contributing to land use change in the Andean grasslands and peatlands, facilitating the upward expansion of agricultural activities and favoring the encroachment of agriculture into high-altitude ecosystems, such as the Jalca grasslands (Tovar et al., 2012). Developing climate-resilient agricultural practices is crucial to adapt to these changes. Heikkinen (2017) also highlights that climate change in the Peruvian Andes threatens lowland communities, particularly through changes in hydrology. Although he notes that climate-related changes contribute to the vulnerability of smallholders, his work also suggests that a complex cluster of economic, political, and social factors are the root causes of their vulnerability, and climate change acts as a multiplying factor for these underlying causes, exacerbating the impacts on land use in the region. Integrating socio-economic factors into climate adaptation strategies is essential for effective mitigation. The Intergovernmental Panel on Climate Change has predicted increasing temperatures, accelerated melting of glaciers, rising sea levels, and increased extreme climate events (Junk, 2012). These changes are expected to strongly affect South American wetlands, particularly those with low hydrologic buffer capacities. Changes in precipitation patterns, with increased rainfall during the rainy season and decreased precipitation during the dry season, are also expected to impact these ecosystems (Junk, 2012). Climate change-induced droughts may further exacerbate soil degradation and biodiversity loss, leading to reduced staple crop production and, consequently, food security (Beltrán-Tolosa et al., 2020).

Afforestation plays a role in land use change in the Andean region. In some cases, the value of increased carbon sequestration provided by tree plantations is outweighed by the loss of water provision for irrigation (Raboin and

Posner, 2012). However, carefully planned afforestation can contribute positively to ecosystem restoration and carbon sequestration. On the other hand, the establishment of mixed perennial cultivated pastures has been found to improve soil structure and build up soil nitrogen compared to native grasslands, potentially offering a more sustainable alternative to afforestation (Rolando et al., 2018).

In conclusion, sustainable land management practices, effective water management policies, and climate change adaptation strategies will be crucial for preserving the Andean region's unique ecosystems, biodiversity, and ecosystem services.

3.2.2 Transformation to an intensive Agricultural food system

The Peruvian High Andes is known for its rich agricultural biodiversity, particularly in tuber crops such as potatoes. However, the region has been experiencing genetic erosion of these traditional crops, which is a matter of concern for environmental and socio-economic reasons (Velásquez-Milla et al., 2011). Agriculture in the Andes has also shown greater sensitivity to climate change, causing soil erosion, the retreat of glaciers, loss of vegetation cover, increased intensity of rainfall, and alterations in the dynamics of regional crops such as potatoes, quinoa, and corn (Lozano-Povis et al., 2021). Climate change has had different effects on Andean countries, with some experiencing higher temperatures and potential evapotranspiration, leading to water scarcity and loss of important crops such as rice, while others experience lower temperatures affecting production and yield in crops like quinoa, potatoes, and tarwi (Lozano-Povis et al., 2021).

The Peruvian High Andes has experienced significant changes in its agricultural food systems practices, which have not only affected greenhouse gas (GHG) emissions but also had a substantial impact on farmers' livelihoods. These changes highlight the importance of sustainable farming practices that balance environmental protection with economic viability.

Agricultural intensification has led to the expansion of crop production into high-altitude native grasslands in the Peruvian High Andes (Rolando et al., 2018). This expansion is driven by environmental and socio-economic factors, such as increased international demand for specific crops, like quinoa (Gamboa et al., 2020), and the transformation of agriculture to meet market demands (Arce et al., 2019; Sanabria et al., 2014). The challenge lies in managing this expansion in a way that preserves the unique ecosystems and biodiversity of the region. The increase in agriculture, especially in the upper zones of the Andes, has led to the upward expansion of crops, contributing to the loss of the native jalca grasslands and montane forest and shrublands (Tovar et al., 2013). As a result, for instance, quinoa farming has expanded rapidly in Peru, transforming traditional farming practices and increasing competition for land use. This agricultural expansion has led to significant land-use changes, including displacement, rebound, and cascade effects (Bedoya-Perales et al., 2018a).

Regarding GHG emissions, the production and distribution of organic quinoa, a crop popular for its high nutritional value, has been linked to relatively high emissions compared to other organic agricultural products (Cancino-Espinoza et al., 2018). However, organic quinoa has considerably lower environmental impacts than other high-protein food products, especially those of animal origin (Cancino-Espinoza et al., 2018). Similarly, the conversion of native grasslands into annual cash crops, such as maca, results in increased nitrogen mineralization, extractable Bray-^{1} P, and K+, which are attributed to tillage-induced nutrient mineralization and the incorporation of manure and native grassland residue (Rolando et al., 2018). Another example of land use change is the shifts in potato cultivation and landrace diversity. Potato cultivation has moved upward by an average of 306 meters since 1975, and landrace diversity is versatile but unevenly distributed across landscapes (Arce et al., 2019).

Agriculture contributes significantly to greenhouse gas emissions, including nitrous oxide, methane, and carbon dioxide. Nitrous oxide emissions are primarily associated with applying nitrogen-based fertilizers and manures, while methane emissions are mostly derived from ruminant livestock and rice production. Carbon dioxide emissions are mainly linked to land-use changes (Rees et al., 2014). Developing and implementing sustainable agricultural practices that reduce GHG emissions is crucial for mitigating climate change.

Different agricultural food systems and crops contribute to greenhouse gas emissions in varying degrees. For instance, the mass consumption of agrochemicals, such as manufactured fertilizers and pesticides, in industrialized agricultural systems worldwide threatens human health and the environment. Increases in exports of agricultural products contribute to increased fertilizer and pesticide consumption within nations, which in turn, exacerbates the environmental impacts associated with agricultural practices (Longo and York, 2008).

Intensive farming practices in the Peruvian Amazon, such as monoculture and the use of chemical fertilizers, have also been linked to greenhouse gas emissions. A study conducted by Palm et al. (2002) found that the average nitrous oxide (N_2O) fluxes from cropping systems were two to three times higher than those from a secondary forest control site. Increased N_2O fluxes in cropping systems were attributed to nitrogen fertilization, while fluxes from tree-based systems were related to litterfall nitrogen.

De Valença et al. (2017) found that land use change and intensification in agricultural landscapes of the Andean highlands have resulted in widespread soil degradation and a loss in soil-based ecosystem services and biodiversity. These changes have considerably impacted greenhouse gas emissions and farmers' livelihoods in the region (Lozano-Povis et al., 2021). In the case of rain-fed potato systems in the Peruvian Central Andes, acidification and eutrophication of soil due to inappropriate or sub-optimal use of fertilizer sources were found to have significant environmental impacts (Grados and Schrevens, 2019). This calls for improved fertilizer management practices that are both environmentally friendly and effective.

To mitigate these impacts, adaptive strategies are proposed in the literature, such as promoting local crop varieties (Beltrán-Tolosa et al., 2020), restoring plant cover after annual cropping, or establishing mixed perennial cultivated pastures (Rolando et al., 2018), among others. These strategies can help maintain biodiversity, improve soil health, and enhance the resilience of agricultural systems to environmental changes.

4 UNDERLYING CAUSES OF LAND USE CHANGE

Besides direct causes, there are multiple underlying causes of the land use change in the Amazon and the Andes. In this chapter we explore the underlying drivers causing those changes.

4.1 Drivers affecting the Amazonian land use change

4.1.1 Economic factors

Economic factors are key indirect causes of deforestation. Arce-Nazario (2007) shows that changes in agricultural policy and local markets have influenced land-use patterns over time. During the 1980s, agricultural credit programs increased farming activity and the highest density of farms in the landscape. However, removing these credits reduced farming activity and increased charcoal production. This demonstrates the significant impact of agricultural policies on land use decisions. Alvarez and Naughton-Treves (2003) also highlight the role of macroeconomic policy and local social factors in shaping deforestation rates in the Peruvian Amazon. They note that during periods of available rural credit and guaranteed markets (1986-1991), the clearing rate was highest along roads, while deforestation slowed after the implementation of structural adjustment measures (1991-1997). Zwane (2007) examined the relationship between income and land clearing in tropical forest regions, including Peru. The study found that lagged income is positively correlated with clearing, though at a decreasing rate, and clearing is positively correlated with household labor availability. This suggests that economic development strategies need to consider their environmental impacts, particularly on deforestation. Coomes et al. (2011) argue that poverty can be linked to deforestation in Amazonian regions through "land-use poverty traps." In this context, they identified two types of land-use poverty traps: a "subsistence crop" trap and a "short fallow" trap. According to their findings, insufficient initial land holdings lead to land use patterns that trap households in low agricultural productivity, which in turn drives deforestation as poor farmers clear more land to make up for the low yields. Addressing these poverty traps requires integrated approaches that combine sustainable land management with socio-economic development.

The expansion of cash crops has also been linked to deforestation in Peru. Blundo-Canto et al. (2020) found that cash crop is associated with reduced agrobiodiversity, of forest cover, and changes in food access. The study observed a transition from diversified production systems and food access towards specialized production systems with less diverse food access and a stronger market orientation. This trend underscores the need for sustainable agricultural practices that maintain biodiversity and ecosystem health. This trend puts pressure on forests as farmers convert land to grow cash crops.

Dourojeanni (2022) identified the lack of technical assistance and credit for farmers and the construction of roads as contributing to deforestation. Most of the deforestation in Peru is informal and occurs on land classified as forest land, which cannot be legally owned. This legal ambiguity hinders sustainable land management and conservation efforts. This prevents long-term investments in sustainable agriculture and reforestation, further driving deforestation to make a living.

On the other hand, extractive industries, such as gold mining, have also been significant contributors to deforestation in Peru. Nicolau et al. (2019) found that large areas of forest loss occurred within buffer zones of protected areas and indigenous territories. Their study indicates that gold mining activity is not restricted to legal mining concession areas, with 49% of forest loss occurring outside these areas. This highlights the need for stronger enforcement of environmental regulations in mining activities.

4.1.2 Policy and Institutional factors

Public policies influence the region's land cover dynamics and deforestation rates (Alvarez and Naughton-Treves, 2003; Chavez, 2014). The establishment of Protected Areas (PAs) in the Peruvian Amazon is an example of conservation efforts that have faced challenges due to deforestation and landscape change (Cotrina Sánchez et al., 2021). Between 2001 and 2019, Cotrina Sánchez et al. (2021) found forest cover losses of 114,463 ha within PAs and 782,781 ha within the buffer zones. This indicates the need for stronger enforcement and management within PAs and their buffer zones. Notably, high deforestation risk zones were identified in the central and southwestern parts of the Peruvian Amazon, primarily near navigable riverbanks.

Grima and Singh (2019) analyzed the post-conflict impacts on ecosystem services provision in four countries, including Peru. They discovered a 68.08% increase in annual forest loss in the five years following the end of conflict compared to the worldwide 7.20% mean. This increase was attributed to inappropriate governance and institutional arrangements during the transition period.

Also, according to Paredes and Manrique (2021), the inefficient development and settlement strategies implemented by the Peruvian government in the Alto Huallaga region during the late 1970s, rather than the absence of government involvement, led to the socio-ecological circumstances that made the area more susceptible to the illegal economy, especially the coca cultivation which is a driver of the deforestation.

The United States-Peru Trade Promotion Agreement (PTPA) aimed to reduce illegal logging and improve forest sector governance but ultimately failed to curb deforestation effectively (Peinhardt et al., 2019). This underscores the complexity of international agreements and the necessity of aligning them with domestic interests and capabilities. Pereira and Viola (2020) argued that current Amazonian policies and global efforts to mitigate climate change are inadequate to prevent deforestation and global warming from tipping the forest into a savanna. They emphasized the need for more effective governance and long-term forest conservation policies in the Amazon region.

Sears et al. (2021) identified four entry points for government action in secondary forest governance in Peru, where the lack of official government statistics and low state capacity hindered the development of governance structures for sustainable management. These entry points included national mapping of the socio-geography of second-growth forests, regularizing property rights for untitled landholders, relaxing forest regulations, and providing incentives rather than sanctions for secondary forest management.

Shanee et al. (2020) examined the growth of privately and/or communally protected areas (PCPAs) in Peru, finding that while PCPAs have spread through conservation contagion, increasing legal and economic requirements, lack of support and negative interactions with state agents have discouraged local conservationists.

Remote sensing and field interviews by Alvarez and Naughton-Treves (2003) showed that the highest clearing rate (1.5% gross) occurred during 1986-1991 along roads. However, structural adjustment measures imposed in 1991-1997 led to a slowing of roadside deforestation (0.7% gross) and extensive regrowth, resulting in a net increase in forest cover (0.5%).

Chavez (2014) evaluated deforestation and fragmentation in the Madre de Dios region, finding that distinct policies led to different deforestation trajectories and fragmentation values. Chavez and Perz (2013) further emphasized the importance of landholder adoption of land use incentives tied to public policies.

According to Zambrano et al. (2010), the causes of deforestation in the southwestern Amazonian localities of Iñapari, Peru, and Assis Brazil, Brazil, cannot be attributed to a single land-use determinant. Deforestation patterns resulted from interactions of national and regional policies affecting financial credit and road infrastructure, together with local processes of the market and domestic resource integration. In evaluating the impact of state-controlled protected areas (Pas), Indigenous Territories (Its), and civil society and private Conservation Concessions (CCs) on deforestation and degradation, Schleicher et al. (2017) found that CCs, state Pas, and Its all avoided deforestation and degradation compared to analogous areas in unprotected landscapes. Interestingly, CCs and ITs were generally more effective than state PAs, indicating that local governance can be equally or more effective than centralized state regimes. Matthews et al. (2014) discussed the REDD-ALERT project, which aimed to evaluate mechanisms that translate international agreements into instruments to help change land user behaviour while minimizing adverse repercussions on their livelihoods. The study highlighted the need for regulatory approaches, market-based instruments, suasive options, and hybrid management measures to avoid deforestation and restore forests.

Scriven (2012) provided contextual data and information for developing policies and measures (PAMs) for the buffer zones of protected areas in the Peruvian Amazon. The study suggested that PAMs in buffer zones could achieve an additional ~10% conservation of remaining forest and between 25 and 70% additional reforestation of non-forest areas on private lands. Da Conceição et al. (2018) analyzed the governance dynamics behind two government-led incentive schemes in Ecuador and Peru. They found that electoral interests and bureaucratic politics pressured policy design teams, prioritizing short-term administrative goals over long-term societal efficiency concerns. Non-environmental concerns were often given priority due to perceptions of political feasibility, the influence of non-environmental government agencies, and beliefs in particular government roles or public response.

In conclusion, policy and institutional factors play a significant role as indirect drivers of deforestation in the Peruvian Amazon. Addressing these issues necessitates a comprehensive approach that includes the development of context-specific policies and measures (PAMs) tailored to local conditions (Scriven, 2012), as well as acknowledging and addressing the influence of electoral interests and bureaucratic politics on policy design and implementation (da Conceição et al., 2018).

4.1.3 Demographic factors and migration

Population growth and migration have been linked to deforestation in some areas of the Amazon basin (Perz et al., 2005). For instance, in Madre de Dios, the paving of the Interoceanic Highway in 2010 led to rapid population growth and environmental degradation (Sánchez-Cuervo et al., 2020). This development highlights the need for sustainable urban planning and resource management in rapidly growing areas. The increase in population and the consequent demand for resources led to the expansion of agriculture, mining, and urbanization, which resulted in the loss of forest cover. In this case, demographic factors such as population growth and migration indirectly caused deforestation through their impact on land use (Perz et al., 2005).

The construction of roads and infrastructure also plays a significant role in deforestation, encouraging population growth and settlement in previously inaccessible areas. This underscores the importance of considering environmental impacts in infrastructure development projects. Expanding the road network in Madre de Dios has resulted in the fragmentation of forest habitats and the loss of large continuous forest areas due to mining and agricultural activities (Sánchez-Cuervo et al., 2020). Consequently, the demographic changes brought about by road construction indirectly contribute to deforestation by driving land use changes.

Perz et al. (2005) states that population fluctuations and net migration play a significant role in the demographic aspect of deforestation in the Pan Amazon basin. However, the relationship between these factors and deforestation is complex due to the presence of other variables, such as land use and contextual elements like frontier development policies. The research also reveals a strong connection between land use and deforestation, implying that land use is somewhat linked to demographic changes and helps to determine the impact of population on deforestation. Understanding these linkages is crucial for developing effective land use policies. Deforestation in the Amazon is a complex process involving various stages, starting with household land use, which is influenced by local population shifts, regional economic transformations, and national development policies. These, in turn, are shaped by both national and international political and economic conditions (Perz et al., 2005).

4.2 Underlying drivers for Andean land use change

Economic factors and market demand contribute to land use change in the Peruvian Andes. Food price changes impact the food consumption of rural producers, revealing low nutritional value consumption and no significant differences in daily food consumption between producers and non-producers (Rosales and Mercado, 2020). This suggests that economic factors not only influence land use but also have broader implications for rural livelihoods and nutrition.

The expansion of crop production into high-altitude native grasslands is occurring due to agricultural intensification (Rolando et al., 2018). An example is the quinoa boom, driven by the increased global demand for this nutrient-rich grain. Bedoya-Perales et al. (2018b) found that the quinoa boom was responsible for an increase of 43% in the number of hectares planted with quinoa in 2014, compared to the number predicted if there had been no boom. This expansion highlights the need for sustainable agricultural practices that balance market demands with environmental conservation. The study also revealed that the boom led to the expansion of quinoa farming into new regions, causing land-use changes such as displacement, rebound, and cascade effects. National and international policies have promoted quinoa consumption, causing an expansion of the crop and generating changes in land use (Huillca et al., 2021).

Other underlying causes of land use change are related to policy and institutional factors. Payne et al. (2020) discuss the importance of effective policies and management approaches to safeguard the ecosystems, biodiversity, and livelihoods in mountain social-ecological systems, including the Peruvian Andes. The authors emphasize the need for policies that are informed by a thorough understanding of the interactions between nature and people. I. Inadequate policy enforcement and governance can exacerbate land use changes and environmental degradation.

Apart from this, population growth and infrastructure impact land use change. Miyamoto et al. (2018) found that human disturbance, including infrastructure development like sheds and trails, influenced tree community composition in Andean forests at higher elevations. Their study suggested that the effects of human disturbance on community composition were more prominent at higher elevations, indicating that human activities play a significant role in land use change in the Peruvian Andes, particularly in forested areas. Another example is the rapid urban growth in the Andean city of Huancayo during the late 1980s and early 1990s, which has led to agricultural intensification and peri-urban condominization at the valley floor (Haller, 2012). As Central Andean cities undergo globalization and urban restructuring, human land use expands even at high altitudes, contrary to rural-urban migration trends and results from extra-Andean studies (Haller, 2012).

5 CONCLUSIONS

In this literature review, we have listed some of the most cited drivers of deforestation and land use change in Peru (Appendix 1), a country highly vulnerable to climate change due to its unique geographical location and socioeconomic conditions. Table 1 shows the number of publications that mention different drivers of deforestation. This data underscores the multifaceted nature of deforestation drivers in Peru. Smallholder farmers face significant challenges adapting to these changes. Their livelihoods are closely tied to natural resources, and socioeconomic factors such as poverty, food insecurity, and poor health exacerbate their vulnerability. Moreover, migration from the Andes highlands to the Amazon has been influenced by various factors, including agricultural conditions and the availability of new land, contributing to deforestation and environmental degradation in the region.

The Amazon and Andean ecosystems in Peru play a crucial role in carbon accumulation and climate regulation, acting as essential carbon sinks that help mitigate climate change. Both regions face numerous challenges, including deforestation, land-use change, and climate variability, which threaten their carbon storage capabilities and the livelihoods of local communities. Effective conservation and sustainable land management strategies are therefore critical to preserving these vital ecosystems. The Amazon rainforest, transitional forests, mangroves, and peatlands store substantial amounts of carbon, making them vital in maintaining global climate stability. However, these ecosystems are increasingly threatened by deforestation, agricultural expansion, and climate change. Similarly, in the high Andes, ecosystems such as wetlands, forests, and grasslands, among others, contribute significantly to carbon accumulation and sequestration. These ecosystems are also threatened by human activities, such as grazing, burning, and land-use changes, which can negatively impact their carbon storage capacity and biodiversity.

The country's diverse ecosystems, complex topography, and agricultural dependence make it highly susceptible to climate-related hazards such as floods, landslides, water scarcity, and vector-borne diseases. Addressing the various climate-related hazards requires a multifaceted approach that includes improving scientific understanding, integrating local knowledge, and implementing early warning systems and hazard monitoring. In addition, addressing the underlying social factors, such as poverty and societal inequality, is crucial for reducing vulnerability and enhancing the adaptive capacity of communities. Furthermore, promoting diversified farming practices, fostering better communication and trust among local communities, scientists, and policymakers, and implementing integrated local assessments can significantly strengthen resilience and reduce vulnerability to climate change.

In the Peruvian Amazon, deforestation is driven by various direct causes, including agricultural expansion, wood extraction, illicit crops, mining, infrastructure and investment projects, environmental causes, among others, and underlying causes such as economic factors, policy and institutional factors and demographic factors and migration. These drivers highlight the complex interplay of environmental, economic, and social factors in shaping land use patterns.

Agricultural expansion, driven by factors such as cash crop production, small-scale and shifting agriculture, and cattle ranching, has emerged as a significant driver of deforestation in the Peruvian Amazon. The studies highlighted in this review reveal the complex relationship between agricultural expansion, food security, and forest conservation. While deforestation has detrimental impacts on the environment, including soil organic carbon stock loss and biodiversity reduction, it is also apparent that there are intricate socio-economic factors that contribute to these patterns of land use change.

Wood extraction, particularly illegal logging and charcoal production has been identified as a significant driver of deforestation in the Peruvian Amazon. The consequences of these activities include the degradation of forest ecosystems, loss of biodiversity, carbon emissions, and socio-economic impacts on local communities. Despite efforts to implement sustainable forestry practices through logging concessions and eco-certifications, these measures have shown limited impacts on reducing deforestation.

In addition, illicit crop cultivation exacerbates deforestation by expanding settlements, agricultural activities, and financing land-intensive practices. Implementing alternative livelihood strategies for local communities, such as shade coffee cultivation, can provide sustainable economic opportunities while reducing pressure on forests. Additionally, strengthening governance, law enforcement, monitoring systems, and collaborative efforts between government, NGOs, and local communities are components of developing holistic solutions.

Mining, particularly illegal and artisanal-scale gold mining, has also been cited in the literature as a significant driver of deforestation and forest loss in the Peruvian Amazon. The expansion of mining activities, driven by factors such as rising gold prices and infrastructure development, has led to extensive environmental, social, and public health impacts, including carbon emissions and mercury pollution.

The development of infrastructure, particularly road construction, also contributes to deforestation in Peru. While roads can facilitate market connections and mobility for local communities, they often lead to increased land use pressure and resource exploitation, particularly in tropical regions. In addition, environmental factors, such as climate conditions, biophysical landscape characteristics, and fires, also affect deforestation in the Peruvian Amazon.

There are also underlying causes contributing to creating the conditions that incentivize deforestation. Economic factors play a crucial role in this. Insufficient initial land holdings and low agricultural productivity prompt poor farmers to clear more land to compensate for low yields, further contributing to forest loss. Macroeconomic policies, local social factors, and poverty confluence for creating this context. The expansion of cash crops and the lack of technical assistance and credit for sustainable agriculture drive deforestation by incentivizing the conversion of forest land into agricultural land. Extractive industries, such as gold mining, compound the problem by causing significant forest loss within and outside legal concession areas.

In addition, the land-use dynamics, conservation efforts, incentive schemes, and forest governance are all influenced by the complex interplay of local, regional, and national policies, as well as political and bureaucratic considerations. Furthermore, population growth and migration increase resource demand and contribute to land use changes, including agricultural expansion, mining, and urbanization. These land use changes, in turn, result in the loss of forest cover and fragmentation of forest habitats.

Apart from this, land use change in the Peruvian Andes has significant implications for ecosystem services, biodiversity, and local communities. The causes of these changes are multifaceted, stemming from a combination of anthropogenic and environmental factors. Some include soil degradation, water resource challenges, climate change, agricultural expansion, and livestock grazing, among others. Agricultural intensification and expansion, driven by increasing market demands and climate change, have led to converting native grasslands and forests to agricultural lands, causing habitat loss and fragmentation. Livestock grazing and unsustainable agricultural practices contribute to soil erosion and degradation, while climate change exacerbates existing vulnerabilities and impacts land use by altering hydrological regimes, facilitating the upward expansion of agriculture, and causing shifts in precipitation patterns.

In turn, migration from the Andes to the Amazon has intensified the pressure on forest ecosystems, contributing to deforestation and habitat loss. The search for new land often clears areas of the Amazon for agricultural purposes. Additionally, the influx of migrants to the Amazon region has created a demand for new infrastructure, such as roads and highways, further accelerating deforestation. These transportation routes often fragment habitats, reducing the ability of species to move and adapt to changing environmental conditions. As more and more migrants arrive in the Amazon, the need for agricultural land and infrastructure continues to grow, placing an even greater strain on the already-threatened forest ecosystems.

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7 APPENDIX

Appendix 1. Number of publications that mention the drivers of deforestation in Peruvian Amazon

Driver	Number of publications
Agricultural expansion	127
Wood extraction	76
Illicit crops	17
Mining	83
Infrastructure and investment projects	89
Economic factors	72
Policy and Institutional factors	59
Demographic factors	27
Agricultural expansion	127

Source: Pradel, Willy; Juarez, Henry; Hualla, Vilma; Suarez, Victor; Cruz, Mariana, 2022, "Dataset for: Revisión de Literatura sobre causas de la Deforestación, cambio de uso de Suelo y Sistemas Alimentarios en Perú", https://doi.org/10.21223/H422YE, International Potato Center, V2

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