Towards sustainable futures for nature and people

An appraisal report for Madre de Dios, Peru

Amor Torre-Marin Rando, Santos J. González-Rojí, Kaspar Hurni, Sarah-Lan Mathez-Stiefel, Martina Messmer, Christoph C. Raible, Mark Snethlage, Thomas F. Stocker, Markus Fischer

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Authors' Affiliations:

Amor Torre-Marin Rando[1], Santos J. González-Rojí[2,3], Kaspar Hurni[4], Sarah-Lan Mathez-Stiefel[4,5], Martina Messmer[2,3], Christoph C. Raible[2,3], Mark Snethlage[1], Thomas F. Stocker[2,3], Markus Fischer[1]

1 Institute of Plant Sciences (IPS), University of Bern, Altenbergrain 21, 3013 Bern, Switzerland

2 Climate and Environmental Physics (CEP), University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

3 Oeschger Centre for Climate Change Research (OCCR), University of Bern, Hochschulstrasse 4, 3012 Bern, Switzerland

4 Centre for Development and Environment (CDE), University of Bern, Mittelstrasse 43, 3012 Bern, Switzerland

5 Wyss Academy for Nature, Kochergasse 4, 3011 Bern, Switzerland

Corresponding author: Amor Torre-Marin Rando, amor.torre@ips.unibe.ch

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Tina Hirschbühl, CDE, University of Bern

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The Wyss Academy for Nature

at the University of Bern is a place of innovation, where researchers, business people, policymakers and communities come together to co-design solutions for sustainable futures.

The Wyss Academy's mission is to transform scientific knowledge into action. Combining ambitious, innovative goals with a transformative approach, it was founded to develop innovative long-term pathways that strengthen and reconcile biodiversity conservation, human well-being and the sustainable use of natural resources in a variety of landscapes throughout the world. We co-design and implement concrete projects across a swathe of regions and countries. This global structure facilitates the replication of successes and learnings. The Wyss Academy for Nature currently operates Hubs in Central Europe (Bern, Switzerland), Southeast Asia (Laos), East Africa (Kenya) and South America (Peru).

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Wyss Academy Reports

The Wyss Academy Reports contain research, analysis, findings and recommendations. They are circulated with the aim of sharing knowledge, initiating debate on emerging issues, and eliciting comments and critical feedback on our current focal topics and regions.

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Executive summary

Sustainability challenges, amplified by the biodiversity and climate crisis and now further exacerbated by the COVID-19 pandemic, call for transformative changes that harmonize nature conservation and human well-being. The Wyss Academy for Nature at the University of Bern aims to address these challenges by transforming scientific knowledge into action. It operates Regional Hubs in Central Europe, Southeast Asia, East Africa, and South America. This appraisal report focuses on the Department of Madre de Dios in Peru. It summarizes the status and trends in the relationship between nature and people in the region, both in terms of nature's contributions to people as well as people's impact on the natural system. Further, it presents an overview of stakeholders relevant for nature and people initiatives and identifies challenges, opportunities, knowledge gaps, and research needs for reconciling nature conservation and human well-being in the region.

The department of Madre de Dios is located in the southeast of Peru, in the Amazon region. Its location between the tri-national border of Bolivia, Brazil, and Peru and the footslopes of the Andes has a strong influence on migration patterns, trade, and the ecological system. Madre de Dios has a rich cultural diversity, being home to indigenous peoples of 7 linguistic groups and 37 native communities. The region was relatively isolated until the arrival of immigrants with the rubber boom in the late 1800s, followed by the construction of a road into the region in the mid-1960s.

Madre de Dios is a biodiversity hotspot and has been officially declared the "Biodiversity Capital of Peru". The region contains large tracts of old growth forest that host some of the world's highest levels of terrestrial species diversity and endemism. A single hectare of forest harbors up to 400 tree species and the density of top predators like jaguars and large primates is among the highest on Earth. Madre de Dios consists of two natural regions: the tropical Amazon forest and the Yungas, dominated by premontane forests on the footslopes of the Andes. Ecosystems in Madre de Dios provide multiple contributions to people such as climate regulation, freshwater, timber, fish and game, Brazil nuts, medicinal plants, and opportunities for ecotourism. However, deforestation, mercury pollution from gold mining, illegal logging, and climate change are threatening biodiversity and its capacity to continue delivering those contributions. The underlying drivers of change include population growth and migration, increases in global gold prices, the construction of roads like the Interoceanic Highway, and insecure land tenure rights.

While gold mining, logging, and other extractive activities sustain many livelihoods and the economy in Madre de Dios, they jeopardize the long-term sustainable development of the region and exacerbate socioeconomic issues such as inequality, crime, and corruption. The planning and management of these extractive activities are hindered by weak institutions and governance. However, alternatives to these poorly planned unsustainable practices exist. Multiple use forest management can benefit a diversity of actors through biodiversity-friendly activities including ecotourism, sustainable logging, and harvesting and processing of non-timber forest products like Brazil nut, “aguaje” palm fruit and “copoazú” (related to cacao). Agroforestry systems (in particular high value native cash crops such as cacao) are an interesting option already being promoted in the region, as is the restoration of degraded lands. Alternatives to gold mining could focus on the development of value-added products that improve income generation of local people. Improving supply chains and access to markets, developing capacities of local people and institutions, and establishing partnerships and associative initiatives are essential conditions to enable such sustainable development paths. It is also key to involve the different stakeholders in decision-making processes, including indigenous peoples and other underrepresented groups, and to better address their needs and interests, especially in the context of complex power relations. Opportunities that harmonize nature conservation and human well-being would strengthen their mutual positive impacts if embedded in a systemic and integrated approach. Targeted and inclusive research to improve the understanding of the intricate interactions of the different elements of the social-ecological system at different scales would enhance the capacity to co-create, implement, and scale up innovative solutions for a more sustainable future for nature and people in Madre de Dios.

Resumen ejecutivo

Los retos para alcanzar un desarrollo sostenible, amplificados por la crisis climática y de biodiversidad, y ahora exacerbados por la pandemia de la COVID-19, exigen cambios transformadores que armonicen la conservación de la naturaleza y el bienestar humano. La Academia Wyss para la Naturaleza de la Universidad de Berna tiene como objetivo abordar estos retos transformando el conocimiento científico en acción. Para ello cuenta con centros regionales en Europa Central, el Sudeste Asiático, África Oriental y Sudamérica. Este informe se centra en el Departamento de Madre de Dios en el Perú. El documento resume el estado y las tendencias de la relación entre la naturaleza y las personas en la región, tanto en términos de las contribuciones que la naturaleza ofrece a las personas como del impacto de las personas en el medio natural. Además, presenta una visión general de los actores relevantes para las iniciativas sobre la naturaleza y las personas e identifica los retos, las oportunidades, los vacíos de conocimiento y las necesidades de investigación para conciliar la conservación de la naturaleza y el bienestar humano en la región.

El departamento de Madre de Dios está situado en el sureste del Perú, en la región amazónica. Su ubicación entre la frontera trinacional de Bolivia, Brasil y Perú y las estribaciones de los Andes tiene una fuerte influencia en los patrones de migración, los intercambios comerciales y los sistemas ecológicos. Madre de Dios tiene una rica diversidad cultural albergando pueblos indígenas de 7 grupos lingüísticos y 37 comunidades nativas. La región estuvo relativamente aislada hasta la llegada de inmigrantes con el auge del caucho a finales del siglo XIX, seguido de la construcción de una carretera hacia la región a mediados de los años sesenta.

Madre de Dios es un ”hotspot” de biodiversidad y ha sido declarada oficialmente “Capital de la Biodiversidad del Perú”. La región contiene grandes extensiones de bosque primario que albergan algunos de los niveles más altos del mundo de diversidad de especies terrestres y endemismo. Una sola hectárea de bosque contiene hasta 400 especies de árboles y la densidad de los principales depredadores, como los jaguares, y de grandes primates es una de las más altas del planeta. Madre de Dios se compone de dos regiones naturales: el bosque tropical amazónico y las Yungas, dominadas por bosques premontanos en las laderas de los Andes. Los ecosistemas de Madre de Dios aportan múltiples contribuciones a las personas, como la regulación del clima, el agua dulce, la madera, la pesca y la caza, la castaña, las plantas medicinales y oportunidades para el ecoturismo. Sin embargo, la deforestación, la contaminación por mercurio derivada de la extracción de oro, la tala ilegal y el cambio climático están amenazando la biodiversidad y su capacidad para seguir aportando esas contribuciones. Entre los factores de cambio subyacentes están el crecimiento demográfico y la migración, el aumento de los precios mundiales del oro, la construcción de carreteras como la Interoceánica y la inseguridad de los derechos de tenencia de la tierra.

Aunque la minería aurífera, la tala de árboles y otras actividades extractivas sostienen muchos de los medios de vida y la economía de Madre de Dios, también amenazan el desarrollo sostenible a largo plazo de la región y agravan problemas socioeconómicos como la desigualdad, la delincuencia y la corrupción. La planificación y la gestión de estas actividades extractivas se ven obstaculizadas por la debilidad de las instituciones y la deficiente gobernanza. Sin embargo, existen alternativas a estas prácticas insostenibles mal planificadas. La gestión forestal de usos múltiples puede beneficiar a una diversidad de actores a través de actividades respetuosas con la biodiversidad, como el ecoturismo, la tala sostenible y la recolección y transformación de productos forestales no maderables como la castaña, el aguaje y el copoazú. Los sistemas agroforestales (en particular los que incluyen cultivos comerciales nativos de alto valor, como el cacao) son una opción interesante que ya se está promoviendo en la región, al igual que la restauración de tierras degradadas. Las alternativas a la extracción de oro podrían centrarse en el desarrollo de productos de valor agregado que mejoren la generación de ingresos de la población local. La mejora de las cadenas de suministro y el acceso a los mercados, el desarrollo de las capacidades de la población y las instituciones locales y el establecimiento de colaboraciones e iniciativas asociativas son condiciones esenciales para posibilitar vías de desarrollo sostenible. También es clave implicar a las distintas partes interesadas en los procesos de toma de decisiones, incluidos los pueblos indígenas y otros grupos subrepresentados, y atender mejor sus necesidades e intereses, especialmente en el contexto de complejas relaciones de poder. Las oportunidades que armonizan la conservación de la naturaleza y el bienestar humano reforzarían sus impactos positivos mutuos si se enmarcan en un enfoque sistémico e integrado. Una investigación focalizada e inclusiva para mejorar la comprensión de las intrincadas interacciones de los distintos elementos del sistema socio-ecológico a diferentes escalas mejoraría la capacidad de crear, implementar y ampliar soluciones innovadoras de forma conjunta para un futuro más sostenible para la naturaleza y las personas en Madre de Dios.

1 Introduction

Sustainability challenges call for transformative changes that harmonize nature conservation and human well-being. The Wyss Academy for Nature at the University of Bern aims to address these challenges by transforming scientific knowledge into action through the co-design of innovative solutions involving research, business, policymakers, and communities. It operates Regional Hubs in Central Europe, Southeast Asia, East Africa, and South America. In this context, the appraisal reports for the Wyss regional hubs summarize the status of and trends in the relationships between nature and people, both in terms of nature's contributions to and limitations for livelihoods and human well-being as well as people's impact on natural resources. This appraisal report focuses on the Department of Madre de Dios in Peru. It provides a description of biodiversity, the values of nature to people, and the underlying drivers of change. Further, it presents an overview of the different stakeholders' perspectives and interests, main challenges, and existing assets and initiatives that could be aligned or overlap with activities of the Wyss Academy. On this basis, the report identifies approaches and opportunities that enable transformations for reconciling nature conservation and human well-being objectives. In addition, it identifies knowledge gaps and research needs related to the different topics addressed.

This report is primarily based on a review of scientific literature. We undertook a literature review using the database of peer-reviewed documents Scopus[1] and the following search string for the fields "article title", "abstract", and "keywords":

Search string	Results	Date
"Madre de Dios"	530	21/01/2021

The first result from the literature search dates from 1958, although the first document considered relevant for this report is from 1995. The results were mainly in English, but also included a few articles in Spanish and Portuguese. The review of scientific literature was complemented with grey literature, such as biodiversity strategies, climate change strategies and action plans, project reports, and government documents. These documents were predominantly in Spanish. In addition, we included custom graphs and maps based on publicly available datasets on population, economic sectors, land use, and biodiversity. The section on climate change integrates first results of high-resolution climate modelling and presents an overview of the

1 https://www.scopus.com/search/form.uri?display=basic

current state of knowledge based on the IPCC (IPCC, 2013). Following the IPBES conceptual framework (Díaz, Demissew, Joly, Lonsdale, & Larigauderie, 2015) we compiled information relevant to status of and trends in biodiversity, ecosystem services and direct drivers of change; links to human well-being; governance and institutional frameworks; as well as opportunities that harmonize sustainable development and nature conservation (Figure 1). Knowledge gaps and research needs specified in the literature were also gathered. The sections on challenges and dilemmas, stakeholders, and assets and opportunities also draw on the results of a stakeholder mapping, a stakeholder survey, and a multi-stakeholder workshop that were held during the Wyss Academy pilot phase (2018–2019) (Appendix 2). In addition, the findings on challenges and dilemmas, assets and opportunities, and knowledge gaps and research needs also draw on a synthesis workshop with regional experts and key partners from the Wyss Academy South America Regional Hub held in June 2021 (Appendix 3).

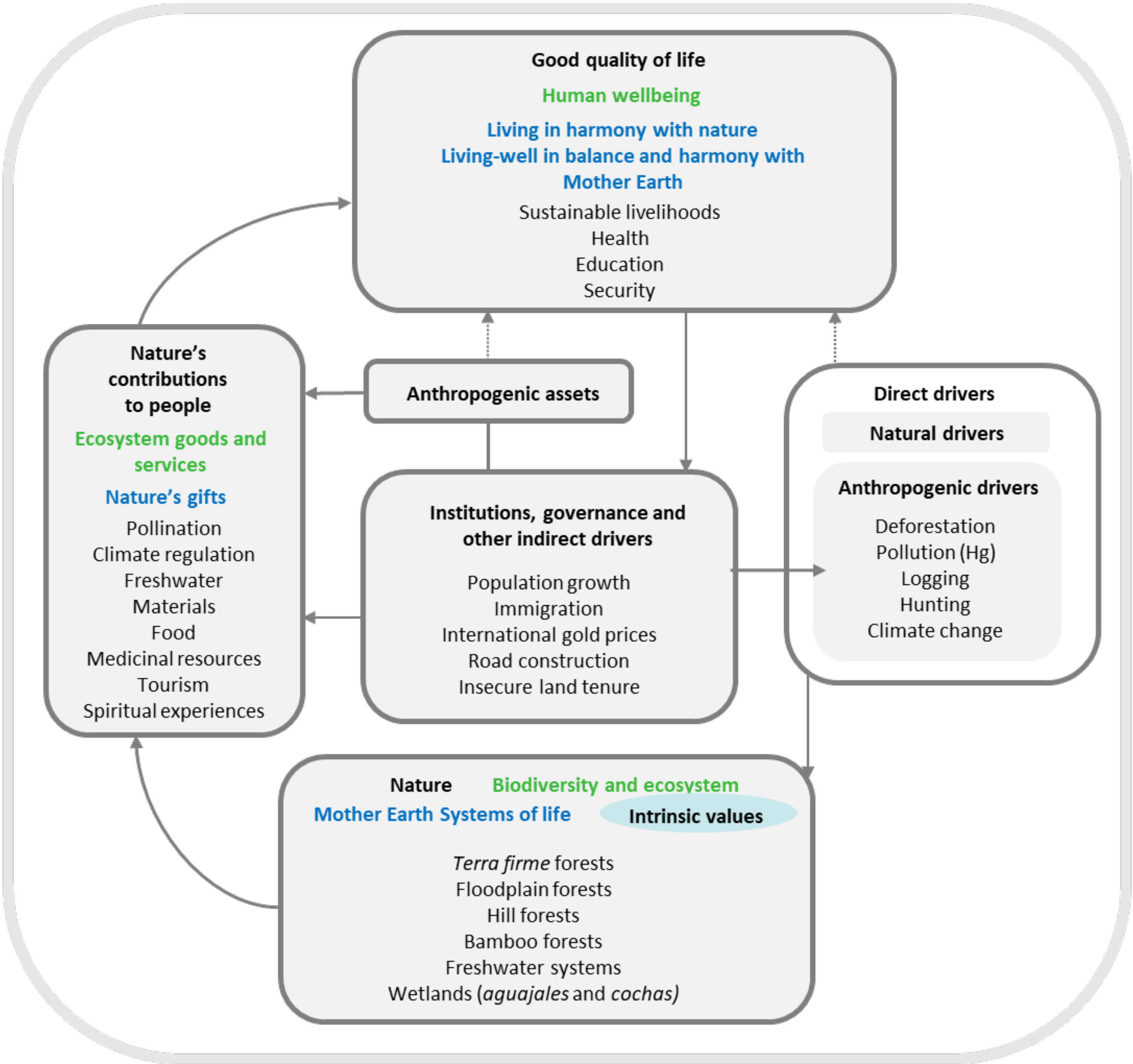
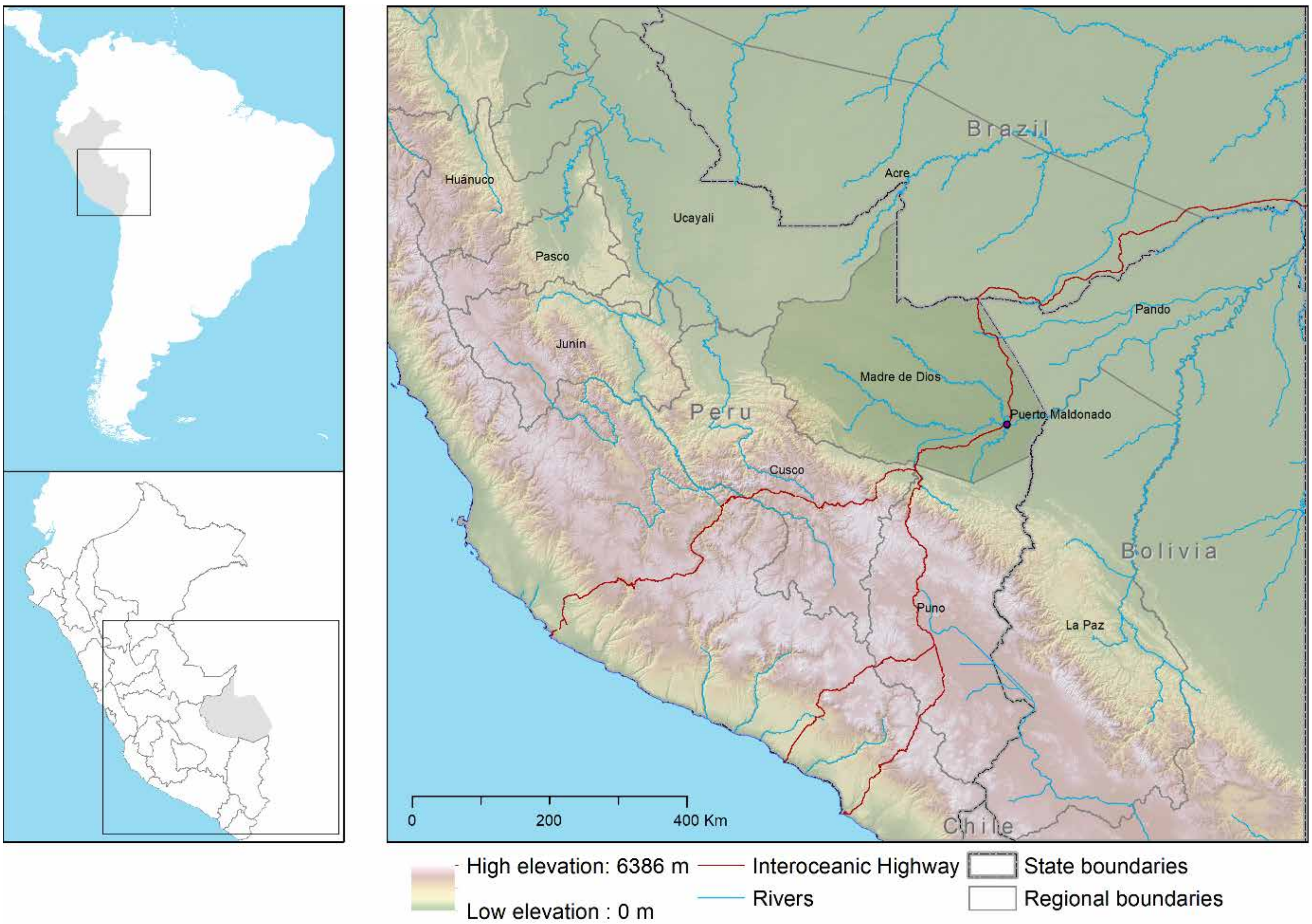


Figure 1. The elements of the IPBES conceptual framework in the Madre de Dios region, Peru. Text in bold are inclusive categories relevant to all stakeholders; green text are the categories according to Western science; blue text are the categories for other knowledge systems; regular text are examples of each category for the Madre de Dios region. Source: adapted from Díaz et al. (2015).

The study region

The department of Madre de Dios is located in the southeast of Peru, in the Amazon region. The department limits to the North with the department of Ucayali and with Brazil, to the East with Bolivia, to the South with the departments of Puno and Cusco and to the West with the departments of Cusco and Ucayali (Figure 2). Madre de Dios has an international border of 584 km: 314 km with Brazil and 270 km with Bolivia. The cross-border region formed by the Region of Madre de Dios (Peru), the State of Acre (Brazil), and the Department of Pando (Bolivia) is often referred to as the "MAP region" and is a focus of cooperation and research. The department of Madre de Dios has an extension of 85,301 km^2 (6.6% of the national territory) with a population of 141,070 representing a density of 1.7 inhabitants/km^2 (Oficina de Gestión de la Información y Estadística, 2019). This very low average population density is strongly concentrated along the main transport corridors (roads and rivers) and urban centers. At the time of the last census (2017), 82% of the population was considered urban (INEI, 2018c). The capital of the department is Puerto Maldonado. The population of Puerto Maldonado was 5,300 in 1972, with the only access to the region being by air or river and it has since grown to over 78,000 (Caballero Espejo et al., 2018), favored by the development of roads. Madre de Dios department is divided in three provinces: Tambopata, Manu, and Tahuamanu (Figure 3).

Figure 2. Madre de Dios in a regional context. Source: based on Natural Earth (Kelso & Patterson, 2009), Hydrosheds (Lehner, Verdin, & Jarvis, 2008), and Database of Global Administrative Areas (GADM, 2021).



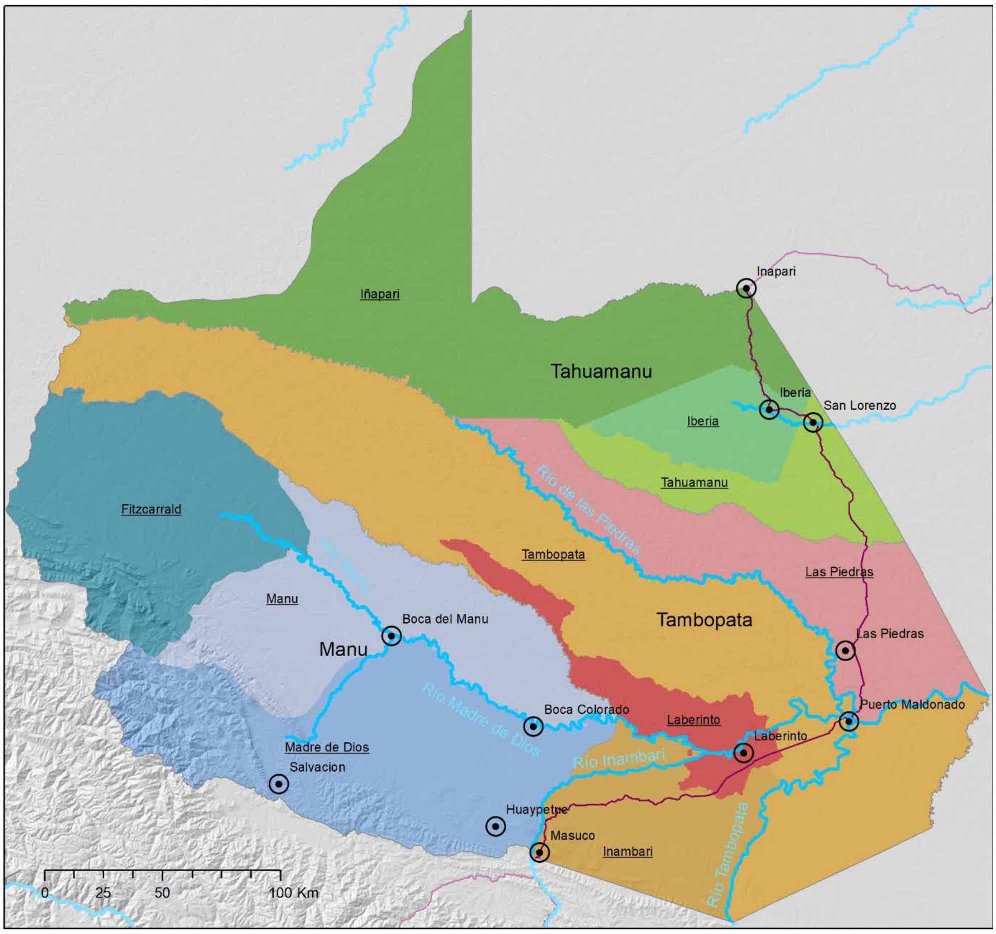


Figure 3. Administrative subdivisions of the Madre de Dios department. Municipalities of Manu province in blues, municipalities of Tambopata province in reds, and municipalities of Tahuamanu province in greens. Names of municipalities are underlined. Source: based on Database of Global Administrative Areas (GADM, 2021) and Hydrosheds (Lehner et al., 2008).

The climate in the region is tropical, warm, and humid, with an annual precipitation above 1,000 mm with slight variations across the territory, ranging from tropical rainforest (Af) to tropical monsoon (Am) and tropical savannah with a dry winter (Aw) according to the Koeppen classification. According to the weather station data in Puerto Maldonado for the period 2013–present (SENAMHI, 2021), mean annual temperature is around 26.5°C, but it can reach up to 40°C in August, October, and November, and during cold spells the temperature can even drop below 10°C. The minimum temperatures are measured during July and August, and the maximum temperatures in September and October. Precipitation is low from June to September and the rainy season lasts from December to March, with measured precipitation in around 13–16 days each month (Table 1).

Situated at the footslopes of the Andes, the total elevation range within Madre de Dios is quite considerable, from 159 to 3,986 m.a.s.l. However, around 40% of the area lies between 300 and 400 m.a.s.l., 87% of the area is comprised between 200 and 500 m.a.s.l., while higher elevations

Table 1. Climate overview of Puerto Maldonado. Source: Puerto Maldonado station (SENAMHI, 2021). Note that the summary was calculated for period 2013–Present, except for T mean and humidity, which were calculated for periods 2013–2018 and 2017–Present respectively due to the availability of data. The threshold of 1 mm was selected for the definition of a rainy day.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T min (°C)	22.9	23.1	22.9	22.3	21.1	20.2	19.3	19.9	21.8	22.9	23.0	23.0
T mean (°C) *	27.1	27.0	27.4	27.1	25.3	24.6	24.8	26.5	27.6	27.9	27.6	27.5
T max (°C)	31.5	31.0	31.7	31.7	29.8	29.2	30.2	32.0	33.4	33.1	32.1	31.5
Humidity (%) *	92.7	93.5	93.1	92.8	93.0	92.6	91.1	89.7	89.2	89.5	91.4	92.2
P (mm/month)	335.9	372.3	294.0	170.4	130.3	60.2	60.1	78.5	70.4	154.5	245.8	333.6
Rainy days	15	16	13	8	8	5	3	4	5	8	11	15

(500–4,000 m.a.s.l.) only account for about 11% (Figure 4). The topography of Madre de Dios is overwhelmingly flat to rolling with only a small area of about 10% with steep slopes in the mountainous southwest (the Yungas) on the footslopes of the Andes.

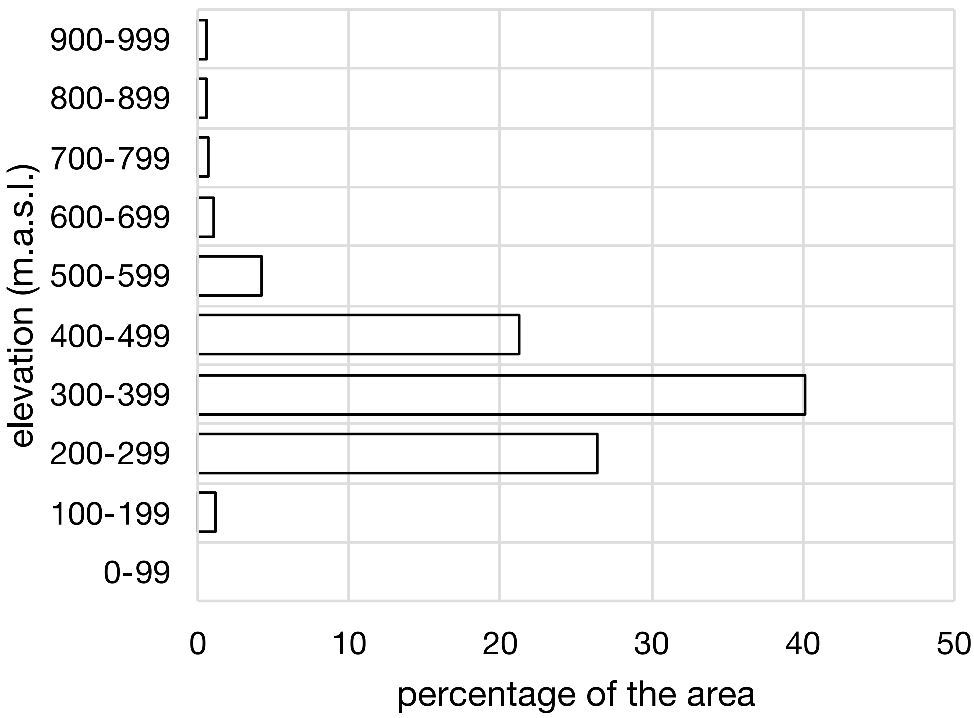


Figure 4. Elevation distribution of the lowest 1,000 m in Madre de Dios. Areas above 1,000 m.a.s.l. account for 4.06% of the area. Source: based on GMTED 2010 7.5 arcsecond DEM (Danielson & Gesch, 2011).

The river system drains the department from west to east and constitutes the main means of transport and communication (Oficina de Gestión de la Información y Estadística, 2019). The main rivers are Madre de Dios, Las Piedras, Manú, Inambari, Tambopata, Tahuamanu, and Heath (Figure 3). The headwaters of many tributaries of the Amazon river are located in the Amazonian Andes west of Madre de Dios and support the geomorphological, ecological, and socioeconomic connectivity between the Andes and the Amazon (Anderson et al., 2018). The significant sediment load of the Amazon rivers of Andean origin drives a number of key processes (sedimentation, including diffusely distributed amounts of gold; accumulation; and meandering and erosion) that are essential for the maintenance of ecological systems in the Madre de Dios basin and their associated biodiversity and ecosystem services (Asner, Llactayo, Tupayachi, & Luna, 2013; Constantine, Dunne, Ahmed, Legleiter, & Lazarus, 2014; Hamilton, Kellndorfer, Lehner, & Tobler, 2007).

Because of its location in the transition between the tropical Andes and the western Amazon, Madre de Dios is a hotspot of biodiversity and has been designated as the "Biodiversity Capital of Peru".

The region has a rich cultural diversity, with indigenous peoples of seven linguistic groups (Gobierno Regional de Madre de Dios, 2018) and 37 Native Communities (Amahuaca [1 community], Ese Eja [3], Harakbut [13], Kichwa [1], Matsigenka [6], Shipibo-konibo [4], Yine [9]) who together represent about 3.4% of the total population (INEI, 2018c, 2018b).

Human populations in Madre de Dios, mainly indigenous, were essentially isolated until the arrival of immigrants with the rubber boom in the late 1800s. The construction of a road into the region in the 1960s, government support to settle the area since the 1980s, the increase in international gold prices following the economic crisis in 2008, and completion of the Interoceanic Highway (IOH) in 2011 have brought rapid population and economic growth to the region. In addition, the situation of Madre de Dios in the “MAP region” promotes the establishment of cross-border cooperation, initiatives, and agreements. However, it also brings high environmental vulnerability and incompatible management systems, and facilitates illegal resource extraction and trafficking (Wong Villanueva, Kidokoro, & Seta, 2020).

The major economic activities in Madre de Dios are agriculture, mining, manufacture, tourism, and financial services. The main agricultural products include yellow maize, banana, yucca, rice, and fodder, which are used principally at local level as the department has a deficit in agricultural production. Livestock farming is one of the activities that has been increasing over recent years, favored in part by the introduction of Zebu cattle, which adapts easily to the environment. Mining is one of the most dynamic activities in the department and is concentrated mainly in the southeast. Madre de Dios has important and diverse forest resources, mainly exploited by the timber industry, which extracts timber in a rudimentary and predatory way (Oficina de Gestión de la Información y Estadística, 2019), but also by local communities who collect, sell, and/or consume non-timber forest products (NTFPs) such as the Brazil nut and various medicinal plants. Economic development is bringing many new opportunities to the region, but also driving unprecedented land use change and putting increasing pressures on the territory’s natural resources.

2 The value of nature, ecosystem services, and biodiversity: status and trends

Ecosystems in Madre de Dios provide multiple services including carbon storage, freshwater regulation, materials (timber, building materials, latex), food and feed (fish, edible plants, and fruits like Brazil nut), medicinal resources, tourism, and spiritual experiences (Janovec et al., 2013; Lawrence et al., 2005). Native communities are particularly dependent on renewable natural resources for their livelihoods. However, activities such as illegal logging, poaching, illegal and informal mining, road construction, and the expansion of unplanned human settlements are the main causes of loss of the ecosystems' potential to deliver services (Gobierno Regional de Madre de Dios, 2014).

A study on local values of useful forest species for indigenous and immigrant communities around Puerto Maldonado found that the most valued plant families are the palms (Arecaceae), followed by the bean family (Fabaceae) and the mulberry or fig family (Moraceae) (Lawrence et al., 2005). Overall, fruit and non-commercialized construction materials are the most valued, but women tend to value fruit and other non-timber species more than timber, while the opposite is shown by men. Indigenous peoples tend to value more the species used for fruit, domestic construction, and other NTFPs, while immigrants tend to favor commercialized timber species. Across all communities, values are influenced by both markets and the availability of the taxa. As markets become more accessible, over-exploitation of the most valuable species and livelihood diversification contribute to a decrease in perceived value of the forest (Lawrence et al., 2005).

Rivers in Madre de Dios provide fish and freshwater to local populations, are used for transport of people and goods, provide habitat for diverse ecological communities, and are important repositories for physical sediments and dissolved organic carbon (Dethier, Sartain, & Lutz, 2019). Riverine clay-licks, where parrots gather to consume soil, are important attractions for the tourism industry (Lee, Marsden, Tatum-Hume, & Brightsmith, 2017). Wetland ecosystems, comprising "aguajales" (palm swamp forest dominated by *Mauritia flexuosa*) and "cochas" (oxbow lakes in abandoned meanders of the river course), have a key function in the provision of freshwater to local communities. "Aguajales" have an important role as carbon stores and provide food such as the "aguaje" (*Mauritia*

Table 2. Use of ecosystem services by different stakeholder groups in Madre de Dios. Ecosystem service categories following IPBES nature's contributions to people categories (IPBES, 2017). Source: based on the literature review.

	Ecosystem service	Final service	Stakeholder group
Regulating	Habitat creation and maintenance		All
	Pollination and dispersal of seeds and other propagules		Local communities; Brazil nut concessionaries
	Regulation of air quality		ND
	Regulation of climate		Farmers; all
	Regulation of ocean acidification		ND
	Regulation of freshwater quantity, flow and timing	Water	Local communities
	Regulation of freshwater and coastal water quality	Water	Local communities
	Formation, protection and decontamination of soils and sediments		Farmers
	Regulation of hazards and extreme events		ND
	Regulation of organisms detrimental to humans	Pest control	Farmers
Provisioning	Energy	Charcoal	Local communities
		Fuelwood	Local communities
	Food and feed	Brazil nut	Local communities; Brazil nut concessionaries
		Livestock	Ranchers
		Bush meat	Local communities; hunters; farmers; immigrants
		Edible plants and fruits	Local communities
		Fish	Local communities; fishermen
		Agriculture products	Local communities; farmers; immigrants
	Materials and assistance	Timber	Local communities; forest concessionaries; immigrants
		Construction and tool making materials	Local communities; immigrants
		Ornaments	Local communities
		Latex	Local communities
	Medicinal, biochemical and genetic resources	Medicinal plants	Local communities

	Ecosystem service	Final service	Stakeholder group
Cultural	Learning and inspiration		ND
	Physical and psychological experiences	Tourism	Tourists; ecotourism companies and concessionaries
		Socio-cultural activities	Local communities
	Supporting identities	Ceremonial and sacred sites, plants and animals	Local communities
	Maintenance of options		ND

ND: No data available in the literature review.

flexuosa) fruits. They are the habitat of plants used for food, medicine, and construction. "Cochas" contribute to local and regional food security, as they host a high diversity and abundance of fish, a crucial source of protein for local populations in the Peruvian Amazon. Wetlands contribute to the well-being of local people, as they have been used for leisure and recreation across generations. They are also important tourist attractions and are included in the majority of tourist itineraries (Janovec et al., 2013).

The information from the literature on the status and trends of ecosystem services in Madre de Dios is not comprehensive and covers a limited number of services summarized below.

2.1 Pollination

Animal pollinators underpin food security and livelihoods in traditional communities in the Amazon (Paz, Pinto, Brito, Imperatriz-Fonseca, & Giannini, 2021). One example of an economically valuable forest product that depends on pollination is the Brazil nut, which supports the livelihoods of many local communities in Madre de Dios. The flowers of Brazil nut trees are pollinated by wild bees (Thomas, Atkinson, & Kettle, 2018) and fruit formation depends on this natural pollinator activity (Baldoni et al., 2017). Natural forests are essential to provide Brazil nut pollinators with food and nesting resources (Kainer, Wadt, & Staudhammer, 2018). Large-scale plantations of Brazil nut for fruit production have not yet proved successful, possibly due in part to the limited presence of effective pollinators (Guariguata, Cronkleton, Duchelle, & Zuidema, 2017). The pollinators of the Brazil nut tree may lose nearly 50% of their suitable distribution in the future due to climate change, with possible implications for fruit production (Sales, Rodrigues, & Masiero, 2021).

2.2 Regulation of climate

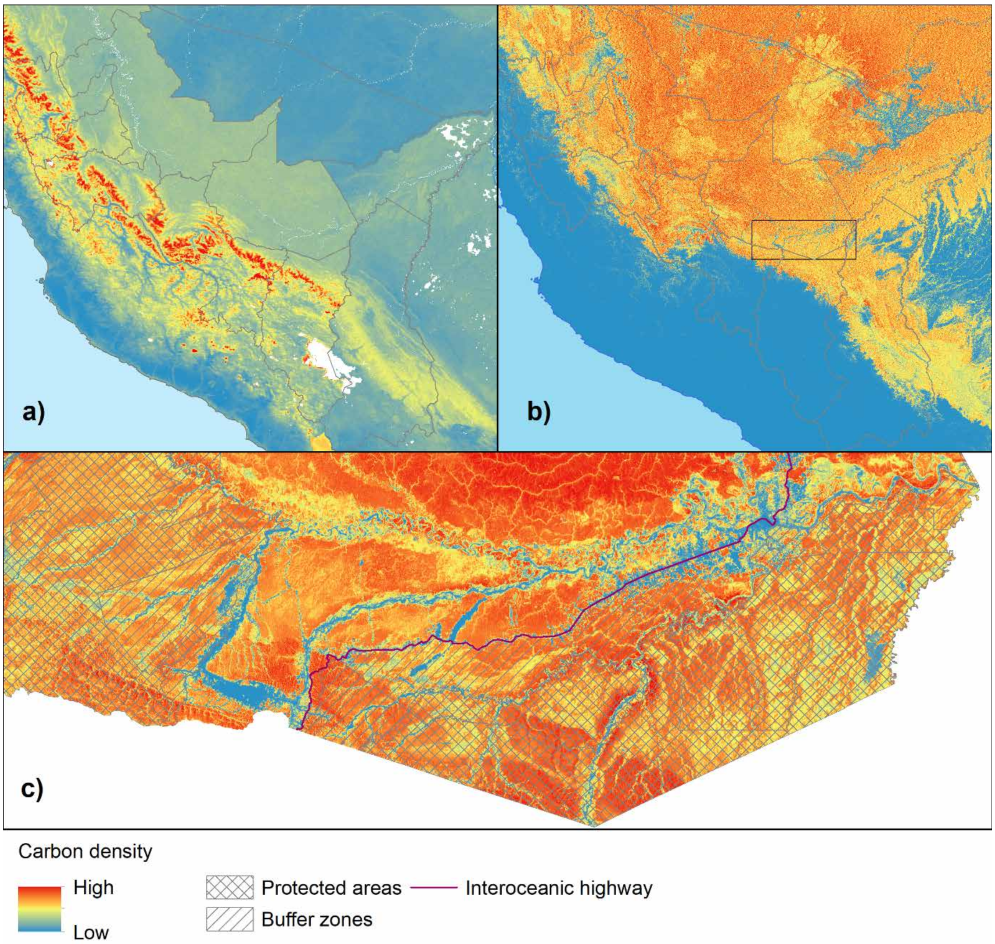
The rainforests of the Amazon basin have an important impact on climate, which is observable in temperature and precipitation through the exchange of heat and moisture between the biosphere and the planetary boundary layer. Over the rainforest, constant evapotranspiration is observed during the entire year, even during drier months when solar radiation is strong (Da Rocha et al., 2004). It is estimated that one third of the total rainfall over the Amazon is water recycled within the basin through tree-transpired moisture. The main source of moisture is located in the northeastern and southern parts of the Amazon basin (Staal et al., 2018). Conversely, the western part of the basin, and particularly the southwestern Amazon, are considered a sink-area for this transpired moisture. As evapotranspiration is one of the main drivers of precipitation, these western regions are highly sensitive to changes in this water cycle (Maeda, Kim, Aragão, Famiglietti, & Oki, 2015; Wright et al., 2017).

The atmosphere over the forest is cooler than over grassland or crops, which is related to the effect of evapotranspiration. Consequently, the forest drives thermal local circulations (Silva Dias & Regnier, 1996; Souza, Renno, & Dias, 2000). Cold air masses tend to converge over warm areas of deforestation, leading to the formation of clouds, and in some cases, deep convection particularly during the dry season (Durieux, Toledo Machado, & Laurent, 2003; Negri, Adler, Xu, & Surratt, 2004), increasing the threat of flash floods. High-resolution experiments coherently simulate an increase in rainfall of around 10% over the entire region associated with deforestation (20–30% reduction in rainforest covered area) (Avissar, 2002; Silva Dias et al., 2002). Another factor relevant for changes in precipitation are controlled fires lit by farmers. Through the burning process the number of particles in the atmosphere, so-called aerosols, are increased by about 10% (Artaxo, 2002). This change in composition of the aerosols can impact the climate via absorption or reflection of radiation and increases the availability of cloud nuclei. This can affect the genesis and formation of clouds (Kaufman, 1997), reducing rainfall amounts. Logging and controlled fires, and associated decreases in tree and leaf cover, can lead to further reductions in rainfall (Nepstad, Stickler, Soares-Filho, & Merry, 2008).

Carbon storage

Average carbon stocks in Madre de Dios exceed 100 Mg (10^2 tonnes) C ha^{-1} (Asner et al., 2013). With close to 1 petagram (10^9 tonnes) Madre de Dios is the third region of Peru in terms of aboveground carbon storage (Csillik & Asner, 2020). Much of this carbon is however stored in economically important tree species, which calls for careful planning when managing forests for multiple services (e.g. timber vs carbon storage) (Selaya et al., 2017). It is estimated that the total stock of carbon stored in deadwood for the entire department of Madre de Dios is approximately 100 mega (10^8) tonnes, ten times more than the annual fossil fuel emissions of Peru between 2000 and 2008. Necromass represents about 11% of the aboveground biomass of forests in Madre de Dios, with higher percentages on "terra firme" than in lowland forests prone to flooding (Araujo-Murakami et al., 2011). While aboveground biomass stored in intact ecosystems is more or less homogeneously distributed throughout the lowland area (Asner et al., 2014), soil organic carbon (in the 30 first cm) is concentrated in the higher elevations of the Yungas in the southwest of the department (Figure 5 a, b). Areas with intense land use change such as the gold mining sites show as depleted areas in aboveground and belowground carbon (Araujo-Murakami et al., 2011). Studies indicate that peatlands in the Amazon play a key role in carbon storage, with total carbon reserves (soil and vegetation) per unit area on average 2–4 times greater than in "terra firme" forests (Gonzales et al., 2020).

Figure 5. Stored carbon in the Madre de Dios region. Panel a) soil organic carbon (SOC) (FAO and ITPS, 2018), panel b) aboveground carbon in 2010 (Spawn & Gibbs, 2020), panel c) high-resolution aboveground carbon density (ACD), detail for the Tambopata region that corresponds to the rectangle in panel b (Csillik & Asner, 2020).



Protected areas, in particular National Parks and their buffer zones, contain a significant proportion of the aboveground carbon in Madre de Dios and thus help maintain the carbon storage ecosystem service. However, different levels of protection and the wide range of enforcement levels result in significant aboveground carbon emissions also in and around protected areas, such as the buffer zones of Tambopata National Reserve and Bahuaja Sonene National Park (Figure 5 c), where large areas are affected by illegal gold mining and deforestation along the IOH (Csillik & Asner, 2020).

2.3 Energy

Household consumption of fuelwood in Madre de Dios seems to have decreased and has been replaced by the use of gas, or charcoal when gas is not available (Garrish, Perales, Duchelle, & Cronkleton, 2014). Charcoal from “shihuahuaco” (*Dipteryx odorata*, Fabaceae) is occasionally commercialized (Lawrence et al., 2005).

2.4 Food and feed

The provision and use of food and feed has changed drastically in Madre de Dios over the last decades. While until the 1940s local (indigenous) communities largely depended on small-scale slash and burn agriculture, fishing, hunting, and gathering, the rapid immigration starting in the 1960s was accompanied by a strong shift in the provision and use of food with the introduction of cattle ranching and various commercially grown crops.

Historically, the indigenous communities in Madre de Dios practiced slash and burn agriculture to provide for their self-sufficient lifestyles. They still produce a great variety of plants in small fields cleared and burned near the compound, but also further afield within patches of thinned forest. The staple crops include banana, yucca, maize, and “pihuayo” (a native palm tree), intercropped with species such as sweet potato, chili pepper, papaya, and pineapple. Immigrants have adopted many of the practices and crops traditionally used by indigenous communities (Huertas Castillo & García Altamirano, 2003; Santos Granero & Barclay, 1994).

Nowadays, the main agricultural crops produced in Madre de Dios are maize, rice, banana, and yucca (Gobierno Regional de Madre de Dios, 2018). In 2017 the department produced 15,516 tonnes of maize, 5,598 tonnes of rice, 25,764 tonnes of banana, 12,765 tonnes of yucca, and 44,317 tonnes of papaya. Numbers of cattle and sheep have increased in Madre de Dios from 51,070 and 7,750 in 2011 to 56,420 and 9,559 in 2017 respectively, while pigs have remained stable at around 13,000 (INEI, 2018a).

Hunting mammals is an important source of protein for local populations. Ungulates like the white-lipped peccary (*Tayassu pecari*), collared peccary (*Peccari tajacu*), lowland tapir (*Tapirus terrestris*), red brocket deer (*Mazama americana*), and grey brocket deer (*M. gouazoubira*) provide a source of food to rural communities and bring revenue to rural hunters who trade the meat. Subsistence hunters show a preference for large game (Licona, McCleery, Collier, Brightsmith, & Lopez, 2011).

Fish capture volume in Madre de Dios has not increased in the last years. An increase in water turbidity and mercury pollution from gold mining activities are affecting this resource. A deterioration in the diversity of fish stocks (less diversity and less capture of fish species with higher preference by consumers) has been observed. Climate change and the development of hydropower might further accentuate these trends. Fishing is mainly concentrated in the Madre de Dios River and some sectors of Tambopata, Las Piedras, Heath, and Tahuamanu Rivers, as well as in some lakes such as Valencia and Inambarillo. These captures supply the market in Puerto Maldonado. In other water bodies fishing is artisanal and the catch used for family consumption. Aquaculture in fish farms has increased notably, from 5 fish farmers in 2002 in the region to 263 in 2010, and fish production in farms in the last years has exceeded captures in natural water bodies in Madre de Dios (Gobierno Regional de Madre de Dios, 2018).

Of note is the Brazil nut tree, "castaña" (*Bertholletia excelsa*), whose seeds are collected from the wild and sold on local, national, and international markets, and the palm species *Oenocarpus bataua* "ungurahui" and *Mauritia flexuosa* "aguaje" which produce oil-rich fruits sold locally (Lawrence et al., 2005). Brazil nut trees are present in mixed natural forests that cover around 30% of the regional territory (Figure 6, left panel). Brazil nut harvesting benefits around 20,000 families in Madre de Dios and generates around two thirds of the total income for the families involved in this activity (Gobierno Regional de Madre de Dios, 2018). "Suri" (*Rhynchophorus palmarum*), a beetle larva found in "aguaje" decomposing trunks, are rich in oils and considered a delicacy in the Peruvian Amazon (Janovec et al., 2013).

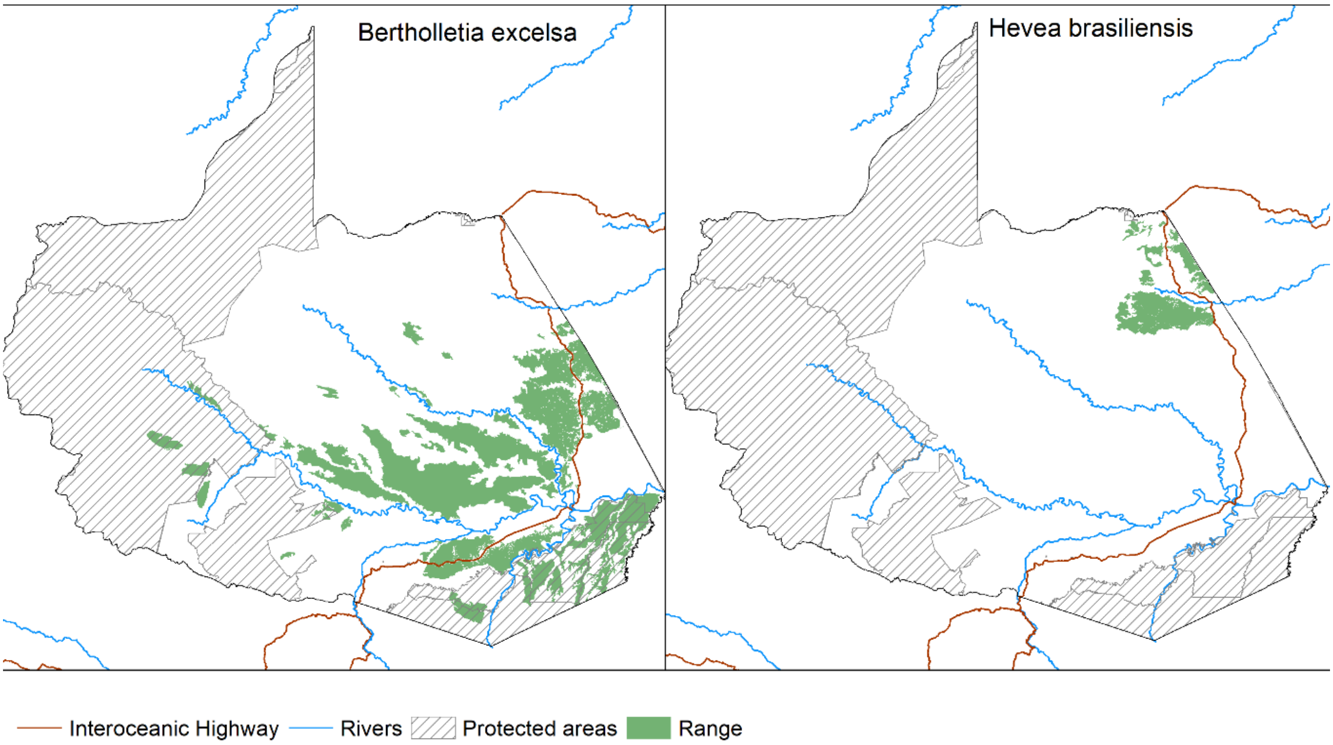


Figure 6. Distribution of Brazil nut trees (*Bertholletia excelsa*) (left panel) and rubber trees (*Hevea brasiliensis*) (right panel) in Madre de Dios. Source: based on Mapa nacional de cobertura vegetal (MINAM, 2015), Hydrosheds (Lehner et al., 2008), Database of Global Administrative Areas (GADM, 2021) and World Database on Protected Areas (WDPA) (UNEP-WCMC and IUCN, 2020).

2.5 Materials

Forestry activities have increased significantly in Madre de Dios in the last decades. Timber extraction has increased from 110,000 m^3 in 1998 to 311,000 m^3 in 2013. However, at national level, Madre de Dios only contributes to 10% of total production. The spatial distribution of timber extraction in the department has not been uniform. In the western sector

(Manu), timber resources are almost depleted. In Tambopata, it is still possible to extract quality timber, mainly in Las Piedras River basin. Lastly, in Tahuamanu there is still high concentration of highly valuable species such as mahogany (*Swietenia macrophylla*), Spanish cedar (*Cedrela odorata*), and "ishpingo" (*Ocotea quixos*), and extractive activities are more intense (Figure 7). According to SERFOR (National Forest and Wildlife Service) annual statistics, only three species represent 47% of the timber volume in Madre de Dios: "shihuahuaco" (*Dipteryx* sp.) (25%), "lupuna" (*Ceiba pentandra*) (11%) and "tornillo" (*Cedrelinga cateniformis*) (11%) (Gobierno Regional de Madre de Dios, 2018).

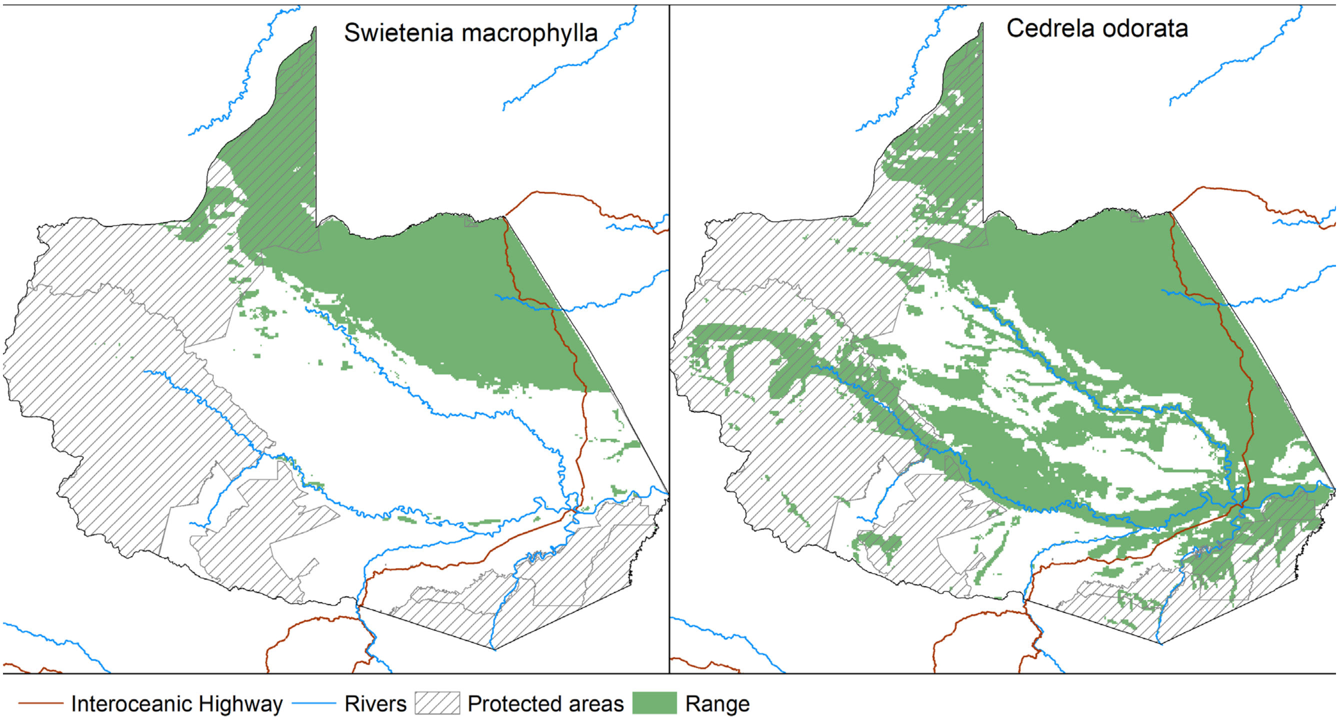


Figure 7. Distribution of mahogany (*Swietenia macrophylla*) (left panel) and Spanish cedar (*Cedrela odorata*) (right panel) in Madre de Dios. Source: based on Mapa nacional de cobertura vegetal (MINAM, 2015), Hydrosheds (Lehner et al., 2008), Database of Global Administrative Areas (GADM, 2021), and World Database on Protected Areas (WDPA) (UNEP-WCMC and IUCN, 2020).

More than 20 forest species have been reported to be used in house building, particularly several trees in the palm family (Arecaceae), for example, *Iriartea deltoidea* (known in Amazonian Peru as "pona") and *Euterpe precatoria* (known as "huasaí"), *Minquartia guianensis* ("huacapú", Olacaceae), and several species of the custard apple family (Annonaceae, collectively known as "espintana") (Lawrence et al., 2005). However, the use of palm leaves for roof thatching has steadily decreased since the IOH was paved and the availability and price of corrugated iron for roofing improved (Garrish et al., 2014). Other commercial products include fiber from "tamshi" (*Heteropsis* spp., arum family or Araceae), used to weave baskets and hats (Lawrence et al., 2005). Another key species in Madre de Dios is the rubber tree or "shiringa" (*Hevea brasiliensis*) (Figure 6, right panel), used for the extraction of latex (Gobierno Regional de Madre de Dios, 2018).

2.6 Medicinal resources

Medicinal plants from more than 20 families have been reported to be widely used by indigenous and local communities in Madre de Dios. Some of the uses include the treatment of respiratory diseases, intestinal infections, rheumatism, liver diseases, fever, snakebites, stingray wounds, external mycosis, and toothaches (Desmarchelier, Gurni, Ciccia, & Giulietti, 1996; Desmarchelier, Repetto, Coussio, Llesuy, & Ciccia, 1997; Molina Ayme, 2011). While the whole plant is used in about 10% of the applications, leaves and stems are the most commonly used parts. Infusion is the most common mode of preparation of plant-based medicines, followed by cooking and patch applications (Molina Ayme, 2011). Research carried out in Tambopata revealed that over 50% of people treat or cure their ailments with medicinal plants. The most popular ones (such as “Cat’s claw” *Uncaria tomentosa*, “Sangre de grado” *Croton palanostigma,* Copaiba oil *Copaifera* sp. and Abuta oil *Cissampelos pareira*), are also a source of alternative income for the population (Paredes Valverde & Quispe Herrera, 2009).

2.7 Tourism and cultural values

Ecotourism in Madre de Dios, and in particular in Tambopata, has been increasing steadily and is considered a great opportunity for green development. In 2003, Tambopata district received approximately 25,000 tourists; in 2014, that number increased to over 70,000, generating an estimated income of USD 6.7 million. There are at least 34 ecotourism lodges in Madre de Dios, located mainly on the riverbanks of the Madre de Dios and Tambopata rivers, many of them within the Tambopata National Reserve Buffer Zone. Maintaining a good conservation status of species and ecosystems in Madre de Dios is key for this economic sector (Gobierno Regional de Madre de Dios, 2018).

Some species have important cultural and spiritual values. The significance of two species in particular, Brazil nut and Spanish cedar, is indicated by the fact that they feature in myths of the *Ese Eja* indigenous groups (Lawrence et al., 2005).

3 Status and trends of ecosystems and biodiversity

To underscore its national importance for conservation, Madre de Dios was legally declared the "Biodiversity Capital of Peru" (Gobierno Regional de Madre de Dios, 2014). At the international level, the region's global significance for biodiversity conservation is reflected in its being partly located in the "Tropical Andes Biodiversity Hotspot" (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000). In addition, Madre de Dios is entirely covered by three "Global 200" ecoregions (Olson & Dinerstein, 2002): the Southwest Amazon moist forests (92%), the Peruvian Yungas (7%, in the southwest of the department), and the Beni Savanna (1%, on the eastern edge of the department). The importance of the region for biodiversity is further underlined by the six key biodiversity areas that have been identified (Key Biodiversity Areas Partnership, 2021). The region contains large tracts of intact forest that host some of the world's highest levels of terrestrial species endemism and diversity as well as globally important stocks of carbon (Fisher, Arora, & Rhee, 2018). A single hectare in the region harbors up to 400 tree species (van Lieshout, Kirkby, & Siepel, 2016) and the density of top predators like jaguars and large-bodied primates is among the highest on Earth (Asner et al., 2013).

Madre de Dios consists of two natural regions: the tropical Amazon forest (or "selva baja", lowland forest) dominated by a soft relief with floodplains, terraces, and low hills; and the Yunga (or "selva alta") dominated by premontane tropical moist forests (MINAM, 2019; Sánchez-Cuervo et al., 2020). The areas with the highest ecological value are located in the southwest of the department, corresponding with the sub-Andean mountain footslopes (the Peruvian Yungas ecoregion). These areas are determined by habitat and ecosystem conditions linked to altitudinal gradients and climatic variations that define the distribution of species and endemism, as well as for the water retention function that maintains and regulates the hydrological cycle in the Madre de Dios River basin. Other areas of high ecological value include the plains of the upper rivers Madre de Dios and Las Piedras, protected areas, forest concessions, and the Madre de Dios Territorial Reserve for indigenous peoples in isolation (Gobierno Regional de Madre de Dios, 2014).

Ecosystems in Madre de Dios are threatened by the conversion of natural habitats to agriculture, cattle ranching and gold mining, as well as by mercury pollution and climate change (Figure 8) (Dethier et al., 2019; Gobierno Regional de Madre de Dios, 2014; Groenendijk et al., 2014; Janovec et al., 2013).

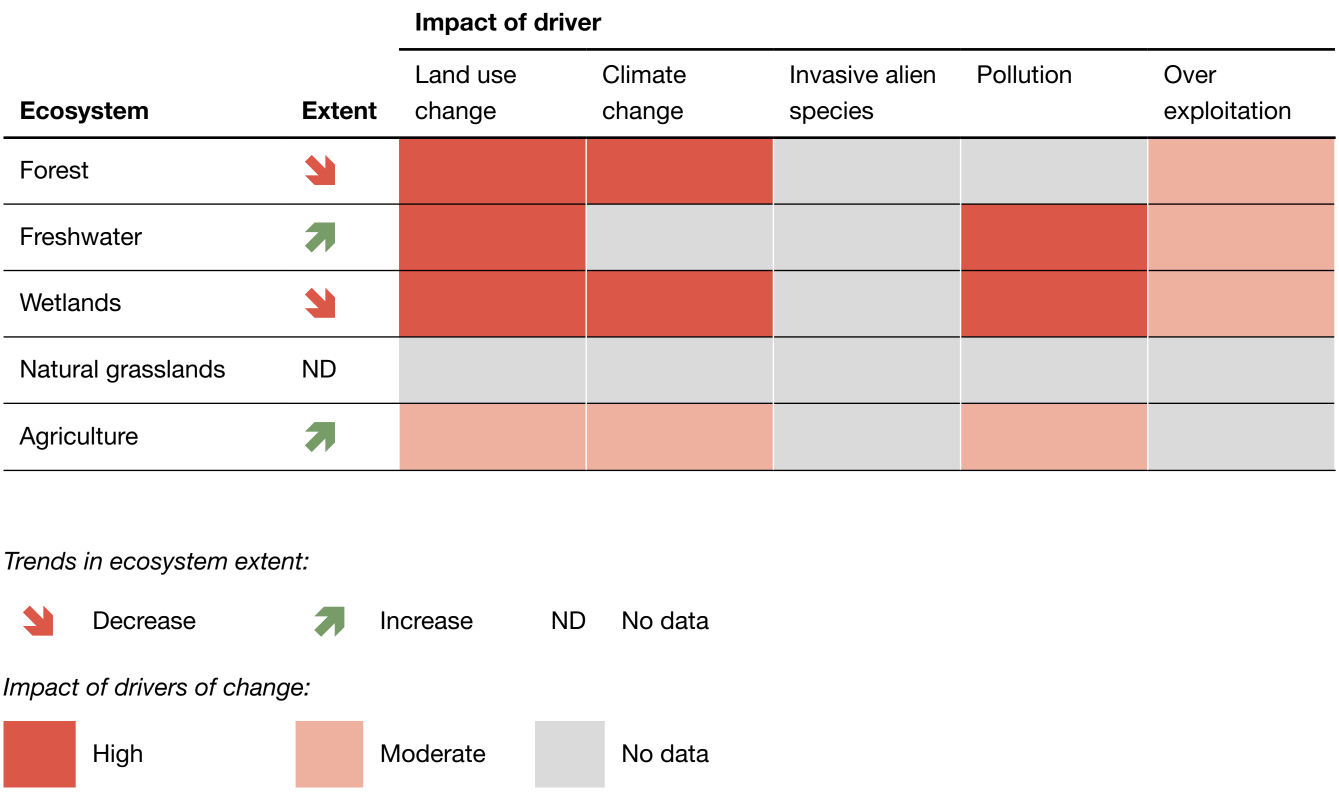


Figure 8. Trends in spatial extent of ecosystems in Madre de Dios and impact of the direct drivers of change on ecosystem status. Source: based on the literature review.

3.1 Ecosystem types

Forests

Madre de Dios is dominated by a mix of humid tropical forests in both elevated ("selva alta", or Yungas) and low-lying floodplain sites ("selva baja"), including "terra firme" forests, floodplain forests, terrace forests, and hill forests. Bamboo (*Guadua* sp.) dominated forests occur both in hill and lowland areas (Figure 9). The department features about 90% forest cover, which is high in comparison with many other regions of the Amazon Basin (Rockwell et al., 2017).

By far the largest area is comprised of low hill forests, which are, together with terrace forests, often referred to as "terra firme" forests in the literature. Low hill forests are not inundated by rivers and occupy dry, well-drained soils that are relatively poor in available nutrients. The dense forest canopy reaches 40 m in height and is usually very rich in tree species (>400 tree species per hectare in some areas), while the interior is relatively dark and open (Balslev, Laumark, Pedersen, & Grández, 2016; Tobler, Janovec, & Cornejo, 2010; van Lieshout et al., 2016). These forests are dominated by tree species in the families Fabaceae, Sapotaceae, Lecythidaceae, Flacourtiaceae, Annonaceae, Moraceae, Myristicaceae, Lauraceae, and others (Tobler et al., 2010) and are characterized by many tropical hardwood trees (van Lieshout et al., 2016).

Floodplain forests, on the other hand, are flooded seasonally and have relatively rich alluvial soils (sand, silt, and clay) from the annual replenishment of nutrients from rivers. Floodplain forests, especially those located on riverbanks and islands, are often short-lived due to the

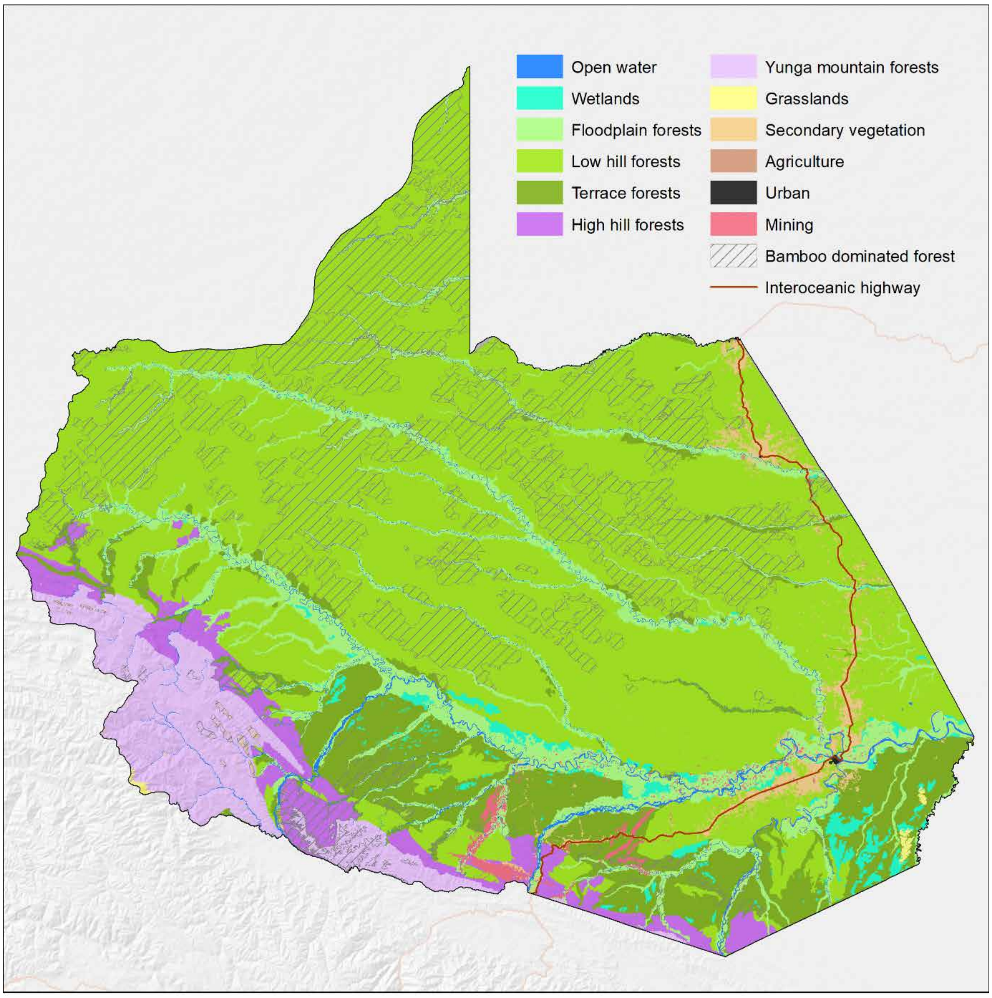


Figure 9. Simplified map of ecosystems in Madre de Dios. Source: based on Mapa nacional de los ecosistemas del Perú (MINAM, 2019) and Database of Global Administrative Areas (GADM, 2021).

meandering nature of tropical lowland rivers (Balslev et al., 2016; van Lieshout et al., 2016). Tropical floodplain forests are one of the most productive ecosystems and harbor a great diversity of (tree) species, albeit lower on average than "terra firme" forests (van Lieshout et al., 2016). Floodplain forests are dominated by tree species in the families Arecaceae, Annonaceae, Moraceae, Fabaceae, Bombacaceae, Myristicaceae, and Euphorbiaceae (Tobler et al., 2010).

Terrace forests are adjacent and similar to floodplain forests, also lying along the rivers, but outside the flood zone. They are no longer subjected to river erosion and the forest is therefore generally older and taller than the floodplain forest (Balslev et al., 2016).

High hill forests (premontane forests) have loamy soils, often rich in nutrients. They are dense, tall broadleaf forests with a high diversity of trees, shrubs, epiphytes, herbs, and also some lianas (Balslev et al., 2016). They constitute the transition between the lowland forests and the Yungas.

The Peruvian subtropical Yungas are montane forests that occupy the eastern slopes of the Andes in the southwest of Madre de Dios at altitudes of 600–3,500 m. They form the transition between the high Andean Puna and the lowland tropical Amazon forest. The relief is very rugged with steep slopes, deep canyons, and ravines which, combined with the strong climatic gradients, produce a complex patchwork of forest types and associated high levels of endemism (in particular birds, butterflies and amphibians) (Olson et al., 2001).

Bamboo (*Guadua weberbaueri* and *G. sarcocarpa*) dominated forests occupy 3,500,000 ha in the Madre de Dios region, which is home to one of the largest mixed bamboo forests in the Amazon basin (Chávez Michaelsen et al., 2017) some of which may be of anthropogenic origin. When dominating, *Guadua* species can inflict significant damage to the surrounding trees, affecting forest growth and regeneration (Griscom & Ashton, 2006). Increasing human activity, including fire and deforestation, combined with projected Amazonian drought, may allow bamboo to expand from its current distribution and replace typical Amazonian closed-canopy forests. These structural changes in the forests could have important implications for carbon storage (McMichael et al., 2013).

Key pressures affecting natural forests in Madre de Dios include the development of unsustainable activities such as agricultural practices without appropriate management, extensive cattle ranching, and illegal logging (Gobierno Regional de Madre de Dios, 2014). However, gold mining is the principal threat to forest ecosystems in the region overall (Fisher et al., 2018). Floodplain forests are the most endangered forest types, owing to their limited extent (Lloyd, 2004) and to the concentration of gold mining, logging, and agricultural activities in floodplains (Groenendijk et al., 2014).

Freshwater

Most rivers flowing through Madre de Dios, classified as white-water rivers, originate in the Andes and carry high loads of sediment. The upper reaches of these rivers are braided and their water levels respond quickly to rainfall in the Andes. Fewer rivers spring from the lowland forest (such as the Río de Las Piedras) and meander slowly through the lowlands. They have very low sediment loads, but feature high levels of humic and fulvic acids that color their water dark brown, such that they are known as black-water rivers (Maco-García, 2006). Episodic and seasonal flooding events in the Madre de Dios River and rapid meandering across the floodplain lead to a patchwork landscape of terrestrial vegetation and permanent lakes (Thieme et al., 2007). This diversity of habitat structures – partly determined by geomorphologic processes – supports high levels of biodiversity, including both unique endemic and threatened aquatic and terrestrial species (Hamilton et al., 2007). At the same time, floodplains are generally the primary location for gold-mining operations and are therefore highly at risk of disturbance (Dethier et al., 2019).

Land use change from forest to agriculture not only affects the terrestrial environment, but also the streams draining those areas, increasing gross primary productivity, ecosystem respiration, and phosphate concentrations (Bott & Newbold, 2013). Mining and road construction also have acute impacts on aquatic communities (Lujan et al., 2013). Gold mining has led to rapid decreases in water quality since the 1980s, including major increases in river suspended-sediment concentrations and mercury-laden sediments, with consequences for aquatic species and human health

(Dethier et al., 2019). At sites with high turbidity, community structure is disturbed and benthic macroinvertebrates and fish are largely absent, including economically important fish such as large species of the catfish family Pimelodidae and characiform family Serrasalmidae (Lujan et al., 2013). However, once abandoned, the gold-mining ponds also create new freshwater habitats with high biodiversity (Caballero et al., 2020).

Wetlands

Wetland ecosystems in Madre de Dios mainly consist of "aguajales" and "cochas". "Cochas" are open-water oxbow lakes surrounded by floodplain forest, with occasional floating aquatic plants, (Janovec et al., 2013; Tobler et al., 2010) and comprise the abandoned meanders of the river course (Janovec et al., 2013). Peatlands are made up largely by "aguajales", palm swamp forest dominated by *Mauritia flexuosa* (Arecaceae), which are maintained by the hydric balance of the ecosystem (Gonzales et al., 2020; Janovec et al., 2013; Tobler et al., 2010).

"Aguajales" host a high plant diversity, with 685 species registered. They also host 42% (73 species) of the ferns reported for Madre de Dios and 50% (64 species) of orchids. Thirty-six species of aquatic fungus have been identified in these wetlands, which presumably have a high level of endemism and specificity. "Aguajales" represent the exclusive habitat type for the reproduction, nesting, and feeding of the blue-and-gold macaw (*Ara ararauna*), as macaws nest in the dead trunks of the "aguajes" and the fruits are their main source of food (Janovec et al., 2013).

The distribution of Western Amazonian peatlands along major floodplains renders them particularly vulnerable to mining activities. Increased deforestation in the uplands threatens to alter the hydrological system that sustains peatlands. The expansion of commercial agriculture is also a serious threat to the hydrological and ecological integrity of peatlands. However, climate change may be the biggest threat to the long-term survival of Amazonian peatlands, possibly contributing to drastic changes and widespread loss of these ecosystems in the coming decades (Householder, Janovec, Tobler, Page, & Lähteenoja, 2012; Winton, Flanagan, & Richardson, 2017). "Aguajales" have suffered great degradation in recent decades due to the unsustainable exploitation of "aguaje" fruits through selective felling of female palms (Gonzales et al., 2020).

Most wetland areas in Madre de Dios fall in one or more categories of land use rights, with partial overlap in some cases and total overlap in others. In the cases of overlap, mining concessions often constitute one of the categories. Any measures to protect wetland should take this situation into account (Janovec et al., 2013).

Grasslands

In addition to pastures created in recent decades by clearing forest areas – mainly along the IOH – two patches of natural grassland exist within the perimeter of Madre de Dios. The Pampas del Heath in the southeast, close to the border with Bolivia, are a hydromorphic savannah vegetation composed of grasses with scattered palms and other trees. In the southwest, above the treeline of the Yungas at about 3,200 m.a.s.l., there are small patches of northern subtropical puna, featuring a high mountain dry tundra climate and moderate rainfall (MINAM, 2019; Sánchez-Cuervo et al., 2020).

Agriculture

Historically, slash-and-burn areas have been the main agricultural systems in Madre de Dios. In recent decades, commercially grown crops such as papaya have been planted, accompanied by increased use of fertilizers and fungicides (Carrasco-Rueda, Loiselle, & Frederick, 2020). Agroforestry systems, for example including papaya or banana combined with cacao and timber species, are also being promoted in the region to diversify production and as a more resilient system to cope with climate change (Gobierno Regional de Madre de Dios, 2018). Adaptable species such as brown agoutis, armadillos, and red brocket deer are able to inhabit disturbed areas such as secondary vegetation, croplands, and agroforests, and provide an additional source of protein to local communities (Naughton-Treves, Mena, Treves, Alvarez, & Radeloff, 2003). Agricultural areas can also maintain a considerable proportion of bat diversity, which can support seed dispersal, pollination, and pest control (Carrasco-Rueda & Loiselle, 2020). The proximity of large tracts of intact forests may explain the dispersal of these species into agricultural lands. Climate change, increasing the frequency of droughts and floods, will affect agricultural systems. Subsistence agriculture may be particularly vulnerable and related crop losses have already been observed (Chavez Michaelsen et al., 2020).

3.2 Species

Peru is one of the world's mega-diverse countries, featuring 3,385 species of birds, mammals, reptiles, and amphibians to which new species are still being added every year (SERFOR, 2018). At the same time, the Red List of Threatened Wildlife of Peru reports 389 threatened mammal, amphibian, reptile, and bird species, of which 64 are critically endangered, 122 endangered, 203 vulnerable, 103 nearly threatened, and 43 data deficient (SERFOR 2018). Madre de Dios, as the Biodiversity Capital of Peru, adds its share to the country's diversity with 6,809 recorded species of plants, 1,212 species of birds, 272 species of freshwater fish, 256 species of mammals, 183 species of amphibians, and 143 species of reptiles (Sánchez-Cuervo et al., 2020). Studying mammal and bird diversity along an elevational gradient in Manu National Park (Patterson, Stotz, Solari, Fitzpatrick, & Pacheco, 1998) demonstrated that the region's great biological diversity is a result of the apposition of three distinctive regions of endemism: lowland Amazonia, the Eastern Andes slopes (Yungas), and the Altiplano.

However, the biodiversity of Madre de Dios is threatened both inside and outside protected areas by habitat destruction and deforestation, unsustainable exploitation (including illegal logging, hunting, and collecting), as well as mercury pollution from gold-mining activities (Figure 10) (Cruz et al., 2020; de la Torre, López, Yglesias, & Cornelius, 2008; Gonzalez, Arain, & Fernandez, 2019; Markham & Sangermano, 2018; Mendoza, Huamani, Sebastián, & Ochoa, 2017; Naughton-Treves et al., 2003; Paniagua Zambrana, Bussmann, & Macía, 2014; Roach, Jacobsen, Fiorello, Stronza, & Winemiller, 2013; Tobler, Carrillo-Percastegui, Zúñiga Hartley, & Powell, 2013).

How these threats affect the status and trends of species is largely unknown due to a lack of general species-level knowledge and standardized long-term surveys (Catenazzi & Von May, 2014). Moreover, species assemblages and their interactions inside hyper-diverse tropical (forest) ecosystems such as those found in Madre de Dios are extremely complex and still poorly understood, further hampering the assessment of potential cascading effects and impacts across the ecological web (Patterson et al 1998). Indeed, information from the literature on the status of and trends in species conservation in Madre de Dios is not comprehensive and covers a limited number of species groups and individual species. Publications on species are mainly related to the description of species, identification of new species, and new records of species for the region, in particular insects, followed by plants, fishes, mammals, and birds.

Figure 10. Trends in and main threats to species groups. Source: based on the literature review.

Species group	Trend	Threats
Palms	↘	Land use change (deforestation) Overexploitation
Fish	↘	Pollution (Hg) Land use change (hydropower)
Amphibians	↘	Land use change (habitat destruction) Pollution (Hg) Climate change Invasive alien species (pathogenic fungus *Batrachochytrium dendrobatidis*)
Birds	↘	Land use change (deforestation) Overexploitation (selective logging)
Mammals	↘	Land use change (deforestation, habitat loss) Overexploitation (hunting) Pollution (Hg)

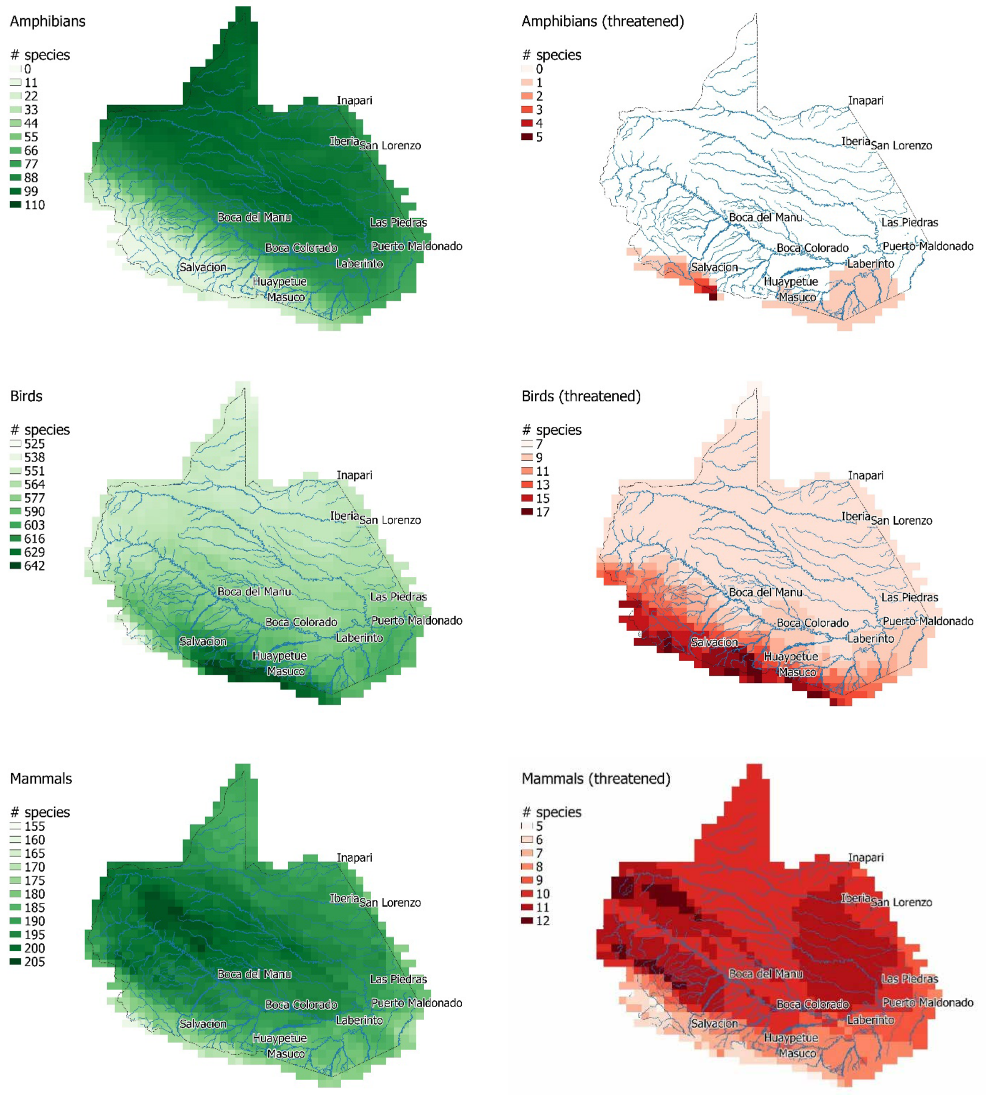
Trends in species group:

↘ Decrease

Patterns of species richness for three vertebrate taxa (amphibians, birds, and mammals) in Madre de Dios are shown in Figure 11. These maps only represent one aspect or dimension of biodiversity: the species richness per unit area. Such information is useful but does not reflect species turnover, namely, how many species are common to two adjacent cells. In these maps, species richness is shown as the number of species per 100 km^2 (10 by 10 km).

The species richness by unit area of amphibians decreases towards the southwest of the department (the higher elevations). The maps mask the fact that most of the species found here are small-range endemics, such that the total species richness for the montane area is far higher than it appears on the map. It is also in these montane footslopes of the Andes that the highest number of threatened amphibians is found. Species richness by unit area of birds increases from the Amazon towards the Andes in the southwest of Madre de Dios, as does the number of threatened bird species by unit area. In contrast, the highest number per unit area of both the total number of species and the total number of threatened species of mammals are found in the central and western "terra firme" forests of the department.

Figure 11. Species richness and number of threatened species of amphibians, birds, and mammals in Madre de Dios. Source: based on raster maps from Jenkins (https://biodiversitymapping.org) and on IUCN Red List Spatial Data (https://www.iucnredlist.org/resources/spatial-data-download).



Plants

Several studies of flora have been carried out in the department of Madre de Dios, documenting approximately 2,429 species of plants including Bryophyta, Pteridophyta, Gymnosperms, and Angiosperms. Up to 2006, 17 endemic species of plants were reported in Madre de Dios (Gobierno Regional de Madre de Dios, 2014). The montane rain and cloud forests of the Yungas are characterized by the high occurrences of epiphytes.

The Madre de Dios region is one of the world's hotspots of palm diversity (Balslev et al., 2016). Palms are a key plant group in the Amazon forests, as they have a major role in forest composition, forest dynamics and structure, and the maintenance of forests' ecological balance. In addition to their ecological importance, palms play a very important role for local communities living in the forest. Palms provide food, medicinal resources, as well as materials for house building, tools, and ornaments (Paniagua Zambrana et al., 2014). The importance and broad use of palms reflects a knowledge that has been gathered and transferred across generations living in constant contact with the forest. Despite the importance of palms, their populations have decreased notably in the last decades due to overexploitation and deforestation. This is causing deterioration of Amazonian rural populations' quality of life and cultural heritage, in addition to irreversible damage to the forest where both communities and palms live (Paniagua Zambrana et al., 2014).

Due to its high visibility and abundance, the genus *Vanilla* is one of the most conspicuous elements of wetland vegetation in Madre de Dios. However, vanilla species are mainly unknown even to local residents (Maruenda & Christenson, 2010). Considering that the fragrant fruits of several species are traded in international markets, the exploitation of this resource could present alternative livelihood opportunities for local residents.

Cedrela odorata ("cedro", Spanish cedar) is one of the most important neotropical timber species. It is threatened by deforestation and unsustainable logging in many parts of its natural range. The timber of *C. odorata* is of high value, and there is demand in domestic and international markets. The species is classed as vulnerable by IUCN. In Peru, it is considered threatened by national authorities. Since 1988, the species has been listed on CITES Appendix III, according to which both exports and imports require export permits from the producing country. In Madre de Dios, many remaining populations of *C. odorata* are riparian, located close to main rivers or to oxbow lakes. Because of their accessibility via navigable rivers, many populations of *C. odorata* in the region have been heavily depleted (de la Torre et al., 2008).

Cedrelinga cateniformis ("tornillo") is a forest species with a wide distribution in the Peruvian Amazon. Unsustainable exploitation of the species has caused losses in its genetic diversity. It has been highlighted for domestication, as well as for its use in agroforestry systems, including with coffee, banana, and cacao (Cruz et al., 2020).

Invertebrates

Individual reports, although somewhat anecdotal, point to extremely high invertebrate diversity across Madre de Dios. For example, at Tambopata, 1,093 species of coleoptera were found in a sample of 3,099 individuals from the canopy of a single type of "terra firme" forest. Studies indicate that many canopy insect species have extremely small ranges in the Amazon Basin, including Madre de Dios, where two plots within the same forest type in Tambopata separated by only 50 m had only about 8.7% of species in common (Erwin, 1988). This represents a challenge for biodiversity conservation.

Fish

With an estimated 3,500 to 5,000 species (2,258 spp. known to date) the Amazon basin is a hotspot of freshwater fish diversity. Many fish depend on intact river systems (connectivity, good ecological status) and special dynamics (e.g. seasonal floods) for their survival. Migratory fish are especially important as they provide much of the protein of riverside communities. Their conservation and sustainable use rely on river conditions that enable their full life cycle, which often depends on both lowland and Andean stretches of rivers, that is, beyond the borders of Madre de Dios (Carvalho et al., 2012; Reis et al., 2016). Existing and planned hydropower infrastructure in the upper and lower reaches of the Madre de Dios River and its tributaries therefore poses an important threat to the region's fish diversity (Anderson et al., 2018).

Contamination of water bodies by inorganic mercury used in gold-mining activities in Madre de Dios contributes to the bioaccumulation of methylmercury (MeHg) in fish tissue (Roach et al., 2013). Local freshwater fish species identified as having high mercury contamination include "chambira" (*Hydrolycus pectoralis/Raphiodon vulpinus*), "corvine" (*Corvina monacantha*), "maparate gordo" (*Ageneiosus brevifilis*), "mota fina" (*Pinirampus pirinampu*), "mota punteada" (*Pimelodina flavipinnis*), "sabalo" (*Salminus affinus*), and "zungaro" (*Zungaro zungaro*) (Gonzalez et al., 2019). Several endemic or threatened freshwater fish may be at risk including *Apistogramma urteagai*, *Ancistrus heterorhynchus*, and *Hyphessobrycon nigricinctus* (Markham & Sangermano, 2018).

Amphibians

The Yungas, representing a transition zone between the Eastern Andes and the Amazon in Peru, are an amphibian diversity hotspot and exhibit high restricted-range amphibian diversity, while the humid tropical lowland forests are dominated by many species with larger distribution areas. Levels of endemism are high, particularly for species occurring at higher elevations. However, knowledge of the status and trends of amphibians in Peru is still very fragmented and incomplete, with the number of known species having doubled in the last two decades. This is of particular concern since the limited existing knowledge indicates massive die-offs and declining amphibian populations, not only in areas of high anthropogenic land use change, but also within protected areas (Catenazzi & Von May, 2014).

Habitat loss and modification are likely the most important threats to amphibians in Peru. In Madre de Dios, in addition to habitat loss (May et al., 2009), amphibians may be particularly at risk due to mercury contamination from mining. Species identified as high risk include *Dendropsophus allenorum* and *Ameerega simulans*, endemic to Peru, as well as species labelled as data deficient by IUCN such as *Hamptophryne alios* (Markham & Sangermano, 2018). It is expected that climate change will play an increasing role in the fate of amphibians, with upward range extensions in the Andes already being observed, while range contractions are expected in the lowlands where temperatures will become prohibitive (SERFOR, 2018).

Montane amphibian fauna within Manu National Park and the adjacent Kosñipata valley have experienced dramatic declines and local extinctions. The collapse was more pronounced at mid-elevations (1,200-2,000 m) and for stream-breeding species. These declines occurred over less than a decade and coincided with the arrival of the pathogenic fungus *Batrachochytrium dendrobatidis* in southern Peru (Catenazzi, Lehr, & May, 2013).

Birds

With 1,877 bird species reported (Plenge, 2021), Peru has one of the richest avifauna of the world, after Brazil and Colombia (SERFOR, 2018). However, beyond the mere existence and presence of many of the bird species in a certain territory, such as Peru or Madre de Dios, little is known about populations, status, trends and ecology. This lack of basic information makes an assessment of the conservation status of individual species very difficult and uncertain. Given the global fame of Tambopata and Manu among ornithologists, surprisingly little has been published about bird diversity and ecology in Madre de Dios. However, some studies indicate that the diversity of avian populations in the region is threatened by deforestation and other anthropogenic factors (van Lieshout et al., 2016), including selective logging (Lloyd, 2004). The tourism industry and boat traffic may also disrupt bird behavior, in particular in clay-licks, locally called “collpas”, where parrots gather to consume soil as a source of sodium (Lee et al., 2017).

Mammals

Madre de Dios hosts several species of endemic mammals such as the maned wolf (*Chrysocyon brachyurus*), marsh deer (*Blastocerus dichotomus*), Sanborn’s squirrel (*Sciurus sanborni*), and Peruvian fish-eating rat (*Neusticomys peruviensis*) (Gobierno Regional de Madre de Dios, 2014).

Adaptable, fast-reproducing species such as brown agoutis (*Dasyprocta variegata*), armadillos (*Dasypus novemcinetus*), and red brocket deer (*Mazama gauazoubira*), which are able to withstand human activity and inhabit highly disturbed areas such as agroforests, have both economic and ecological value. Agoutis are the key seed disperser and consumer of Brazil nuts. Medium-sized mammals may also serve as a source of protein, particularly in areas where large species have been depleted (Naughton-Treves et al., 2003). Agricultural areas can also maintain a considerable share of bat diversity and of the services these species provide to landowners (Carrasco-Rueda & Loiselle, 2020). However, large herbivores, large carnivores, and most primates are unlikely to persist in multiple-use zones in Amazonian forests unless hunting is effectively restricted (Naughton-Treves et al., 2003; Tobler et al., 2013).

The jaguar (*Panthera onca*) is classified as near threatened in Peru. The major threats to the species are hunting and deforestation due to expansion of agriculture and gold mining. With an increase of cattle ranching and small-scale agriculture, more conflicts are also expected between jaguars and ranchers. While Peruvian law prohibits any killing of jaguars as well as all trade of jaguar parts, there is little enforcement and jaguar teeth, claws, skin parts, and even whole skins are often seen for sale in local markets (Tobler et al., 2013).

The giant otter (*Pteronura brasiliensis*) is one of the most threatened species in the Amazonian region. It is listed as endangered by IUCN and included in CITES Appendix I. In Peru, the species is considered endangered and it is officially protected (Mendoza et al., 2017). Giant otters are considered a flagship species for both conservation and ecotourism in the Madre de Dios region (Roach et al., 2013) and represent an important source of income for local populations (Mendoza et al., 2017). The giant otter population in Peru was close to extinction due to illegal hunting in the 1970s, but started to recover due to the establishment of protected areas in the Amazon and due to control of hunting. Populations of giant otter in relatively good shape can be found within protected areas like Manu National Park, Tambopata National Reserve, and Bahuaja Sonene National Park. However, outside protected areas, populations are decreasing due to the destruction, degradation, and fragmentation of their habitats – mainly caused by gold mining, agriculture, and logging (Mendoza et al., 2017). As apex predators, giant otters are of particular concern regarding mercury pollution and bioaccumulation (Roach et al., 2013). The species is considered a good indicator of ecological disturbances and habitat conservation status, as their presence indicates good water quality (Mendoza et al., 2017).

4 Direct drivers of change

Beginning in the last decades of the 20th century, and accelerating greatly after the paving of the IOH in 2011, the region of Madre de Dios has been subject to extreme environmental changes, including deforestation, mercury contamination from mining, and forest degradation (Duff & Downs, 2019). Projected climate change will interact with the other drivers and exacerbate their impacts (Chávez Michaelsen et al., 2017).

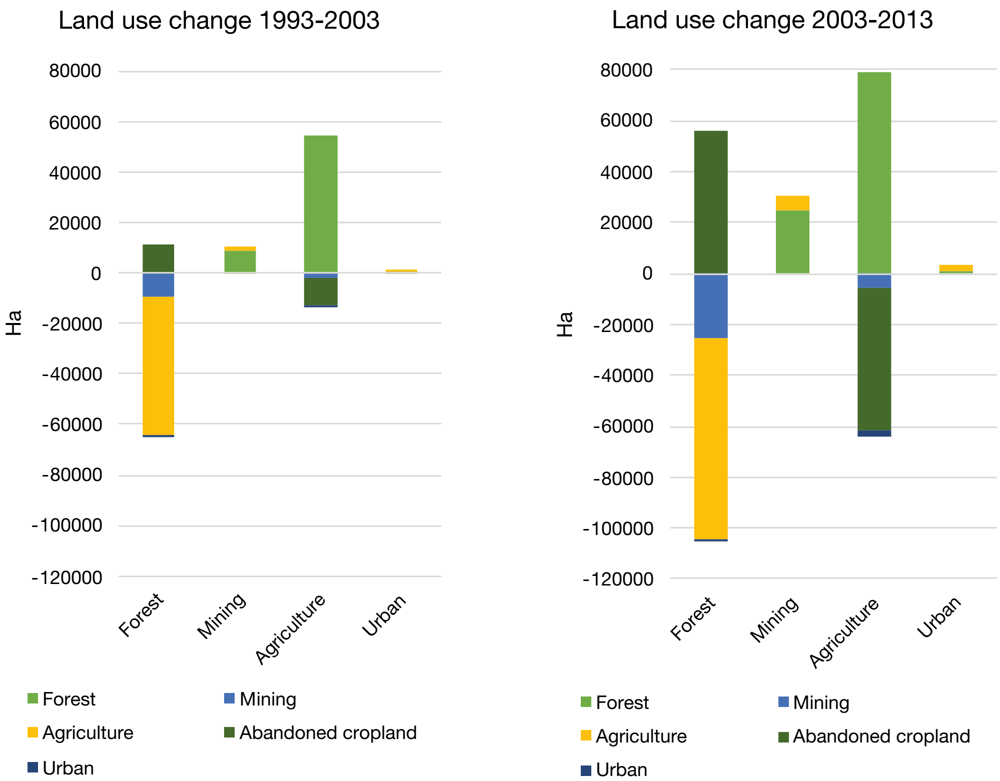
Direct drivers of change (e.g. land use change, exploitation of resources, pollution, climate change, and invasive species) are addressed in this chapter, while indirect or underlying drivers (e.g. demographic, economic or institutional) are addressed in the following chapter. Drivers are described individually, however studies for the Andes Amazon (Geist & Lambin, 2002) region show that these drivers act in a complex web of interactions and operate at different spatial and temporal scales to produce the local outcomes in terms of socioeconomic development and environmental conservation and degradation. Environmental processes like deforestation are rarely caused by one factor in isolation, whether population growth or road construction (Geist & Lambin, 2002). A number of studies have been carried out in the tri-national border area of Bolivia, Brazil, and Peru to investigate the interplay and feedback loops between the different direct and indirect factors of deforestation (Klarenberg, Muñoz-Carpena, Campo-Bescós, & Perz, 2018; Southworth et al., 2011). These interactions are predicted to drive the Amazon system towards thresholds which, if crossed, could lead to regime shifts such as that from forest to savannah (Staal et al., 2020), releasing vast quantities of carbon into the atmosphere and further accelerating the change (Nepstad et al., 2008).

4.1 Land use change

Inadequate development policies in the Amazon region, migration, and population growth have been identified as main causes of land use change in Madre de Dios (Gobierno Regional de Madre de Dios, 2014). Completion of the IOH in 2011 increased migration, connectivity, and land invasions, rapidly exacerbating the drivers of forest loss and land use change (Fisher et al., 2018; Rodriguez-Ward, Larson, & Ruesta, 2018; Sánchez-Cuervo et al., 2020). The main landscape dynamics in Madre de Dios include deforestation following completion of the IOH and expansion of secondary roads; agriculture expansion in forest areas along the IOH and secondary roads; mining expansion into forest areas and agricultural land; and land abandonment in rural areas with forest regrowth (Sánchez-Cuervo et al., 2020).

Land cover change between 1993 and 2003 was characterized by a net loss of forest cover of 52,597 ha. Forest was mostly converted to agricultural land, while forest regrowth mainly occurred in abandoned croplands. Agricultural areas increased by 41,229 ha, expanding mainly into forest areas. Mining had the second highest increase at 10,792 ha, expanding mostly into forest. Urban areas expanded by 576 ha, mainly into surrounding agricultural areas. The period from 2003 to 2013 was characterized by an increase in deforestation (104,663 ha), forest regrowth (56,059 ha), mining expansion (30,509 ha), and urban expansion (3,133 ha). Forest was mostly converted to agriculture and mining areas, with a net loss of forest cover of 48,604 ha. Agriculture showed the highest expansion (78,926 ha), but also experienced losses due to forest regrowth (Figure 12) (Sánchez-Cuervo et al., 2020). Overall, between 1993 and 2013, forest cover was mostly converted to agriculture (470% increase) and mining areas (938% increase), while urban areas (187% increase) expanded into surrounding agricultural lands (Sánchez-Cuervo et al., 2020).

Figure 12. Land use changes from forest, mining, agriculture and urban to the other classes in Madre de Dios in the periods 1993–2003 and 2003–2013. Source: based on Sánchez-Cuervo et al. (2020).



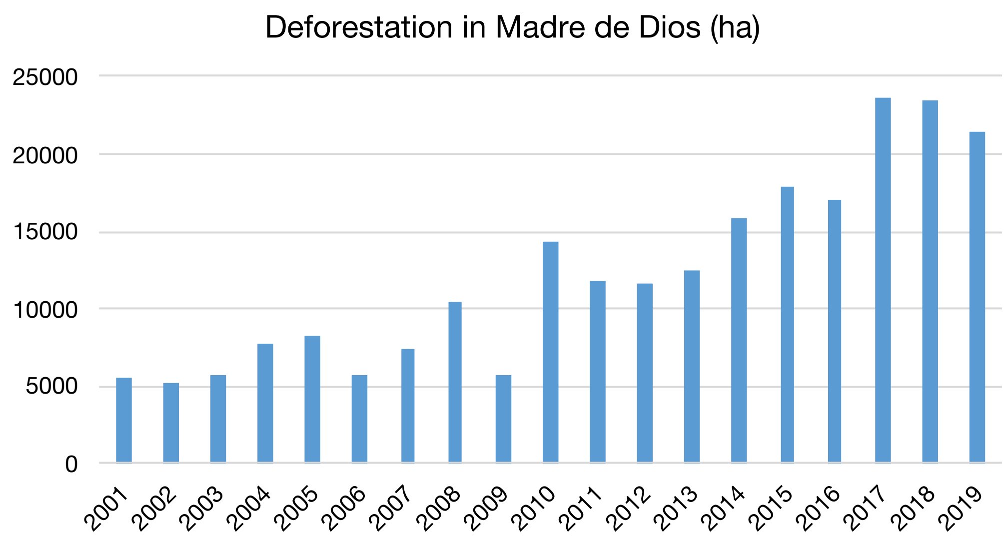
Deforestation

Deforestation is on the rise in Madre de Dios (Rodriguez-Ward et al., 2018). The region lost over 168,000 ha (2%) of primary tropical forests between 1993 and 2013. The forest was converted mainly to agriculture and mining areas (Sánchez-Cuervo et al., 2020). Deforestation is mainly driven by road network development, migration, population growth, land invasions, and forest fires (Dupuits & Cronkleton, 2020; Rodriguez-Ward et al., 2018; Sánchez-Cuervo et al., 2020). While agricultural practices are considered a slow driver of deforestation in Madre de Dios, current mining practices are considered to be driving deforestation at a faster rate (Rodriguez-Ward et al., 2018). An additional underlying deforestation driver is insecure land tenure and overlapping land titles or concessions (Rodriguez-Ward et al., 2018).

During the 1980s and 1990s, the loss of natural forests in the region was primarily caused by government-subsidized agricultural expansion (Sánchez-Cuervo et al., 2020; Scullion, Vogt, Sienkiewicz, Gmur, & Trujillo, 2014). Agroforestry, such as the establishment of tree and cash crop plantations (e.g. teak, mahogany, cacao) combined with crops and/or animal production, is a driver of forest loss in some areas (Fisher et al., 2018), but its impact on biodiversity is often more modest than conversion to other forms of land cover and use. In the 2000s, gold mining became an important driver of deforestation following the discovery of gold deposits and an increase in the international price of gold beginning in 2008 (Rodriguez-Ward et al., 2018; Scullion et al., 2014). The extent of gold mining increased from less than 10,000 ha in 1999 to more than 50,000 ha by 2012, with a rate of expansion of 6,145 ha year^{-1} after 2008 (Asner et al., 2013). From 2012 to 2016, another 20,000 ha were deforested due to gold mining in the region (Martinez et al., 2018). Gold mining-related losses of forest in Madre de Dios averaged 4,437 ha year^{-1} from 1999 to 2016 (Asner & Tupayachi, 2017). A further study identified nearly 100,000 ha of deforestation due to gold mining in a 34-year period (1984–2017) (Caballero Espejo et al., 2018).

Overall, the region lost 76,080 ha of forest from 2001 to 2010. This amount more than doubled from 2011 to 2019, with 155,033 ha deforested. The highest forest loss was registered in 2017, with 23,669 ha deforested, in connection with the extension and improvement of secondary roads connected to the IOH (Figure 13) (Nicolau, Herndon, Flores-Anderson, & Griffin, 2019).

Figure 13. Annual deforestation in Madre de Dios. Source: Geobosques (2021).



The major surfaces of deforestation are located in the medium and low sections of the Madre de Dios River, and in the subbasins Colorado (Puquiri and Huepetuhe microbasins), Inambari (Caychive and Huacamayo microbasins), and Tambopata (Malinowski microbasin) (Figure 14) (MINAM, 2016). Key government and private actors continue to support and promote land use changes from forested areas to agriculture (e.g. papaya plantations) and mining (Rodriguez-Ward et al., 2018). In line with recent general findings for Latin America (FAO and FILAC, 2021), protected areas and indigenous communities, in particular, have proven to be important players in conserving forests by reducing deforestation and carbon emissions in the Amazon and in Madre de Dios specifically (Nicolau et al., 2019). However, the buffer zones of protected areas seem less effective in limiting deforestation and illegal mining in the region (Caballero Espejo et al., 2018; Weisse & Naughton-Treves, 2016).

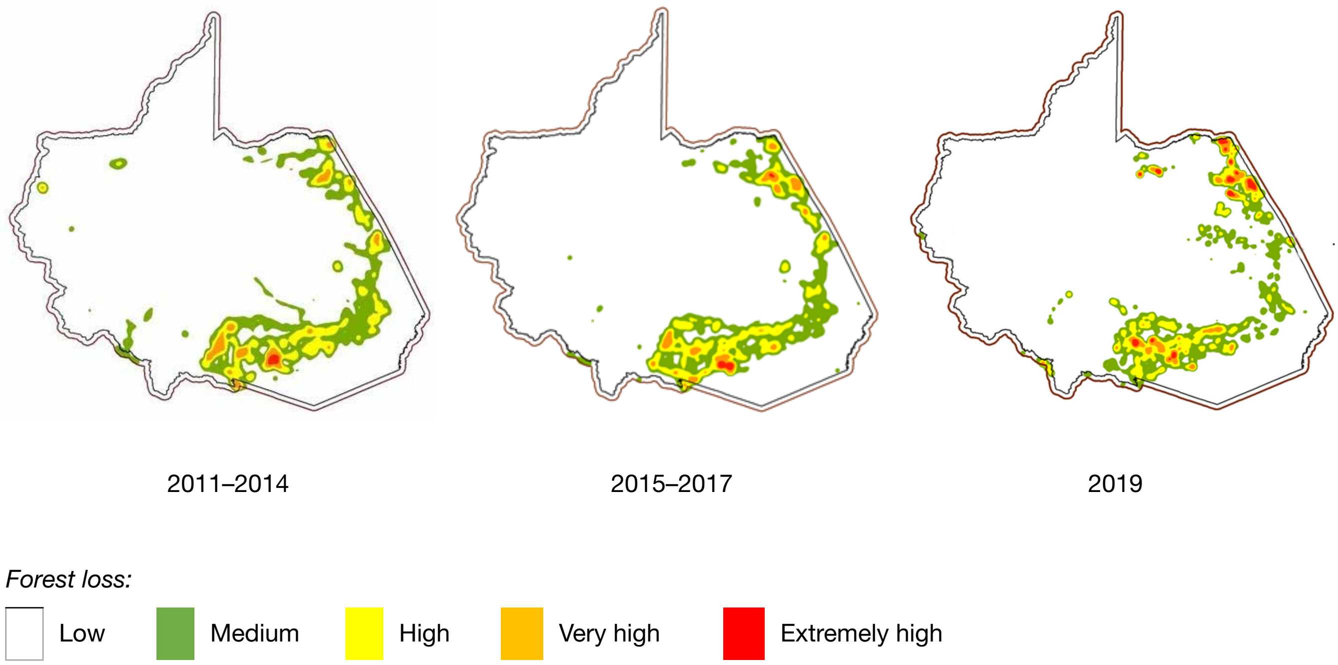


Figure 14. Distribution of forest loss in Madre de Dios in the periods 2011–2014, 2015–2017, and 2019. Source: Geobosques (2021).

While total deforestation – mainly concentrated along the IOH (Figure 14) – is still moderate in comparison to other nearby Amazon regions like Acre or Rondônia, the deforested areas disrupt the ecological connectivity between the Eastern Andes (Manu) and the Southwestern Amazon (Tambopata). This has prompted conservation organizations to promote local implementation of ecological corridors (Rosenthal, Stutzman, & Forsyth, 2012).

Forest fires

Another important factor for the degradation of the Amazon rainforest are human-made fires. These could, along with forest clearing and fragmentation, further contribute to the savannization process mentioned above, generating unprecedented impacts on biodiversity, forest carbon, human livelihoods, and economic development (Chávez Michaelsen et al., 2017). Fire or controlled burning is a common agricultural management practice throughout the Amazon, owing to its effectiveness in removing unwanted vegetation, releasing nutrients, and controlling pests. However, in the context of climate change, especially during extremely hot and dry years, fires can accidentally escape into much wider areas, becoming a severe social, health, and environmental problem. As a result, large areas of adjacent forest or cropland and pasture have been and will be burned unintentionally (Chavez Michaelsen et al., 2020).

Hydropower dams

There are currently no major hydropower dams in Madre de Dios. However, with the transition to sustainable energy resources to combat climate change, hydropower projects may be implemented in the future. Hydropower infrastructure in the upper reaches of Madre de Dios River tributaries, in the Andes, has far-reaching impacts on local river ecology, in particular on river connectivity for migratory (fish) species and sediment loads, geomorphological processes, biodiversity, and associated ecosystem services. At the level of the Andes Amazon ecosystem, of which the River Madre de Dios forms a part, the impact of the hydropower projects is significant (Anderson et al., 2018).

4.2 Exploitation of resources

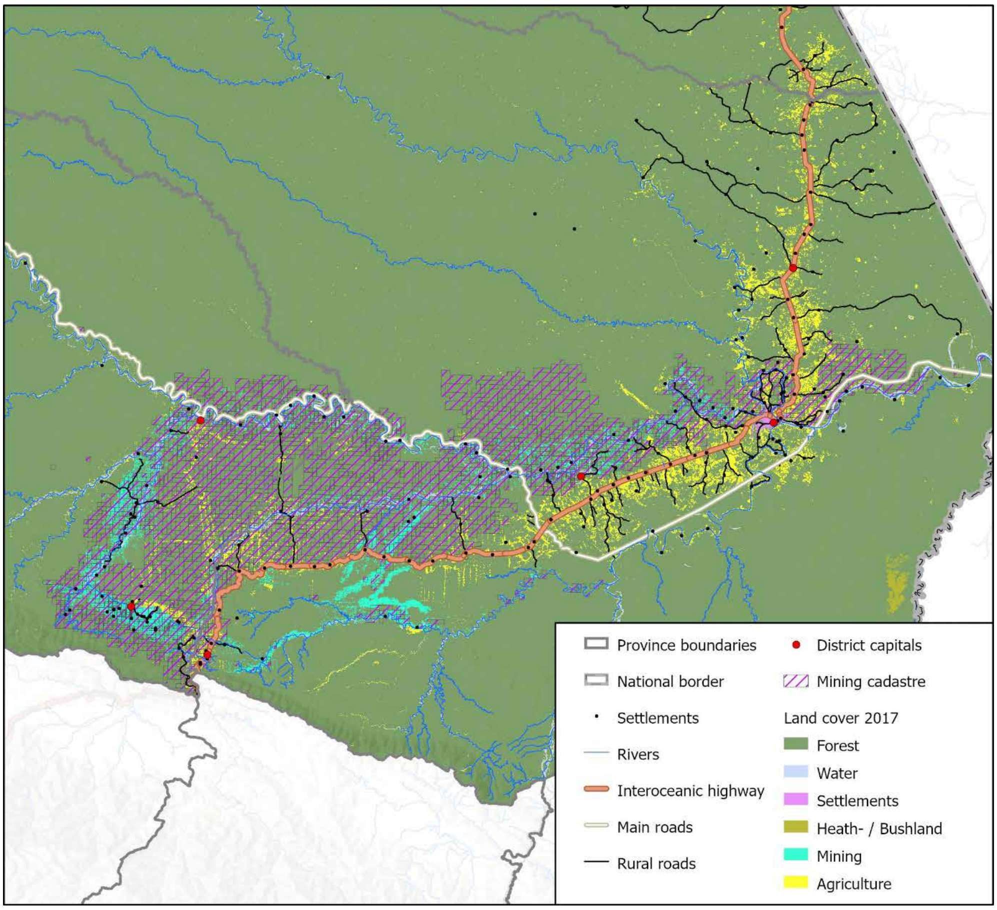
Logging

Forestry activities have increased significantly in Madre de Dios in recent decades, causing depletion of timber resources in certain areas like the Western sector (Manu). If current exploitation rates continue, social and environmental problems caused by their unplanned use may increase (Gobierno Regional de Madre de Dios, 2018). Illegal logging, still widespread and systematic (Global Witness, 2019), is also contributing to forest degradation in the region (Gobierno Regional de Madre de Dios, 2014). On the other hand, certified logging concessions can add value to forest products (Duchelle et al., 2012) and maintain high levels of biodiversity (Campos-Cerqueira et al., 2019).

Gold mining

Mining for gold has historically been undertaken at low intensities in the Andean foothills and along riverbanks in the Amazon lowlands (Asner et al., 2013). However, gold commodity prices increased substantially following the 2008 global financial crisis, triggering a boom in illegal and informal alluvial gold mining in Madre de Dios. This was further enabled by the improved accessibility of the region after the completion of the IOH, which also increased migration (Asner et al., 2013; Csillik & Asner, 2020; Damonte, 2018; Fisher et al., 2018). Most of the mining activities are unregulated, artisanal in nature, and illegal (Csillik & Asner, 2020). One study suggests that – in comparison with activities like agriculture and cattle ranching – gold-mining activities occur closer to indigenous communities, protected areas, and protected-area buffer zones (Nicolau et al., 2019). Mining operations are mainly concentrated in the district of Laberinto in the basins of the rivers Colorado, Inambari, Madre de Dios, Malinowski, Tambopata, Huepetuhe, and Caychihue (Figure 15) (Gobierno Regional de Madre de Dios, 2018).

Figure 15. Location of areas designated for mining (mining cadaster) and actual mining operations (turquoise blue) in 2017 in Madre de Dios. Source: based on data from Esri, CGIAR, and USGS.



Alluvial gold mining in Madre de Dios has become a key driver of land degradation and deforestation, causing extensive environmental damage to the rainforest ecosystem (Csillik & Asner, 2020; Damonte, 2018; Velásquez Ramírez et al., 2020). Gold mining in Amazonia involves forest removal, soil excavation, and the use of liquid mercury, which together pose a major threat to biodiversity, water quality, forest carbon stocks, and human health (Asner & Tupayachi, 2017; Swenson, Carter, Domec, & Delgado, 2011). Mercury is released in large quantities into the atmosphere, sediments, and watersheds (Groenendijk et al., 2014). After gold mining, soils are found to be highly degraded, displaying loss of fine sediment and reduced organic matter and carbon content, compromising soil fertility and productivity (Román-Dañobeytia et al., 2020; Velásquez Ramírez et al., 2020). This presents severe limitations for agricultural development and the recovery of native forest. Active restoration interventions are needed to restart natural processes (Román-Dañobeytia et al., 2015). The removal of forest biomass leads to increases in sediment concentration, turbidity, and conductivity in nearby streams and rivers (Dethier et al., 2019). The effects of sediment loads in rivers can persist for hundreds of kilometers (Asner et al., 2013). Hunting is also widely associated with gold miners who search the forest for game (Asner et al., 2013). In addition to the ecological and health consequences of gold mining, violence and human trafficking for sexual and labor exploitation have been reported in some mining camps. Further, gold mining has been linked to social conflicts, transnational crime networks, drug trafficking, and other illegal economies (Cortés-McPherson, 2019; Espin & Perz, 2020; Markham & Sangermano, 2018).

The Peruvian government has been trying to control the growth of illegal gold-mining activities in Madre de Dios via implementation of legal decrees and police interventions, including a ban on the import of mercury in 2015 (Rubiano Galvis, 2018). Most recently, from February to May 2019, the Peruvian Ministry of Interior managed the Mercury Operation intervention to eradicate illegal mining activities in the site of La Pampa. It has been reported that this operation contributed to a 92% decrease (2018–2019) in gold mining-related deforestation in the region (Nicolau et al., 2019).

4.3 Pollution

Rapid expansion of gold-mining activities in Madre de Dios has resulted in increasing loading of mercury into the environment, with consequences for ecosystems and human health (Martinez et al., 2018; Velásquez Ramírez et al., 2020). Mercury contaminates rivers and lakes, where it rapidly converts to methylmercury, and river sediments, bioaccumulating in fish tissues and reaching human populations through the food chain (Dethier et al., 2019; Fisher et al., 2018; Gerson et al., 2020; Kumar, Divoll, Ganguli, Trama, & Lamborg, 2018; Markham & Sangermano, 2018). Several studies throughout Madre de Dios have reported mercury contamination levels in fish that exceed international standards for human consumption (Ashe, 2012; Diringer et al., 2015; Gonzalez et al., 2019; Roach et al., 2013). Local communities in the region, including children and indigenous communities, are highly susceptible to mercury contamination as they heavily rely on fish as a source of protein (Ashe, 2012; Diringer et al., 2015; Kumar et al., 2018; Martinez et al., 2018; Roach et al., 2013). Studies found that over 30% of the population in Madre de Dios had hair mercury concentrations above the 2.2 μg/g reference dose established by the World Health Organization (WHO) (Feingold, Berky, Hsu-Kim, Rojas Jurado, & Pan, 2020; Gonzalez et al., 2019; Reuben et al., 2020). Exposure to mercury affects the central and peripheral nervous systems, cardiovascular system, urinary system, immune system, skin, and lungs (Gonzalez et al., 2019). Mercury bioaccumulation also poses developmental, hormonal, and neurological threats to wildlife (Markham & Sangermano, 2018).

4.4 Climate change

The Peruvian climate is rather diverse as a consequence of the mix between steep and complex Andean topography, the desert along the Pacific coast, and the unique climate modulated by the tropical rainforest in the Amazon basin. As a result, abundant precipitation is measured from November to March in the mountain ranges and the rainforest, while rainfall is scarce from April to October. Near the Pacific coast, precipitation is rather limited, except in the northern part where some precipitation is observed between December and March. These typical conditions can be altered by the “El Niño-Southern Oscillation” phenomenon (Imfeld et al., 2019; Sanabria et al., 2018), surface temperatures over the Atlantic ocean (Espinoza et al., 2011), and wind intensities and patterns over the Amazon basin.

Studying climate and its variability is important for the Amazon, as it is threatened by anthropogenic climate change. For example, observations show an increase in the frequency and intensity of drought events in the past two decades (Lewis, Brando, Phillips, van der Heijden, & Nepstad, 2011; Marengo et al., 2013). Not only extreme droughts, but also floods could become a more regular event in the future (Chávez Michaelsen et al., 2017). In terms of temperature, changes are already evident, showing an increase in annual mean temperature of 0.25°C per decade since the mid-1970s. The regional climate model simulation presented here projects a temperature increase of around 2–3°C across most of Peru in the wetter months at the end of the century (2070–2100) based on the high emission scenario RCP8.5 in comparison with the present climate (1981–2010). In the dry season, this warming trend is projected to further increase by about 3–4°C (Figure 16, left panel). The variability in temperature is larger in the future compared to the past over Madre de Dios. This is especially true for the wet season and the driest months, namely June and July. The increase in temperature is mainly related to reductions in precipitation, which lead to stronger heating effects and more extreme temperatures. The simulated temperature change by the regional climate model is within the range of IPCC-AR5 projections (IPCC, 2013), which extend as high as 5–6°C.

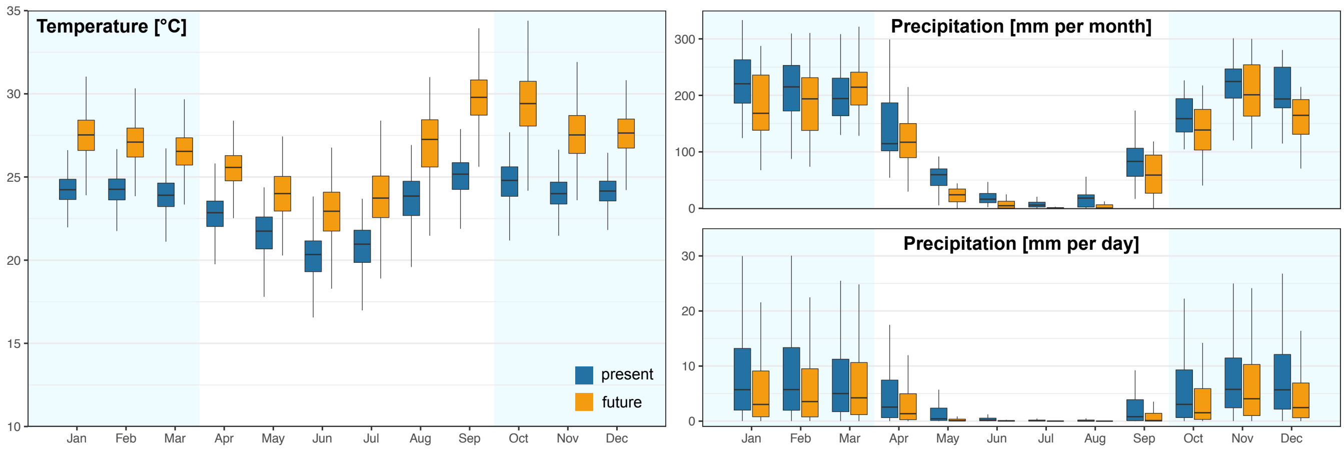


Figure 16. Climatology for each month using daily mean two-meter temperature (in °C, left) and precipitation sums (in mm, right) monthly (top) and daily (bottom) over the Madre de Dios region depicted as boxplots. The blue boxes represent the present climate (1981–2010), while the orange boxes depict the future one (2071–2100). The boxes cover the range of the 25th to the 75th quartile, while the whiskers extend a maximum of 1.5 times plus or minus the distance between the first and third quartiles. Outliers are not shown, so as to simplify the plots. Blue shading indicates the wet months. Source: authors’ own elaboration.

In the regional climate model simulation presented here, precipitation is projected to change significantly in the future. Precipitation will reduce around 50–100 mm per month (about 30%) in Madre de Dios in the rainy season, and about 20–100 mm between May and August. This means that in the driest months – June and July – precipitation could be almost completely absent by the end of the century. The only months that could remain relatively stable are February to April and September to November (Figure 16, monthly precipitation). These are months in the transition phase between the rainy and dry season. By contrast, along the western slopes of the Andes, precipitation in the rainy season (October to April) is projected to increase by around 75–150 mm per month (locally up to 200 mm per month), whereas drying trends are projected for the rest of the year. The reduction and changes in the variability of precipitation, especially in the driest months (Figure 16, right panels), are likely causes of extreme climatic events projected for the Amazon region (Malhi et al., 2008). For the analysis presented here, it should be noted that more El Niño events are included in the present climate simulation (around eight) compared to the future climate simulation (around six), whereas the number of La Niña events is similar in both periods (eight events), but the intensity is slightly reduced in the future. If a longer climatology for the future climate would be employed, the current underrepresentation of El Niño events could be balanced out. Inclusion of an equal number of El Niño and La Niña events in a longer climatology might project further drying since El Niño events are linked to drier conditions over the Amazon (Cai et al., 2020).

The analyzed CMIP5 models in IPCC-AR5 (IPCC, 2013) project an overall tendency towards a reduction in precipitation during the dry season, while precipitation is expected to remain unchanged during the wet season. However, in the dry season, greater variability in the direction of reduced rainfall is projected, which could trigger more recurrent droughts. Changes in the dry season are consistent with those observed in our regional climate simulation; it also projects a reduction in precipitation during the rainy season, which could further enhance the severity and length of droughts. The standardized precipitation index (SPI) can help to study characteristics of droughts, as the SPI can be interpreted as the number of standard deviations by which the observed anomaly deviates from the long-term mean. Analysis of the SPI projects drying over Madre de Dios in the future. It confirms an increased occurrence of extremely dry periods, which will most likely last several months or years. Such anomalies in the duration and intensity of the dry season are further enhanced by the El Niño-Southern Oscillation, namely, by El Niño events through warm eastern Pacific currents (Malhi et al., 2008). It should be noted that a significant reduction in the SPI of around 0.32 per decade was already observed in the final 30 years of the last century (Li, Fu, Juárez, & Fernandes, 2008).

The temperature increases described – occurring not only in the air, but also at the Earth's surface – in combination with changes in the water cycle, could severely impact the functioning of the unique ecosystem of the Amazonian forest. With such a projected increase in temperature and other human pressures on the Amazon ecosystem, the rainforest could be forced into a gradual process of savannization, including carbon loss and increased drying (Marengo et al., 2013; Staal et al., 2018).

Specific ecosystem services such as Brazil nut production could be affected by climate change. An important parameter for the distribution of the species seems to be the yearly precipitation sum, with Brazil nut trees present in areas where precipitation exceeds 1,400 mm per year (Wadt, Faustino, Staudhammer, Kainer, & Evangelista, 2018). Under present conditions, this occurs in most of Madre de Dios according to the regional climate simulation presented here (Figure 17, 1st and 3rd panel). This may be different in the future, as especially the northern part of the area lacks the necessary water amounts indicated by the climatological annual precipitation sums (Figure 17, 2nd panel). Looking at year-to-year variability, there are years where this limit could still be exceeded throughout much of Madre de Dios. However, in the northern part, the necessary threshold is exceeded only one out of every three years (Figure 17, 4th panel). These changes could substantially impact the production and growth of Brazil nuts, rendering communities that depend on this forest product especially vulnerable in the coming decades.

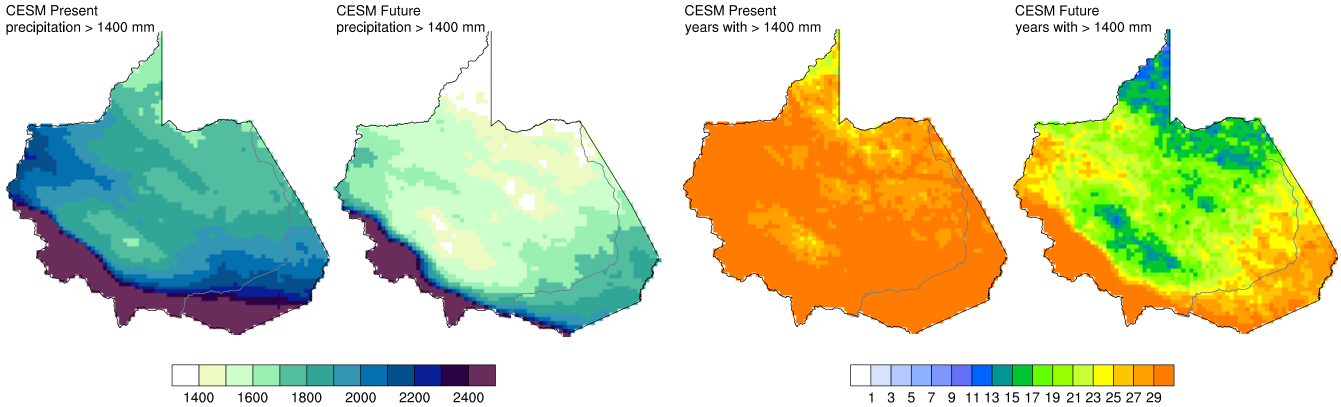


Figure 17. Annual precipitation sums (in mm) for the present climate (1981–2010, first panel) and a possible future climate (2071–2100, second panel). Depicted are only sums that exceed the threshold of 1,440 mm, the lower limit for Brazil nut distribution areas. The shading indicates annual precipitation in mm. The two right panels indicate the number of years in which this threshold is exceeded for each of the two periods. The grey line indicates the Interoceanic Highway. Source: authors' own elaboration.

The accidental spread of agriculture-related human-made fires may become an increasing threat in the context of climate change. To obtain a rough estimate of changes in future fire risk, we calculated the fire weather index (FWI), which classifies fire danger into six categories from "very low" to "extreme" (Lawson & Armitage, 2008). On a monthly mean basis, the FWI is "very low" or "low" in the rainy season regardless of whether this is in the past or the future. This is mainly related to the abundant water and high relative humidity. In the regional climate model, the FWI only occasionally reaches "very high" fire danger from July to September in the past; in the future model, however, this level is already reached in the month of June. The highest fire danger in the future is expected in August, as has been the case in the past. By the end of the century, the FWI is projected to reach even "extreme" levels in the southeastern part of Madre de Dios, while most of the domain exhibits "very high" fires danger (Figure 18). This result further confirms the threat of burning large areas unintentionally in the near future.

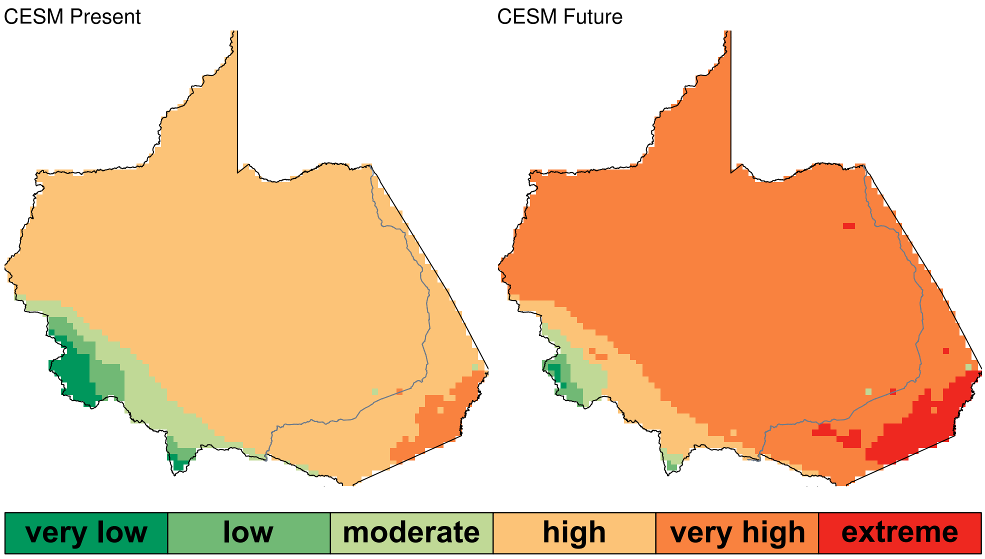


Figure 18. The fire weather index (FWI) for Madre de Dios is depicted for the present climate (1981–2010, left) and a possible future climate (2071–2100, right) for August (month with highest risks according to model simulations). The grey line indicates the Interoceanic Highway. Source: authors' own elaboration.

All these changes in the climate and climate variability in the Madre de Dios region have already harmed natural and human systems. Increasing droughts will cause human-made fires to trigger emergency situations that damage infrastructure, agricultural areas, and forests. Droughts will reduce the productivity of Amazon forests, and water for human consumption and agriculture will be less accessible. There is also the possibility that droughts will be followed by intense rainfall, causing floods and further damage to infrastructure. These phenomena will impact the livelihoods of local people and the economic development of the region, increasing the vulnerability of rural communities (Gobierno Regional de Madre de Dios, 2018). Vulnerability is particularly high in the subsistence agriculture economy, followed by Brazil nut production, livestock, and aquaculture. Communities are already experiencing losses of crops and animals. Fishing patterns have been affected by drastic reductions in precipitation and water levels in rivers and creeks (Chavez Michaelsen et al., 2020). Notably, these changes will also significantly impact indigenous communities. Indigenous communities are essential to conservation of the ecosystems in which they live. They interpret the effects of climate change and react in a creative manner, making use of their traditional knowledge and practices. This knowledge could serve to find solutions and applications at broader scales (Gobierno Regional de Madre de Dios, 2018).

4.5 Invasive alien species

Invasive species have not been reported in the literature as a main threat to biodiversity in Madre de Dios. One species that may require attention is the "paiche" (*Arapaima gigas*), a fish species introduced in Madre de Dios to obtain fish meat for the local population and to sell commercially. Currently the species has expanded to Bolivian territory; its impacts on local fish populations remain unknown (Gobierno Regional de Madre de Dios, 2014).

5 Indirect drivers of change

5.1 Demographic drivers

Human populations in Madre de Dios, consisting mainly of indigenous communities, were virtually isolated from the rest of the world until the rubber boom of the late 1800s drew immigrants known as “ribereños” (Menton & Cronkleton, 2019). After the collapse of the rubber industry in the early 1900s, the local population of Madre de Dios remained very low in number and relatively stable until the mid-1960s, when a road was constructed into the region (Jensen et al., 2018; Naughton-Treves et al., 2003). Migrants from the Andes moved initially to trade with skins, wild rubber, Brazil nut, and, beginning in the late 1970s, timber (IIAP, 2001; Lawrence et al., 2005). In the 1980s, Madre de Dios underwent a government-sponsored effort to settle the area, including settlement projects and road openings (Almeyda Zambrano, Broadbent, Schmink, Perz, & Asner, 2010). With the paving of the IOH in 2011, migrants were attracted to Madre de Dios for gold mining, available land, and economic incentives

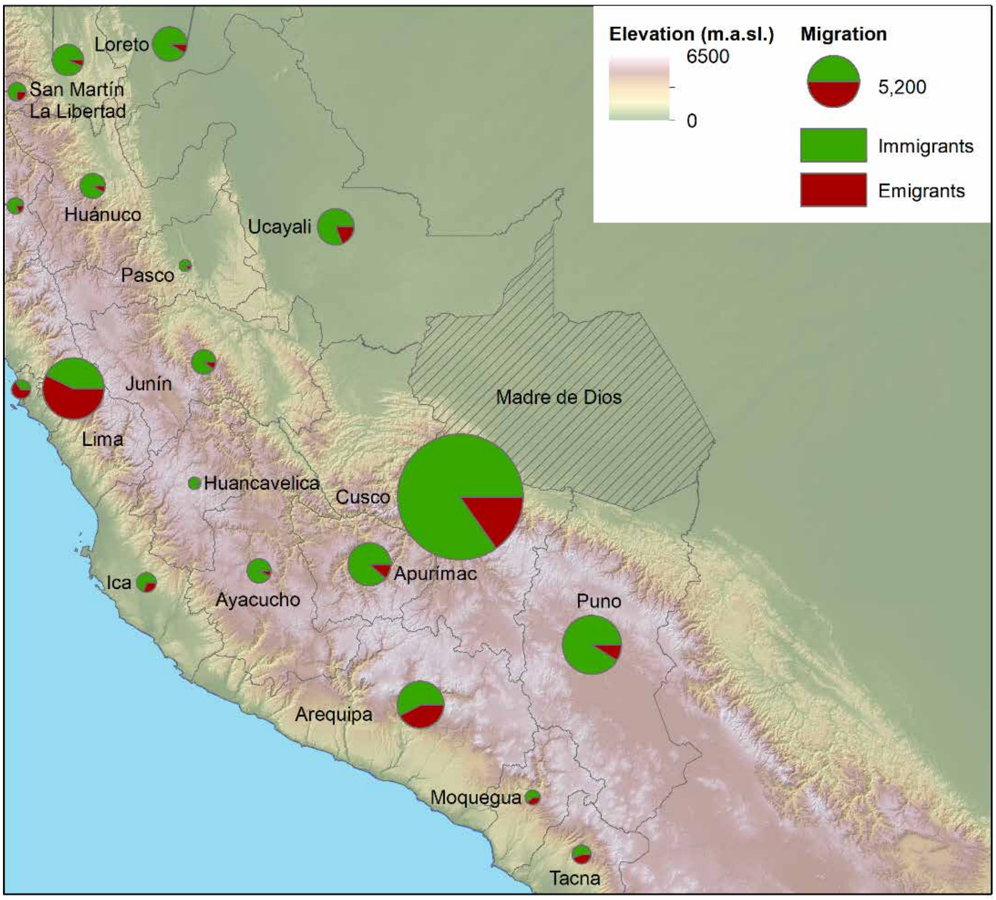
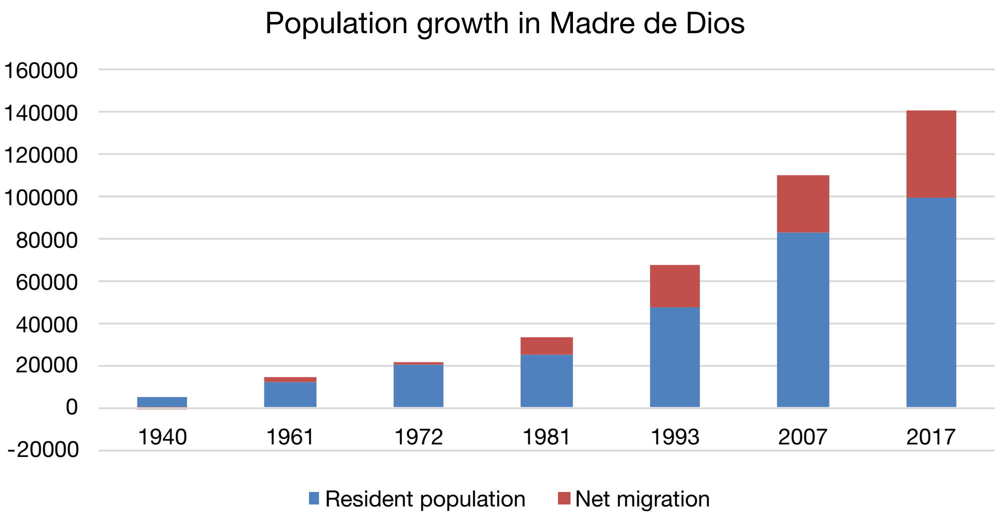


Figure 19. Migrant population related to Madre de Dios within southern Peru in 2017. Number of people whose birthplace was outside of Madre de Dios (immigrants, green) and number of people born in Madre de Dios living in other departments (emigrants, red). The size of the circle represents the total number of migrants. Source: based on INEI (2018c).

for ranching and farming. Current migrants mainly come from the Andean regions of Cusco and Puno, with possible Quechua and Aymara culture and language influences, as well as from other parts of the Peruvian Amazon (Figure 19) and other South American countries (IOM, 2015; Jensen et al., 2018; Naughton-Treves et al., 2003; Oliveira et al., 2019; Perz et al., 2016). All these factors have led to steady population growth in the region in recent decades (Figure 20).

Figure 20. Development of population including net migration in Madre de Dios. Source: INEI (2021).



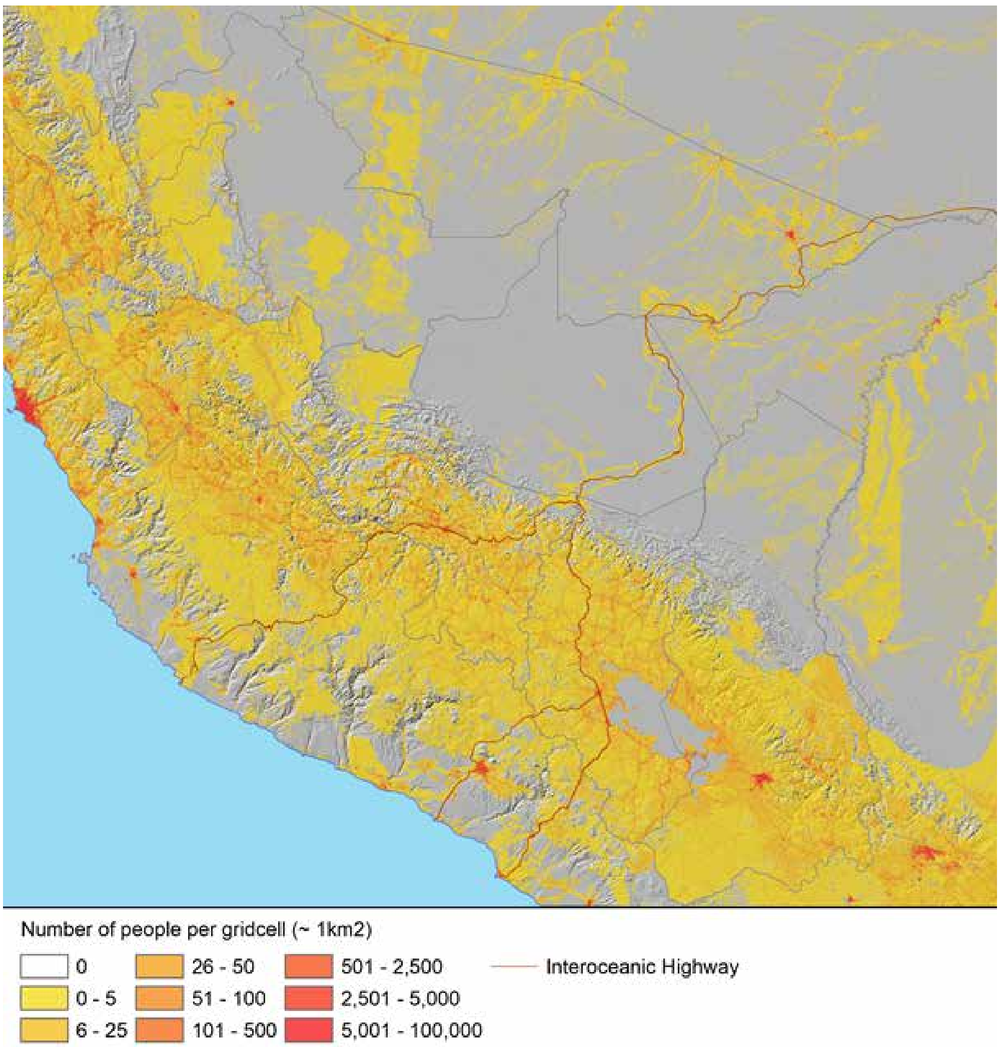


Figure 21. Population distribution in Madre de Dios and surrounding departments in 2019. Source: based on LandScan (Rose et al., 2020) and Database of Global Administrative Areas (GADM, 2021).

The average rate of human population growth in Madre de Dios between 2007 and 2017 was 2.6%, the highest in the country, in part due to net positive migration (Figure 20). In 2017, out of 105,503 people older than 12 years, 3,592 (3.4%) identified as Amazonian indigenous; 38,564 (36.5%) identified as Quechua or Aymara; and 48,411 (45.8%) identified as Mestizo, with the remaining 14,936 (14.2%) belonging to other groups (INEI, 2018c). The demographic dynamics resulted in an unprecedented land use change in the region, mainly surrounding the IOH (Oliveira et al., 2019), leaving large parts of the territory not inhabited or only very sparsely (Figure 21). It also led to the loss of cultural identity and of traditional and indigenous practices in the region (Gobierno Regional de Madre de Dios, 2014). Much of the population growth in the period 2007–2017 was concentrated in urban areas (annual growth rate of 4.4%), while rural areas saw an absolute population decrease (annual growth rate of -3.2%) (INEI, 2018c).

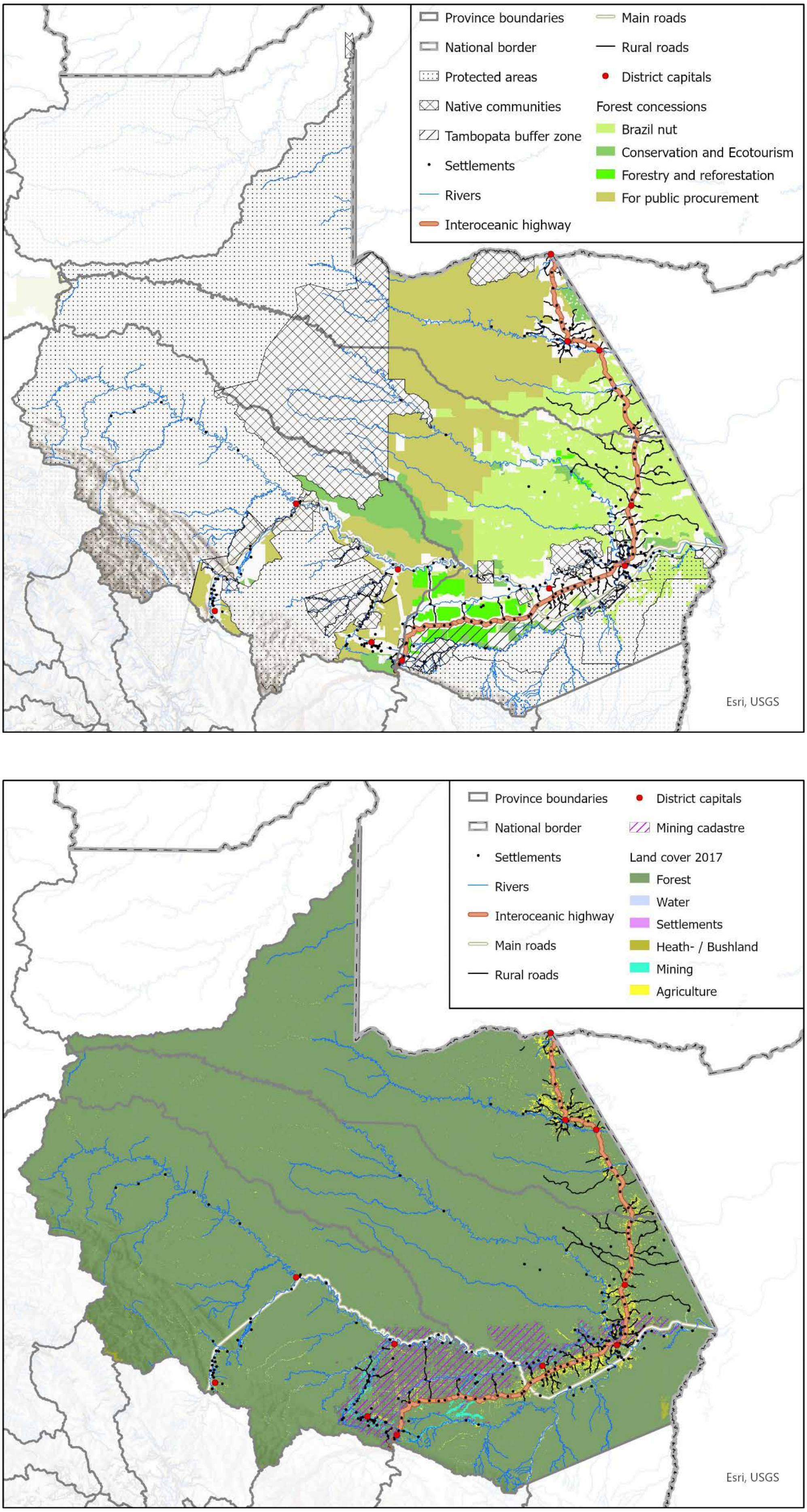
5.2 Economic drivers

Madre de Dios is a frontier region that has experienced four main economic booms based on different extractive commodities: rubber, Brazil nut, gold, and timber (Chavez & Perz, 2012). These rich natural resources, combined with waterways for transport and the improved IOH, present economic opportunities for the local communities, but also act as a strong pull factor for immigrants in search of a better life, such as neighboring populations from the Peruvian Andes. In the period 2002–2011, the average annual growth of the economy in Madre de Dios was 7.3% – higher than the national average growth of 6.4% (Groenendijk et al., 2014). Table 3 shows the share of the different economic sectors in comparison with the gross domestic product of Madre de Dios over the last six years. There has been a slight increase in agriculture, with about one third of the economy depending on extractive industries – mainly gold mining.

Table 3. Share of different economic sectors in the gross domestic product of Madre de Dios. Source: INEI (2021).

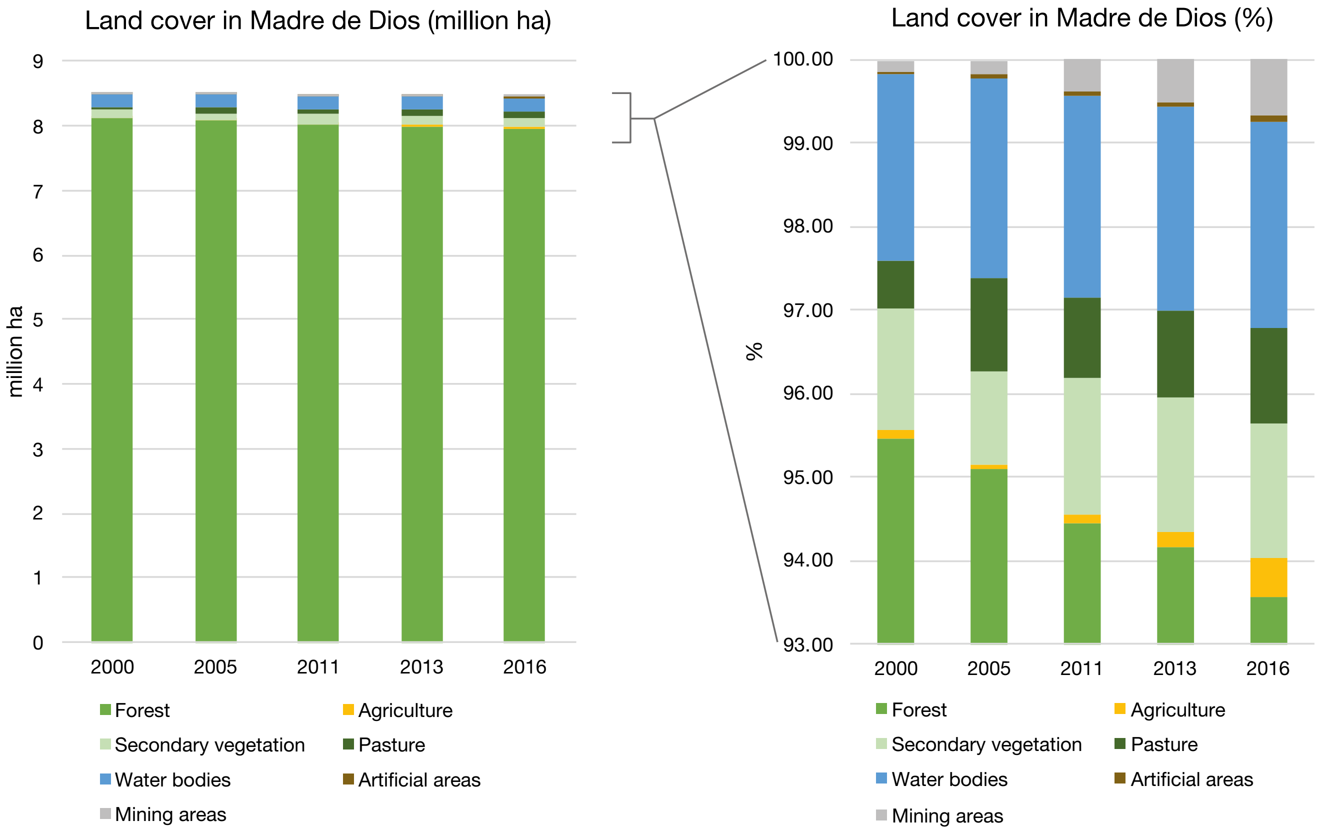
Sector	2014	2015	2016	2017	2018	2019
Agriculture, forestry, and fisheries	8	6.9	6.1	7.6	8.5	9.4
Extractive activities	34.9	45	52.4	44.3	37.2	31
Manufacture and retail	18.6	15.1	12.5	14.3	15.8	17.2
Energy, transport, and construction	13.7	12	11.1	12.3	13.8	14.9
Other (mainly services)	24.8	21.1	18.1	21.5	24.6	27.5

Figure 22. Land uses in Madre de Dios. Top panel: forest concessions, protected areas, buffer zones, and native community territories. Bottom panel: areas designated for mining (mining cadaster), actual mining operations, agriculture, and settlements. Source: based on data from Esri, CGIAR, and USGS.



Much of the economy in Madre de Dios is based on exploitation of natural resources, often resulting in conflicting forms of land use. Different land use designations, tenure rights, and livelihood activities (legal or illegal) may overlap in the same area. Current land uses in Madre de Dios include concessions for forestry, Brazil nut, conservation, and ecotourism; areas designated for gold mining; cropland, pasture, and recent slash and burn; indigenous community territories and protected areas; small urban towns and settlements; and paved and unpaved roads (Figure 22). Water bodies include lakes, rivers and creeks, riverbanks and fish farms, as well as gold-mining ponds (Chávez Michaelsen et al., 2017; Fisher et al., 2018; Oliveira et al., 2019). In 2016, forests made up 93.6% of the territory, followed by water bodies (2.5%) and secondary vegetation (1.6%) (Figure 23). Farmers, loggers, and Brazil nut collectors represent around 60% of the regional population of Madre de Dios (Damonte, 2016). There are 37 native communities legally documented in the region, only six of which still lack property titles. Their total area covers approximately 5% of the region (Rodriguez-Ward et al., 2018; Zamora & Monterroso, 2019).

Figure 23. Land cover in Madre de Dios in million hectares (left panel) and in percentage (right panel). Source: Geobosques (2021).



With the exception of the short-lived rubber boom at the turn of the 19th century, up until the 1960s, the main economic activities were concentrated in the region itself and involved subsistence and local markets. Following the decline in rubber prices in the 1920s, Brazil nut stands increased in value (Almeyda Zambrano et al., 2010). With the construction of the first roads in the 1960s and the further opening up of the region with the construction of the IOH in 2011, Madre de Dios was increasingly integrated in the world economy through exports of raw materials (gold, timber) and imports of manufactured goods. With this came an increased dependence on international commodity price fluctuations for gold, timber, and various agricultural products such as papaya. A number of key sectors described in greater detail in the following sections dominate in Madre de Dios, sustaining the local economy and livelihoods while also fueling the direct drivers of environmental change described in the previous chapter.

Sustainable economic opportunities in Madre de Dios include ecotourism, Brazil nut harvesting, fish farming, agroforestry, and certified forest management (Fisher et al., 2018; Rodriguez-Ward et al., 2018; Vanthomme, Sánchez-Cuervo, Gárate, Bravo, & Dallmeier, 2019). For example, Brazil nut production in Madre de Dios generates about two million Nuevos Soles (around USD 540,000 based on the 2021 exchange rate) per year (Gobierno Regional de Madre de Dios, 2014) and more than 40,000 tourists visit protected areas in the region each year (Gobierno Regional de Madre de Dios, 2020). However, despite the area's increased accessibility due to the IOH, forest livelihoods in the region still rely mainly on regional market niches and the economy tends to be informal (Oliveira et al., 2019).

Gold mining

Artisanal and small-scale gold mining in the department of Madre de Dios accounts for 8% of the total annual gold production in Peru of approximately 151 metric tonnes (Velásquez Ramírez et al., 2020) and for one third to one half of the local economy (INEI, 2021). Mining in Madre de Dios distinguishes between small-scale mining, involving 10 or more individuals who mine on an area of 1,000–2,000 ha, and artisanal mining, involving individuals or small groups of 2–5 people who mine on small tracts of land up to 1,000 ha (Fisher et al., 2018). There are also differences in the legality of the operations: miners may have legal titles on the land they work; informal mining occurs in areas zoned for mining where, however, the mining operation in question has not been approved; illegal mining operations are those that do not have permission to operate and do so on land where mining is not permitted and/or using prohibited processes (Piñeiro, Thomas, & Elverdin, 2016). Since the early 2000s, the Peruvian government has tried to implement a formalization plan to regulate informal miners and eradicate illegal mining in Madre de Dios (Cortés-McPherson, 2019; Damonte, 2018; Nicolau et al., 2019). Since 2006, a number of mining issues have been transferred from the central government to regional governments based on political decentralization processes. In this function, the regional government of Madre de Dios approved a "Formalization and Restructuring Plan" for the mining sector in Madre de Dios in 2011, which includes six required normative steps (Duff & Downs, 2019; Salo et al., 2016). The mining concessions allow the holders the right to explore and exploit mineral resources within the area covered by the concession, according to the General Mining Law (Supreme Decree No. 014-92-EM) (Nicolau et al., 2019). However, few miners manage to fulfill the requirements necessary for obtaining a mining permit

(Cortés-McPherson, 2019; Duff & Downs, 2019). Peru's national government continues to promote formalization and, since 2011, several military interventions have been launched to destroy illegal mining equipment, arrest illegal miners, and eradicate illegal sites. However, little progress has been made for over a decade, exacerbating social tensions and conflicts (Cortés-McPherson, 2019; Damonte, 2018; Diringer et al., 2019; Duff & Downs, 2019; Espin & Perz, 2020; Nicolau et al., 2019). Overall, gold mining remains a central driver of land use change and pollution (see above).

Agriculture

Agriculture in Madre de Dios is dominated by a traditional migratory system adapted to regional conditions. Prevailing activities include use of non-improved seeds, slash-and-burn practices, manual harvesting, and limited or inadequate application of external inputs. This system depends largely on climatic conditions, which, combined with poor and acidic soils, results in low yields used mainly for subsistence by local communities or sold in local markets when small surpluses allow. In addition, this type of agriculture is frequently located along riverbanks that are very susceptible to floods (Gobierno Regional de Madre de Dios, 2018). The main agricultural crops produced in Madre de Dios are maize, rice, banana, and yucca (Oficina de Gestión de la Información y Estadística, 2019). Overall, agricultural land in Madre de Dios is mainly located along the IOH (Figure 22). Cultivation of papaya (*Carica papaya*) is increasing in the region, as Madre de Dios is one of the few places left in Peru that is free of key diseases that impact this tree crop. The arrival of the IOH helped stimulate a papaya boom, primarily on underused pastures along the IOH. This has modified the use of labor on small farms, since papaya is established in large plantations and owners require substantial labor to maintain the trees and harvest the crop (Perz et al., 2016).

From 1985 to 1990, policies established under the first presidency of Alan Garcia encouraged agricultural expansion and favored the establishment of annual crops and pasture with available credit and incentives through the Agrarian Bank. From 1990 to 2000, policies under the presidency of Alberto Fujimori removed agricultural support. Economic liberalization reforms and new markets to increase crop yields were established, including improved seeds and agroforestry. From 2001 to 2006 and from 2006 to 2011, under the presidencies of Alejandro Toledo and Alan Garcia, respectively, official policies favored farm diversification including support for cattle insemination, "copoazú" (*Theobroma grandiflorum*, related to cacao) cultivation, agricultural mechanization, and fish farming (Alvarez & Naughton-Treves, 2003; Chávez, Broadbent, & Almeyda Zambrano, 2014; Chavez & Perz, 2012; Sánchez-Cuervo et al., 2020).

In contrast to other regions in the Amazon, medium property sizes (20–50 ha) predominate. The average land size cultivated per farmer is 4.5 ha (Gobierno Regional de Madre de Dios, 2018). Migrants tend to own smaller plots measuring less than one hectare, while nearly one third of non-migrants own more than 20 hectares (Jensen et al., 2018). Migrants' lands are mainly located in a zone of 30 km on either side of the IOH, where about two thirds of smallholdings can be found, closer to the main regional market in Puerto Maldonado (Oliveira et al., 2019). Though providing local communities with their subsistence and the agribusiness sector with commodities, local agricultural expansion, although still modest and concentrated in the east of the department, is a primary driver of land use change (mainly deforestation); meanwhile, its impacts on pollution have not yet been clearly documented.

Forestry

In 2000, the Peruvian government passed a new Forestry and Wildlife law (Ley Forestal y de Fauna Silvestre, Ley N° 27308) that designated about eight million hectares of permanent production forest. Within these areas, the government can grant concessions of 5,000–50,000 ha for periods of up to 40 years. The concession holders are required to develop a five-year management plan and an annual operating plan in which they agree to specific restrictions including limits on timber extraction of 5% of the available basal area and limits on subsistence hunting (commercial hunting is strictly prohibited) (Tobler et al., 2018). In Madre de Dios, forest concessions represent around 15% of the total area (Figure 22) (Rodriguez-Ward et al., 2018). The reforestation concessions were established with the objective of promoting afforestation and reforestation for production purposes, protection, and environmental services, in particular on lands with greater forest use capacity and without vegetation cover or with only scarce tree cover (Nicolau et al., 2019). Brazil nut concessions operate under a different tenure regime than forest concessions (Perz et al., 2016). They cover about one million hectares in Madre de Dios and are granted under two different arrangements, namely, for those inside or outside of protected areas (Willem, Ingram, & Guariguata, 2019). Timber is also extracted in Brazil nut concessions subject to complementary management plans. Other concessions for NTFPs include rubber tree, "aguaje", and medicinal plants (Gobierno Regional de Madre de Dios, 2018). Forest governance in Peru is characterized by multiple public authorities at the national scale, inadequate decentralization, and limited participation of community stakeholders in decision-making processes. Moreover, community forestry management is not sufficiently promoted by public authorities (Dupuits & Cronkleton, 2020).

Formal credit remains rare in Madre de Dios, forcing many landowners to rely on informal credit, notably the "habilito" arrangement used for "castaña" (Brazil nut) harvest. Under "habilito", Brazil nut buyers will advance cash to families with concessions on the condition that they, in turn, will sell their harvest to the buyers for a set price (Perz et al., 2016).

Tourism

Ecotourism is an important economic activity in Madre de Dios, based mainly on the rich biodiversity of the region and its proximity to Machu Picchu, the main tourist attraction in Peru. Tourism is mainly concentrated in Tambopata and Manu provinces, where the majority of local tourist infrastructure has been developed (Gobierno Regional de Madre de Dios, 2018) and growing since the mid-1990s (Kirkby et al., 2010). The economic returns of this profitable sector and demand among tourists for an immersive experience – in combination with appropriate incentives and institutions – are strong drivers of local acquisition of large areas of rainforest for conservation (Kirkby et al., 2011).

Infrastructure

Historically, socioeconomic development phases of Madre de Dios have been closely linked to the development of local road infrastructure. A first wave of development followed the construction of the unpaved road to Puerto Maldonado in the 1960s. In 2005, construction started on the IOH joining the Pacific ports of Peru with the Atlantic ports of southern Brazil, traversing Madre de Dios and going through Puerto Maldonado. Finalization of paving of the IOH in 2011 and a suspension bridge spanning the Madre de Dios River in 2012 together marked the completion of the IOH (Caballero Espejo et al., 2018; Perz et al., 2016). The IOH is part of the Initiative for the Integration of the Regional Infrastructure of South America (IIRSA), which aims to increase cross-border infrastructure and economic development on the continent (Almeyda Zambrano et al., 2010; Jensen et al., 2018). However, in Madre de Dios, only 1.5% of the cost of the highway was dedicated to promote development in the region (Dourojeanni, Barandiarán, & Dourojeanni, 2009). The highway has been a driver of change, including rapid population growth, increased movement of people and goods, changes to economic opportunities, urban expansion, as well as land invasions by illegal gold miners, farmers, and loggers (Caballero Espejo et al., 2018; Perz et al., 2016; Riley-Powell et al., 2018; Rodriguez-Ward et al., 2018). With the IOH, migration has increased rapidly, leading to changes to cultural and societal norms within communities. At the same time, changes in land use have been associated with increased incidence of malaria, metal poisoning, and possible increases in rodent-borne diseases. However, the highway has also been associated with improved health thanks to improved accessibility of the health system (Riley-Powell et al., 2018). As in other regions of the Amazon, the opening of paved roads correlates directly with deforestation (Barber, Cochrane, Souza, & Laurance, 2014). A comparative study across the tri-border area between Madre de Dios, Acre (Brazil), and Pando (Bolivia) revealed that the level of deforestation decreased as the distance to the IOH increased; the span of the effect was larger in the more developed state of Acre and shorter in the less developed department of Pando (Southworth et al., 2011).

In the light of such experience with the IOH, the ongoing construction of a road in the buffer zones of the Amarakaeri Communal Reserve and Manu National Park is cause for major concern. Road expansion is likely to result in uncontrolled colonization, deforestation, and the illicit extraction of timber and other natural resources, as well as an increase in social conflict between resource extractors and indigenous communities (Gallice, Larrea-Gallegos, & Vázquez-Rowe, 2019).

5.3 Governance

In 2002, through a constitutional reform, Peru initiated a decentralization process that established three levels of government: national, regional (Departments), and local (Provinces, Districts, and Municipalities) (McNulty & Guerra Garcia, 2019; Telis, 2016). Through this process, the central government transferred responsibilities to regional governments in certain spheres, such as the granting of land titles and forest concessions. Regional governments are in charge of the development of participatory land use plans for their jurisdictions (such as the Ecological and Economic Zoning Plan) under the auspices of the central government's Ministry of Environment. The regional governments also grant artisanal and small-scale mining concessions, whereas large-scale mining, gas and road infrastructure concessions are granted by the central government (Rodriguez-Ward et al., 2018). Decentralization has brought certain benefits like the emergence of new regional actors and increased participation in subnational decisions. However, it also poses challenges such as overlapping responsibilities between bodies, levels, and sectors of the government, as well as poor coordination and inefficient distribution of resources (McNulty & Guerra Garcia, 2019; Telis, 2016).

In 2005, the Peruvian government passed the Environment Act, defining the guidelines for environmental management, sustainable use of natural resources, and land planning and zoning in Peru (Damonte, 2016). This was followed by the creation of the Ministry of the Environment (MINAM), the Peruvian National Protected Areas Service (SERNANP), and the Agency for Environmental Assessment and Enforcement (OEFA) in 2008. The Regional and Municipal Environmental Commissions serve as a forum for dialogue and coordination among state entities and civil society for addressing environmental issues of regional or municipal concern (ECLAC and OECD, 2016). Other relevant bodies for environmental management and governance include the Specialized Prosecutor for Environmental Matters in Madre de Dios, created in 2010, which has competences to prevent and investigate environmental-related crimes (MINAM, 2010) and the Protected Area Management Committees (Comités de Gestión), which are important platforms to involve local population, public institutions, and the private sector in the management of protected areas (MINAM, 2021).

Native communities

Although the Peruvian Government recognized indigenous communities in the Constitution of 1920, formal titling of native communities only began in 1974. Article 89 of the Political Constitution of Peru (1993) states that Peasant and Native Communities have legal existence and are legal persons (Peña Jumpa, 2013). The Law of Native Communities and Agrarian Development in the Lower and Upper Rainforest (Decree Law 22175 of 1978) sets out the procedures for granting communities legal titles. Areas classified as suitable for agriculture and livestock can be given an agrarian title, while areas classified as forest require native communities to obtain a usufruct contract. However, legal security of native communities' land is still not guaranteed, mainly due to lack of a national registry (Blackman, Corral, Lima, & Asner, 2017; Monterroso & Larson, 2018; Zamora & Monterroso, 2019). Of the native communities present in Madre de Dios, two are pending recognition and six are pending titling (Zamora & Monterroso, 2019). In order to make their voices heard in political processes that affect their rights and livelihoods, many indigenous communities have self-organized in representative organizations. In Madre de Dios, the percentage of indigenous communities that are represented in such a way (86%) is higher than at the national level (73%) (INEI, 2018b). Territorial reserves were created by the Peruvian State to protect communities in situation of isolation and initial contact, and to guarantee their life, health, and continuation of traditional lifestyles. The Territorial Reserve of Madre de Dios, created in 2002, has an area of 829,941 ha spread between the districts of Laberinto, Tambopata, Las Piedras, Madre de Dios, Fitzcarrald, and Iñapari. The ethnic group Mashco Piro (in isolation) and another non-identified group inhabit the reserve (Ministerio de Cultura, n.d.).

Spatial planning and land use rights

Immigration and the occupation and use of land in Madre de Dios have long lacked adequate planning, resulting in disorganized, chaotic land use (Guevara et al., 2020). The Regional Government of Madre de Dios (GOREMAD) started a process of land use planning in 1988 to improve the political organization of Manu province (IIAP, 2004). This process was later extended to the entire territory in collaboration with the Research Institute of the Peruvian Amazon (IIAP). In 2001, an ecological and economic zoning (ZEE) study was developed as a tool for improved, evidence-based spatial planning in the department, as well as to address the uncontrolled development and use of natural resources (IIAP, 2001). The territory was divided into 34 ecological economic zones grouped into four main land use types: productive zones, ecological protection zones, special treatment zones (including those for mining operations), and urban and industrial zones (IIAP, 2002). The ecological and economic zoning study for the Department of Madre de Dios was approved in 2009 (GOREMAD, 2009).

In spite of such efforts, Madre de Dios is known for having problems of overlapping land use concessions and conflicts over land use rights (Figure 24) (Oliveira et al., 2019; Perz et al., 2016; Rodriguez-Ward et al., 2018). The problems were created in part when corresponding competences were handed over from the central government to the regional government under decentralization. In addition, the single regional cadaster of Madre de Dios has not been implemented yet (GOREMAD, 2017). In 2013, there were over one million hectares (about 20% of the region) subject to some kind of overlap. Such overlapping also occurs because different national institutions with weak inter-sectorial coordination grant incompatible land use rights in the same area (Rodriguez-Ward et al., 2018).

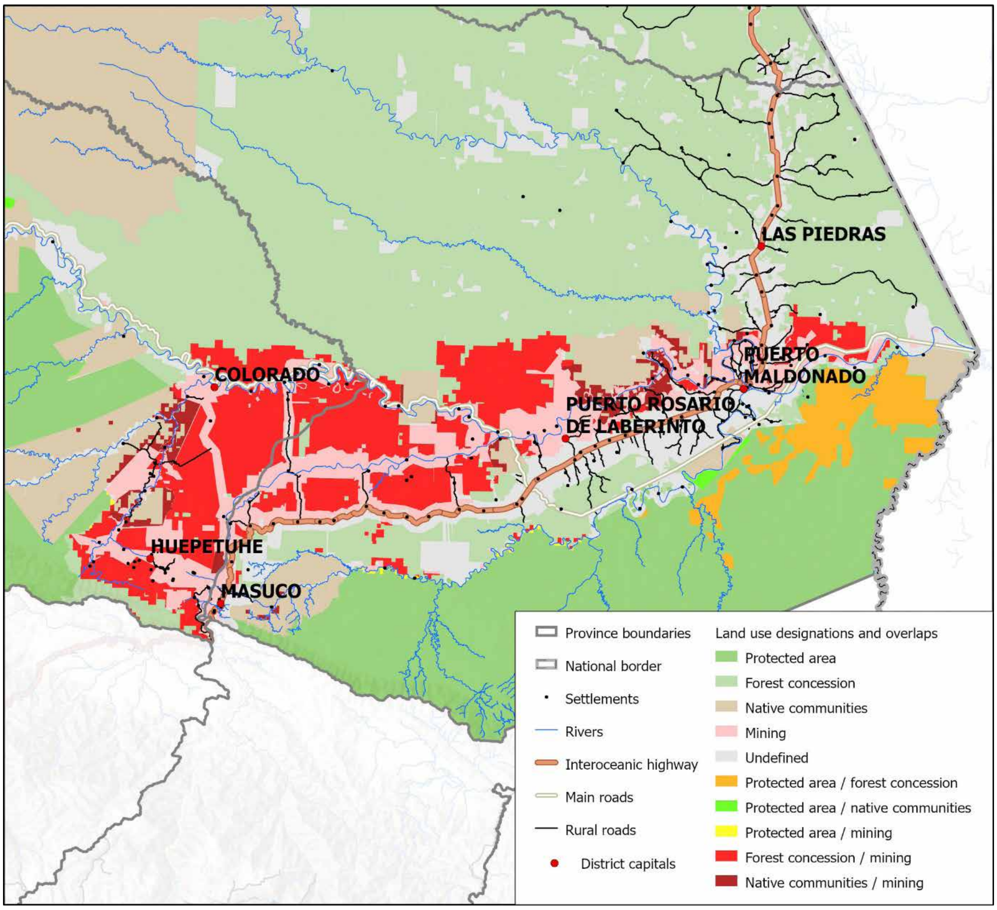


Figure 24. Land use designations and overlaps in Madre de Dios. Source: based on data from Esri, CGIAR, and USGS.

Nature conservation

Madre de Dios Regional Strategy for Biodiversity to 2021

The Madre de Dios Regional Strategy for Biodiversity to 2021 was approved by Regional Decree N 13 – 2014-RMDD/CR on 9 October 2014. The strategy aims to manage biodiversity better through sustainable use for the benefit of all inhabitants. The Regional Strategy is embedded in the commitments under the Convention on Biological Diversity that Peru ratified in 1993 and is aligned with the National Strategy to 2021 (Gobierno Regional de Madre de Dios, 2014).

The Regional Strategy identifies four conservation objectives:

- Maintain the extent and quality of terrestrial ecosystems at levels of 2013.
- Maintain the quality of aquatic ecosystems in the Madre de Dios region.
- Maintain the populations of species of flora and fauna used by humans at levels of 2013.
- Maintain the populations of endemic, threatened and key species and landscapes in the Madre de Dios region.

The Action Plan 2014–2021 of the Regional Strategy lists a number of actions under different action lines and strategic objectives, including responsible institutions, goals, and monitoring activities. Some of the activities listed are: creation and implementation of a research program for biological monitoring in wetlands; creation and implementation of a program to validate pilot projects (demonstration plots) for the restoration of areas degraded by alluvial gold mining; promote the designation of Lake Valencia and Lake Huitoto as Ramsar sites; promote the exchange of biodiversity information; generate a regional biodiversity monitoring system; provide technical assistance to local governments for the development of micro-spatial ecological and economic planning with a landscape and ecosystem approach; develop mechanisms for payment for ecosystem services that contribute to the conservation and sustainable use of biodiversity; develop and implement sustainable and competitive value chains based on the biological diversity of Madre de Dios; implement an inventory of traditional knowledge of biodiversity; awareness-raising, communication, and education on biodiversity issues at different levels (Gobierno Regional de Madre de Dios, 2014).

Protected areas

There are six natural protected areas in Madre de Dios: three National Parks (Alto Purus, Bahuaja Sonene, and Manu); one National Reserve (Tambopata), and two Communal Reserves (Amarakaeri and Purus) (Román-Dañobeytia et al., 2015) (Table 4). Taken together, the Manu National Park, the Amarakaeri Communal Reserve, the Tambopata National Reserve, and the Bahuaja Sonene National Park form the central portion of the Vilcabamba-Amboro Conservation Corridor, which was established in the late 1990s to preserve biodiversity, ecosystems, and lands of various ethnic groups across the Tropical Andes and the western Amazon (Sánchez-Cuervo et al., 2020).

Table 4. Natural protected areas in Madre de Dios. Source: Gobierno Regional de Madre de Dios (2014); MINAM (2020).

Protected Area	Total surface (ha)	Location	Surface in Madre de Dios (ha)
Alto Purus National Park	2,510,694	Madre de Dios and Ucayali	1,250,007
Bahuaja Sonene National Park	1,091,416	Madre de Dios and Puno	315,563
Manu National Park	1,716,295	Madre de Dios and Cuzco	1,542,693
Tambopata National Reserve	274,690	Madre de Dios	274,690
Amarakaeri Communal Reserve	402,335	Madre de Dios	402,335
Purus Communal reserve	202,033	Madre de Dios and Ucayali	n/a

Protected areas (not including buffer zones and other non-core designations) in Madre de Dios are generally effective in preventing deforestation (Caballero Espejo et al., 2018; Nicolau et al., 2019). Although mining-related deforestation within the Tambopata National Reserve rose to nearly 400 ha yr^{-1} in 2016 and 2017, this still represents a small fraction (~4%) of total deforestation from mining and does not represent a significant portion of the core protected area (Caballero Espejo et al., 2018). According to one study, the protected areas with the highest effectiveness in Madre de Dios are those for ecotourism and conservation concessions; here, monitoring and surveillance activities and good relations with surrounding communities were reported as possible factors behind decreasing deforestation rates. Native community areas had the lowest scores, with deforestation mainly driven by internal resource use and population growth. Weak local governance and immigration were identified as underlying factors decreasing the effectiveness of protection (Vuohelainen, Coad, Marthews, Malhi, & Killeen, 2012).

Buffer zones

Buffer zones were created in Peru in 1997 with the passage of a new National Protected Areas Law (Law No. 26834, Article 25). By law, "the activities realized in the Buffer Zones should not put the objectives of the Natural Protected Area at risk." The legislation was intended to reduce harmful impacts from the rapid expansion of mining, oil, and natural gas extraction around Peru's protected areas (Weisse & Naughton-Treves, 2016). Buffer zones are managed in part by Peru's National Service of Natural Protected Areas (SERNANP). SERNANP is obliged to issue a binding opinion before the granting of rights for the use of natural resources and/or the modification of infrastructure (Supreme Decree No. 038-2001-AG, Article 116) within the buffer zone. However, the legislation does not specify which agencies are responsible for monitoring and enforcement in buffer zones (Weisse & Naughton-Treves, 2016).

Even though the granting of mining concessions in Madre de Dios is slower in buffer zones than in other areas, the buffer zones have not effectively limited the spread of illegal mining (Weisse & Naughton-Treves, 2016). Since 2010, deforestation has occurred at an average rate of 3,157 ha yr^{-1} in the buffer zones of the Tambopata National Reserve, Bahuaja Sonene National Park, and Amarakaeri Communal Reserve, with a total of 31,148 ha deforested. In addition, a total of 72,446 ha of mining concessions exist within these buffer zones (Caballero Espejo et al., 2018).

Box 1. The Tambopata National Reserve.

The Tambopata National Reserve was created in the year 2000 in order to protect an intact forest landscape encompassing 274,690 ha. In 2001, a buffer zone of 186,450 ha was established to protect the reserve from the threats of illegal gold mining, illegal logging, agricultural expansion, and road construction (Fisher et al., 2018). The buffer zone is intended to provide forest access to communities existing before the creation of the reserve, with the stated intention of preserving livelihoods while ensuring sustainable forest use and conservation measures (Asner & Tupayachi, 2017). The buffer zone reaches the Interoceanic Highway (IOH) and the region's capital of Puerto Maldonado to the north (Weisse

& Naughton-Treves, 2016). According to the Law of National Protected Areas of Peru (Law 26834), the Tambopata National Reserve falls into the category of “areas of direct use”, where the extraction of natural resources is permitted, primarily by the local population, and under a management plan (Nicolau et al., 2019).

The Tambopata National Reserve contains more than 3,000 registered plant and animal species, record diversity of butterflies and birds, as well as intact populations of several threatened species such as white-lipped peccaries, giant otters, and jaguars (Weisse & Naughton-Treves, 2016). Forests of the Tambopata National Reserve contain some of the highest biomass stocks in the western Amazon, and the watershed is a key freshwater resource for communities downstream of the reserve, including in Brazil (Asner & Tupayachi, 2017).

Gold mining in the reserve, and in its ecological buffer zone to the north, directly impact the reserve’s resources (Asner & Tupayachi, 2017). The buffer zone is also threatened by illegal logging (Fisher et al., 2018) and advocacy groups have suggested that forest losses are underway due to these activities. In 2006, a new major site of illegal mining, known as “La Pampa,” emerged running straight through the Tambopata buffer zone (Weisse & Naughton-Treves, 2016). A total of 521 ha of forest were lost to gold mining in the reserve by October 2016. The buffer zone eventually experienced even greater losses, equal to 30,047 ha in total. Since 1999, mining-related deforestation in the buffer zone has accounted for 44% of total mining throughout Madre de Dios (Asner & Tupayachi, 2017). Unclear division of responsibilities, poor inter-agency coordination, and lack of resources for monitoring and enforcement are cited as major constraints on the management of illegal activities in the buffer zone (Weisse & Naughton-Treves, 2016).

Climate action

A big step for Peru’s climate action has been the passing of its first institutional framework law on climate change in 2018. The new law aims to provide climate adaptation and mitigation solutions via binding legal instruments, which call for participatory, transparent, and integrated climate governance. A major highlight of the new law is the requirement for climate risk analysis and vulnerability assessment for new investment projects following the national environmental impact assessment process. Further, the law distinguishes the role and voice of indigenous communities and civil society within the climate change high-level commission working on adaptation and mitigation measures. However, the region of Madre de Dios has not yet integrated climate change issues into public policies that deal with poverty reduction, gender issues, and other regional developmental programs (Chavez Michaelsen et al., 2020).

In 2011, Peru joined the UN-REDD program and became a member of the REDD+ Partnership. Madre de Dios was one of two pilot sites selected by the Ministry of Environment (MINAM) for the implementation of REDD+ (Dupuits & Cronkleton, 2020). REDD+ initiatives were initiated through the combined efforts and partnerships of actors from multiple levels and sectors with varying levels of participation and decision-making power (Rodriguez-Ward et al., 2018). However, overlapping land use rights complicate efforts to allocate carbon rights and responsibilities for forest conservation (Dupuits & Cronkleton, 2020). The Indigenous Amazonian REDD (RIA) was created in 2011 by indigenous federations to secure property rights and with the objective of reducing forest emissions through the Integrated Territoriality of Indigenous Peoples and their Collective Life Plans, instead of through a market-based instrument (Gobierno Regional de Madre de Dios, 2018). In addition, the National Forest Conservation Program (PNCB), created in 2010, offers conditional payments to indigenous communities to promote forest management. These initiatives are promoting interactions among government agencies and indigenous peoples that could improve governance institutions and tenure security for the implementation of REDD+ (Dupuits & Cronkleton, 2020). Existing examples include the use of territorial indicators like the living hectare “hectárea viva”, which measure, in addition to carbon sequestration, governance issues (e.g. the number of indigenous communities titled) and ecosystem services (e.g. water preservation and biodiversity conservation) (Dupuits & Cronkleton, 2020).

6 Current and future interactions between nature and people

A recent study (Vanthomme et al., 2019) outlined four future scenarios for the Madre de Dios region: a) current trends, b) expansion of gold mining, c) land use planning, and d) landscape conservation. The study modelled changes in land cover until 2040 and evaluated future landscapes according to 15 indicators that address economic prosperity, human well-being, and environmental integrity.

a) In the *current trends* scenario, ongoing political, economic, and social trends are maintained. Informal and illegal extractive activities drive the economy with limited active regional management. Gold mining and agriculture support economic growth in Madre de Dios at the expense of increased deforestation, degradation of ecosystem services, mercury contamination, public health issues, and social conflicts.
b) In the *expansion of gold mining* scenario, informal and illegal gold mining expands due to poor land use management, insufficient law enforcement, increasing migration, and high international prices of gold. Economic productivity is high in the mining and agriculture sectors, resulting in reduced logging and Brazil nut harvesting, but alarming environmental degradation and reduced human well-being.
c) In the *land use planning* scenario, a sustainable development-oriented land use management plan is implemented from 2020 onwards. All economic activities are formalized and implemented according to the plan, successfully slowing down the expansion of mining. This results in good economic development of other sectors and improvements in ecosystem services and human well-being.
d) In the *landscape conservation* scenario, a new land use management plan focused on biodiversity and landscape conservation is implemented from 2020 onwards. Protected areas are considered sanctuaries, deforestation is very limited, and degraded areas are restored. These actions result in limited economic growth in the mining and agriculture sectors, good human well-being, and optimal environmental achievements.

It is worth noting that none of the four scenarios described offers the best performance for all indicators and all represent different compromises among economic development, human well-being, and environmental conservation (Vanthomme et al., 2019).

Another recent study suggests that if deforestation continues to increase at its current exponential rate through 2030, the annual mobilization of soil and mercury may increase by an additional 20–25% relative to 2014 levels (Diringer et al., 2019).

7 Challenges, assets, and opportunities for nature and people

The information contained in the following chapter draws from several sources: a synthesis workshop with regional experts and key partners from the Wyss Academy South America Regional Hub held in June 2021 (Appendix 3)[2]; a stakeholder mapping, a stakeholder survey, and a multi-stakeholder workshop held during the Wyss Academy pilot phase (2018–2019) (Appendix 2); and information from the literature review.

7.1 Challenges and existing dilemmas

Figure 25 lists the main development challenges in Madre de Dios according to the results of the stakeholder survey. According to responses, the most pressing issues in the region are gold mining, logging, and other extractive activities, usually done illegally and often leading to social conflicts. A second major area of concern comprises socioeconomic issues, including social instability (crime, violence, chaos, human trafficking), often directly linked to mining activities, migration, and poverty (Mathez-Stiefel et al., 2020). The COVID-19 pandemic is having a strong impact on the local economy and employment dynamics as well as on local and international trade, with direct consequences for local livelihoods. This has accentuated social challenges and environmental pressures, as people are relying on the exploitation of natural resources, often illegally, as a source of income during the COVID-19 crisis. Improved income generation for small-scale producers in Madre de Dios is still hindered by issues such as a lack of access to education, economic incentives, production factors, and markets. Improved government extension programs including assistance and credit as well as education, legal and technical advice, capacity building, and professional training activities are necessary (Oliveira et al., 2019).

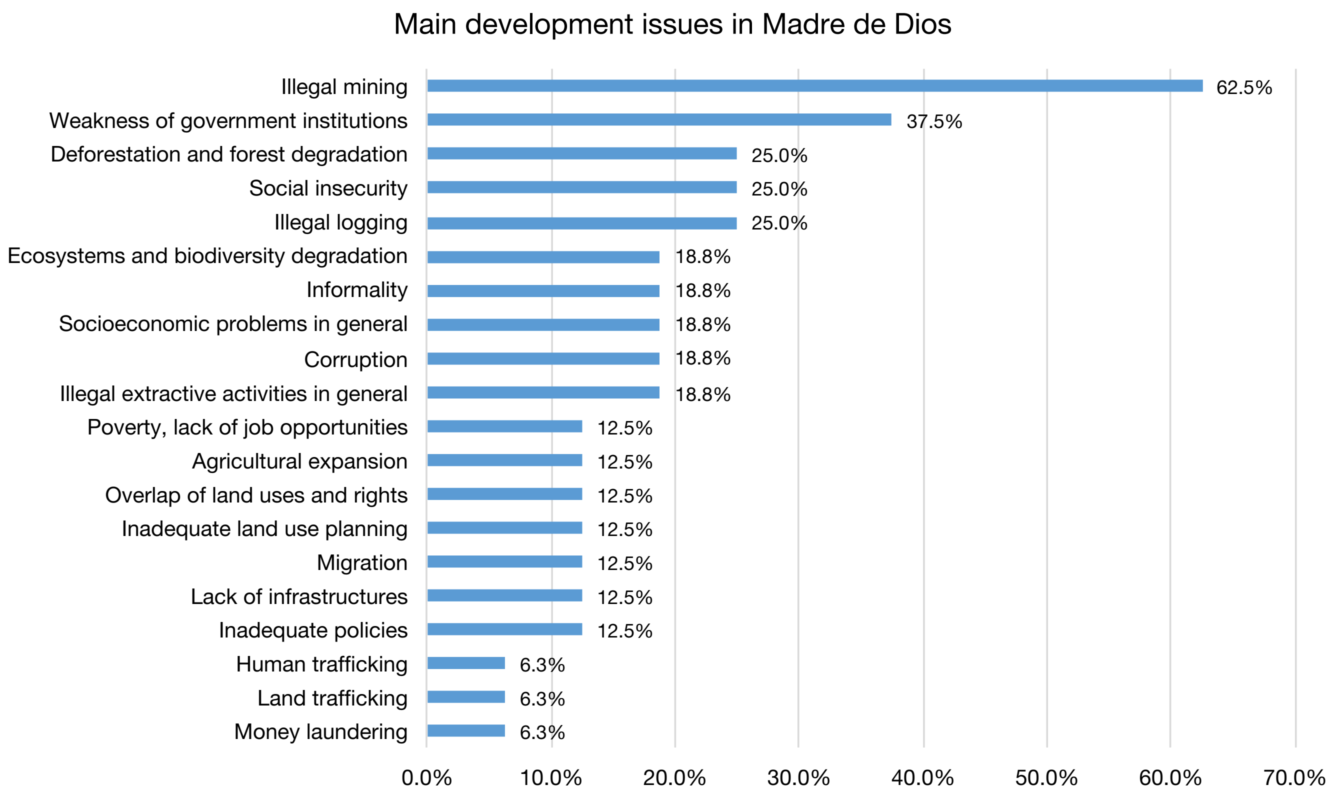
Although governance in Peru and, in particular, in Madre de Dios seems to have improved in recent years with the current regional government (e.g. command and control mechanisms, processes of formalization, etc.), pressing concerns still include the perceived weakness of government institutions, their lack of leadership and political will, as well as corruption, nepotism, and the presence of mafias (again typically related to illegal mining and logging activities). Government budget expenditures do

2 Text without citations throughout this chapter.

not appear to be well aligned with local demands, needs, and priorities. The drivers of deforestation and ecosystem degradation, as well as land tenure problems, cannot be exclusively solved at the local level, and the design of sustainable development pathways requires support from a state authority (Rodriguez-Ward et al., 2018) with coherent and integrative policy frameworks. Overlapping and unclear division of responsibilities between regional governments and the central government as well as lack of collaboration among agencies at different levels have created governance issues that result in duplication of titles and concessions, poor levels of enforcement, budget limitations, and capacity challenges (Espin & Perz, 2020; Rodriguez-Ward et al., 2018; Willem et al., 2019). The general presidential elections in Peru in 2021 and upcoming changes that will be associated with the new administration represent areas of uncertainty; either way, they will shape economic dynamics and the post-pandemic recovery model, with important consequences for sustainable development. This could affect recent efforts in Madre de Dios to steer the region's development in a sustainable way that meets people's needs while combatting unsustainable and illegal activities.

Other key challenges include inadequate land planning and management, overlapping land uses, and lack of land rights (e.g. of agricultural land or native community territories). In this regard, land trafficking, land invasions, and overlapping land titles are considered sources of social conflict in the region (Mathez-Stiefel et al., 2020). Indigenous territories are particularly vulnerable to the expansion of illegal activities, especially mining. The problem of legitimacy and indigenous land tenure limits the exercise of indigenous peoples' rights on the ground (Dupuits &

Figure 25. Main development issues in Madre de Dios, Peru, according to local stakeholders. Percentage of survey participants that mentioned the problem as being one of the most pressing (N=16). Source: translated from Mathez-Stiefel et al. (2020)



Cronkleton, 2020). Developing fine-resolution land use planning for Madre de Dios, adopting a Concerted Development Plan and establishing a single cadaster to identify and resolve land use rights are needed. This will require further control and enforcement to ensure the development of legal activities in the region (Vanthomme et al., 2019).

Deforestation, forest degradation, and the expansion of agricultural crops (Mathez-Stiefel et al., 2020) like rice and papaya (as in the neighboring Ucayali) are also areas of concern.

Due to the high returns associated with gold mining, as well as related economic activities, it is likely that mining operations will continue in the future. Efforts should therefore focus on formalizing mining activities, concentrating them in designated areas, minimizing their impacts, and restoring degraded areas. Government interventions to eradicate the main areas of illegal mining have led to the appearance of small mining spots that are more difficult to control. In areas designated for mining, requirements to comply with regulations are challenging to fulfil for concessionaries. According to estimates, only 2,000 of the 9,000 artisanal and small-scale miners identified in Madre de Dios actually comply with existing regulations. At the same time, the conflicts, risks, and insecurity associated with mining activities might incentivize the adoption of more sustainable livelihood alternatives. In terms of public health, multidisciplinary research and engagement with the Ministries of Health and Environment are required to better understand the sources of mercury pollution and its environmental and human health impacts. The development of sustainable policies and programs involving local communities and other stakeholders is needed to promote the necessary behavioral changes to reduce mercury exposure (Feingold et al., 2020), including support for legal mining operations that integrate mercury capture systems, environmental remediation and health monitoring (Diringer et al., 2015).

Ecotourism has been highlighted as a sustainable economic opportunity in Madre de Dios (Csillik & Asner, 2020; Doan, 2013; Kirkby et al., 2010; Salvador, Clavero, & Leite Pitman, 2011). However, ecotourism can result in more interactions between humans and wildlife, which may generate disturbances (Karp & Guevara, 2011). Minimizing the impacts of ecotourism on wildlife is necessary to ensure the long-term sustainability of this activity and tourist satisfaction with wildlife sightings (Lee et al., 2017). Tourism companies, communities, researchers, and governments need to work together to create and implement guidelines for fauna observation throughout the region, including noise reduction and specific guidelines for clay-lick observation (Karp & Guevara, 2011; Lee et al., 2017).

The buffer zones of protected areas in Madre de Dios are effectively limiting legal activities within their boundaries. However, limiting illegal activities appears more difficult (Caballero Espejo et al., 2018; Nicolau et al., 2019; Weisse & Naughton-Treves, 2016). This may be due, in part, to a lack of clear mandates among different government institutions regarding the management of buffer zones. Peru's National Service of Natural Protected Areas (SERNANP) must issue a binding opinion before the granting of rights for the use of natural resources in protected areas and buffer zones. However, SERNANP does not have responsibility for enforcement in the buffer zone and current legislation does not specify which agencies are responsible for monitoring and enforcement in these areas (Weisse & Naughton-Treves, 2016).

Although the homelands of indigenous communities often represent significant assets in terms of biodiversity conservation, the establishment of protected areas in regions inhabited by these communities can also lead to conflicts, in particular as these communities gradually westernize, and cease their low-impact traditional lifestyles. For example, the perceived threat to biodiversity posed by the changed lifestyles of the Machiguenga indigenous peoples inside Manu National Park's core zone led some to suggest resettling them outside the park, even though such an action had no political, legal, or practical basis. Instead of such an eviction approach, stewardship-oriented models such as "tenure for defense" where the communities receive benefits in exchange for protecting the park could be considered (Shepard, Rummenhoeller, Ohl-Schacherer, & Yu, 2010).

7.2 Stakeholder analysis

Stakeholders relevant to initiatives for nature and people

The effort to map stakeholders in Madre de Dios conducted in the Wyss Academy pilot phase identified 16 main actor categories relevant to local initiatives for nature and people. These include direct land resource users, indirect land resource users, the public sector, civil society, and research institutions (Table 5). However, the landscape of stakeholders is very complex and fragmented, and attention should be paid to many subtle details and differences. In particular, there are several extremely vulnerable stakeholder groups, such as poorly educated migrant communities, which require attention in order to understand current sustainability challenges and integrate them in the design of sustainable pathways.

The direct land resource users encompass indigenous peoples, organized in 37 recognized native communities belonging to seven different indigenous peoples, as well as two tribes of "indigenous peoples in isolation or initial contact" (referred to as PIACI, the official acronym). Native communities rely on hunting, gathering, subsistence agriculture, and, occasionally, non-traditional practices such as ecotourism and gold mining. Other direct land users include small-scale farmers (cultivating 5–10 ha) and medium-scale farmers (cultivating 10–50 ha). Both types of farmers maintain monocultures (papaya, maize, banana, yucca, etc.) and/or agroforestry systems (cacao, "copoazú", Brazil nut, fruit trees, etc.). Logging is another important activity in Madre de Dios, involving stakeholders such as logging concessionaires, illegal loggers, and traders of other forest products – the latter often controlled by powerful mafias. Brazil nut concessionaires are also a notable stakeholder category, given the potential of Brazil nut as a high value NTFP. Finally, illegal and informal gold miners have recently emerged as key stakeholders, including migrants from the neighboring highland departments of Cusco and Puno (Mathez-Stiefel et al., 2020).

Table 5. Stakeholders relevant to initiatives for nature and people in Madre de Dios, Peru. Source: translated from Mathez-Stiefel et al. (2020).

Sector	Category	Stakeholder
Direct land resource users	Indigenous peoples	CCNN, FENAMAD, AFIMAD, COHARYIMA, COIMBAMAD, ECA-RCA.
	Small-scale farmers	Small-scale producers (5–10 ha) of monocultures (papaya, maize, banana, yucca, etc.) and agroforestry systems (cacao, copoazú, Brazil nut, fruit trees, etc.). FADEMAD, other farmer organizations.
	Medium-scale farmers	Medium-scale producers (10–50 ha) of monocultures (papaya, maize, banana, yucca, etc.) and agroforestry systems (cacao, copoazú, Brazil nut, fruit trees, etc.).
	Logging concessionaires and companies	Large transnational companies, large, medium, and small concessionaires. Forest concessionaires associations. Maderacre, Maderija SAC, Consorcio Bosovich, Maderera Espinoza, etc.
	Brazil nut concessionaires	Brazil nut associations. ASCART, RONAP, FREPROCAM, etc.
	Informal and illegal gold miners	Independent miners and miner associations. FEDEMIN
	Illegal loggers and traders of other forest products	Mafias that control the exploitation and trafficking of wood, wildlife, and other products.
Indirect land resource users	Natural resource processing companies	Sawmill companies, Brazil nut peelers, food industry companies. Manutata, Candela, La Nuez, ASCART, etc.
	Ecotourism companies and concessionaires	Large, medium, and small ecotourism companies and concessionaires. RFE, Inkaterra, Inotawa, Corto Maltes, TPL, Sotupa, Amazon Yoga Center, Kerenda Homet, Mariposario Tambopata, etc.
	Tourists	National tourists, international tourists, etc.
	Urban population	Migrants from other departments of Peru, descendants of Japanese origin, indigenous peoples, public servants, company workers from other departments, traders, small entrepreneurs, transporters, taxi drivers, etc.
Public sector	National government agencies	MINAM (SERNANP), MIDAGRI (SERFOR), MINEM, MINCU, MIMP OEFA
	Departmental and provincial government agencies	DRA, DREMEH, DFFS, DRTC, DIRCYT, COER
Civil society and research institutions	Conservation and development NGOs	ACCA, AIDER, WWF, CARITAS, CARE, WCS, Fauna Forever, Rainforest Foundation UK, etc.
	International cooperation	Private foundations, multilateral banks, governments, private donors. Wyss Foundation, Moore Foundation, NORAD, USAID, FONDAM, BID, etc.
	Research institutions	Universities (UNAMAD, UNSAAC), independent researchers, CINCIA, ACCA, CIFOR, ICRAF, IIAP, CITE Productivo, etc.

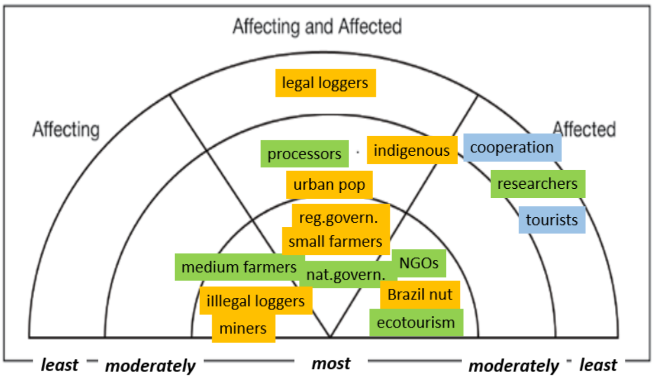
Indirect land resource users comprise processing companies such as sawmills, Brazil nut peelers, and food industry companies. They also include service providers such as local and international ecotourism companies and concessionaires who cater to the growing number of national and international tourists attracted by the region's biodiversity, forested landscapes, and cultural richness. Most of the population of Madre de Dios is urban, which constitutes a major indirect resource user (Mathez-Stiefel et al., 2020).

The public sector may be subdivided between the national government and the departmental and provincial governments. National agencies – such as the Ministry of the Environment (MINAM), the Ministry of Agricultural Development and Irrigation (MIDAGRI, formerly MINAGRI), and the Ministry of Energy and Mines (MINEM) – shape policies on the conservation and management of natural resources. The departmental government (GOREMAD) – through its directorates and departments – implements national policies and is in charge of granting or lifting forest and mining concessions, for example (Mathez-Stiefel et al., 2020).

Civil society is strongly represented in Madre de Dios, including not only associations of indigenous peoples, farmers, and miners, but also many conservation- and development-focused non-governmental organizations (NGOs) supported by international donor agencies. Conservation and sustainable natural resource management initiatives have been on the rise in recent decades, promoted by local activists, national, and international NGOs – sometimes in alliance with indigenous peoples. Madre de Dios is home to many research activities, with a strong focus on biodiversity and natural resources. Studies are carried out by local and national universities and institutes, international research organizations, and sometimes also by NGOs (Mathez-Stiefel et al., 2020).

Relationships between stakeholders: losers and winners

At the multi-stakeholder workshop held during the Wyss Academy pilot phase, including participants representing the different actor categories, the analysis of stakeholders' position and relationships in an affecting/affected diagram revealed a complex picture (Figure 26). Participants highlighted two major competing dynamics in the social-ecological systems of Madre de Dios: (i) a process of degradation of natural resources, and (ii) a process of conservation and sustainable natural resource management. These two processes require differentiated analysis, as shown in Figure 26. Comparing trends of resource degradation with trends of sustainable initiatives, the main actors behind the degradation of natural resources (e.g. illegal miners and loggers, medium-scale farmers) move from the "affecting" to the "affected" side of the diagram. Conversely, the main promoters of sustainable initiatives (e.g. Brazil nut concessionaires, ecotourism companies, NGOs) move from the "affected" to the "affecting" side of the diagram. Certain actor categories – namely those that both affect and are affected by the state of nature and natural resources (e.g. indigenous peoples, small-scale farmers, national and departmental government, processors of natural resources, etc.) – occupy the same position in the diagram with respect to either trend (Mathez-Stiefel et al., 2020).



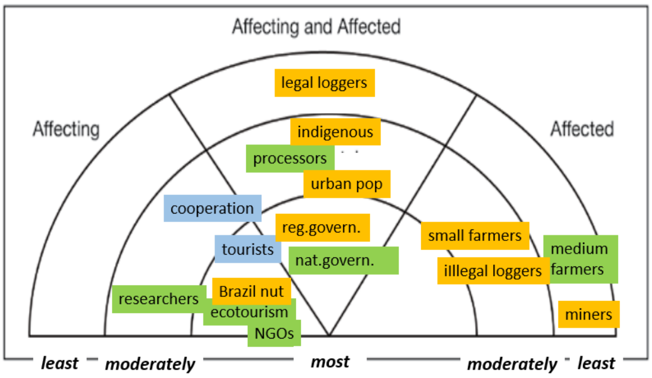


Figure 26. Stakeholder analysis for Madre de Dios: affecting and affected actors in relation to degradation (left) and conservation/sustainable management (right) of nature and natural resources in Madre de Dios, Peru. Colors indicate the scale of actors' activities (blue: national to international; green: departmental to national; orange: local to departmental). Source: translated from Mathez-Stiefel et al. (2020).

Notably, the parallel degradation and conservation trends make it difficult to identify clear losers or winners of current social-ecological system dynamics. Adding to the complexity, the same individuals may belong to several actor categories – sometimes with contradictory impacts on nature (e.g. a Brazil nut concessionaire may also be illegally logging wood in their concession). Often, decisions and interests of stakeholders operating at different scales apply to the same territory. Nevertheless, it was acknowledged that some groups are particularly vulnerable, independent of their impact on natural resources (e.g. indigenous communities, small-scale farmers, migrant communities). Similarly, the pressing need for land use planning that affords equitable benefits to diverse actors was highlighted (Mathez-Stiefel et al., 2020).

7.3 Assets and opportunities

To develop opportunities that harmonize nature conservation and human well-being it is crucial to use a systemic, integrated approach that includes social, economic, political, and environmental aspects. Government recovery plans to reactivate the economy after the COVID-19 pandemic provide an excellent opportunity to build back better. Promising approaches include establishing new partnerships and associated initiatives – and strengthening those that already exist – for the equitable and sustainable management of natural resources in collaboration with diverse actors pursuing a variety of interests. Existing initiatives could be evaluated to identify successful examples and best practices, such as the co-designed Strategic Buffer Zone Plan (PEZA) for the Tambopata National Reserve (see Box 2), the co-management model (native communities and government) of the Amarakaeri Communal Reserve, or the public–private partnership to produce soft drinks from "aguaje" fruits involving private companies, government institutions, indigenous communities, and NGOs. Technical Working Groups or "Mesas Técnicas" – e.g. for Brazil nut, "copoazú", cacao or aquaculture – that include public and private institutions and producer organizations are also important platforms to engage different actors, as well as strengthen supply chains and governance systems. Important assets for the sustainable development of the region are support from international agencies, as well as low-emission and rural development strategies. Capacity development of local people and institutions with an understanding of Madre de Dios' context is another important element, as well as participatory planning and management.

In this regard, multiple use forest management has been highlighted as an opportunity to increase economic returns from the sustainable use of forests while bringing together different stakeholders and promoting effective, equitable conservation. Ecological factors such as seasonality of production, habitat type, and management practices need to be taken into account to ensure the compatibility of different uses (Duchelle et al., 2012). In addition, to improve smallholders' incomes, sustainable products derived from native biodiversity have to be integrated in more efficient supply chains and benefit from technological innovations (Vanthomme et al., 2019).

Brazil nut is one of the cornerstone NTFPs in Amazonia, integrating sustainable development and conservation (Batista et al., 2019; Caetano Andrade et al., 2019; Porcher, Thomas, Corvera Gomringer, & Bardales Lozano, 2018; Rockwell et al., 2015). Many smallholders in Madre de Dios have historically depended on Brazil nut harvests to support their families. Brazil nut seeds are collected locally and traded in international markets (Bongiolo, Kainer, Cropper, Staudhammer, & Wadt, 2020; Caetano Andrade et al., 2019; Rockwell et al., 2015). The Brazil nut sector is not just an important economic activity in Madre de Dios, it also strengthens social cohesion by involving different actors, in particular women, in different phases of the supply chain. Organic and "fair trade" certification of Brazil nuts adds value to this forest product and enables access to more competitive market niches. However, for the Brazil nut sector to be sustainable and competitive in the long term, it will need to recognize the multiplicity of land uses, implement sound silvicultural approaches, and establish effective negotiation platforms with different productive sectors and specialized markets (Willem et al., 2019).

Agroforestry is being promoted in Madre de Dios as a more resilient agricultural system capable of dealing with climate variability, low-fertility soils, and diseases, as well as diversifying production. For example, production of cacao and "copoazú" in agroforestry systems is being developed in the region (Gobierno Regional de Madre de Dios, 2018). Biodiversity products like "copoazú" and "açaí" (*Euterpe oleracea*) have major potential and will benefit from better access to markets, efficient supply chains, and demand-stimulating awareness-raising at the national level. Opportunities also exist in the identification, conservation, and utilization of native varieties of crops that originated in the Amazon (e.g. cacao). Local crop varieties could be better adapted to local conditions, more resilient to change, rich in flavors, and qualify for denomination of origin certification. Indigenous knowledge could help to identify products with market potential. Other important opportunities include increasing local processing to produce more value-added products, rather than solely trading raw materials (e.g. timber). In this regard, sawmills could be transformed into factories selling final products like furniture or parquet flooring. However, in addition to expertise and technical skills, production of such value-added products will require more access to energy, which is currently limited in Madre de Dios. This highlights the opportunity to develop renewable energy initiatives in the region.

Box 2. Buffer zones: reconciling conservation and sustainable livelihoods.

Buffer zones around conservation areas provide opportunities to test innovative management models that enable local livelihoods while reducing pressure on natural resources. One key Wyss Academy incubator project – an innovative platform for collaboration between science, practice, and policy – is being implemented in cooperation with ACCA and focuses on the strategic plan for the buffer zone of the Tambopata National Reserve (Madre de Dios, Peru). It is referred to as PEZA, based on its Spanish acronym. A study carried out within the project has already shown that the participative co-design approach used in Tambopata is unique in the Peruvian context. It is a significant success factor, enabling the development of joint objectives by the diverse stakeholders of the National Reserve, as well as delegation of clear roles among them. In addition, the introduction of incentives for local people in the form of capacity development and technical assistance for sustainable economic activities – like agroforestry, fish farming, or NTFP harvesting – has played a decisive role in the successful management of the buffer zone. The project has supported the development and testing of an integrated participatory monitoring tool for the buffer zone, which plays an important role in promoting the adherence of involved stakeholders to jointly agreed roles and responsibilities. Further, the project investigated which aspects of the overall management approach can be transferred to other conservation areas in Peru, and what strategies could be used to do so. The PEZA model proved its usefulness in practice, as well as its major potential for scaling at the national level. In Peru, the buffer zones of the national protected areas – encompassing over 14 million hectares – remain a challenging area for management, in particular due to lack of clear institutional competencies and policy guidelines.

With over 100,000 ha of land deforested in Madre de Dios due to mining activities, restoration of degraded lands has great potential, including in the context of global and regional initiatives like the United Nations Decade on Ecosystem Restoration[3] as well as the Initiative 20x20 in Latin America and the Caribbean[4]. Restoration efforts could be scaled up by building on

3 https://www.decadeonrestoration.org/
4 https://initiative20x20.org/

lessons learned from existing initiatives. Secondary forests and fallow lands also provide interesting opportunities. They are hotspots for Brazil nut regeneration and, if properly managed (e.g. through enrichment planting), can be converted into valuable forest stands – also for timber production. REDD+ projects are also seen as an opportunity for international investors, although a stable political situation will be needed to enable their establishment. However, complex bureaucratic requirements, lack of technical knowledge, and capacity-building needs might limit their development by local actors. Further, corresponding mechanisms might need to be redesigned to reduce the transaction costs of intermediaries.

In the department of Madre de Dios, there are 1.3 million hectares of logging concessions, including 422,959 ha that are FSC-certified (Tobler et al., 2018). Certification schemes can add value to forest goods produced by smallholders, targeting niche international markets and enabling higher economic returns (Duchelle et al., 2012; Oliveira et al., 2019). Certified forests can maintain levels of fauna biodiversity similar to those of undisturbed primary forest in Madre de Dios (Campos-Cerqueira et al., 2019) as long as hunting is controlled and the volumes of timber extracted are low (Tobler et al., 2018). In addition, carbon emissions from logging operations can be reduced if reduced-impact logging practices are applied (Goodman et al., 2019).

Ecotourism provides a promising opportunity to generate income for local populations while conserving nature (Csillik & Asner, 2020; Doan, 2013; Kirkby et al., 2010; Salvador et al., 2011). Protected areas in Madre de Dios offer great opportunities for this economic activity. In addition, ecotourism concessions can help to sequester the aboveground carbon (Csillik & Asner, 2020; Kirkby et al., 2010; Puhakka, Salo, & Sääksjärvi, 2011). At the same time, the promotion of sustainable tourism could be one of the main strategies for conservation of emblematic species like the giant otter, one of the main tourist attractions in the Madre de Dios region and an important source of income for the local population (Mendoza et al., 2017).

Sustainable uses of wetlands in Madre de Dios include the non-destructive harvesting of "aguaje" fruits and other palm products. Improved understanding of the production capacity of different "aguajales" and capacity-development programs on non-destructive harvesting techniques could support the sustainable use of these species. Opportunities may also emerge from the development of products from "aguaje" fruits, such as ice cream and other edible goods, and from non-fruit related products such as fibers, oils, and handicrafts (Janovec et al., 2013). The exploitation of *Vanilla* species, present in wetland ecosystems in Madre de Dios, could provide alternative livelihood opportunities for local residents. *Vanilla pompon*, for example, has been found to produce aromatic fruits with commercialization potential (Janovec et al., 2013).

Fish farming in Madre de Dios could become more lucrative by addressing operational barriers, including limited distribution, lack of access to building equipment, and operating costs. Despite higher demand in regional markets, most of the fish is currently sold locally due to lack of regional transportation. Fish farmers could benefit from economies of scale through collective digging of ponds and transportation to regional markets (Fisher et al., 2018).

In terms of enabling conditions, strong stakeholder engagement and commitment are the most important success factors behind initiatives for nature sustainability and human well-being in Madre de Dios, according to the results of the stakeholder survey conducted during the Wyss Academy pilot phase. In addition, broad local participation is considered key to success. The role of a solid scientific basis for overall success is considered less relevant, but its importance is highlighted in specific projects requiring technological support. As shown in Figure 27, bottom-up solutions, political dialogue, and incentive-based initiatives are the most recommended approaches. By contrast, science-based approaches, social innovation, and regulations are given less emphasis. Finally, top-down and/or technological solutions are not considered promising (Mathez-Stiefel et al., 2020).

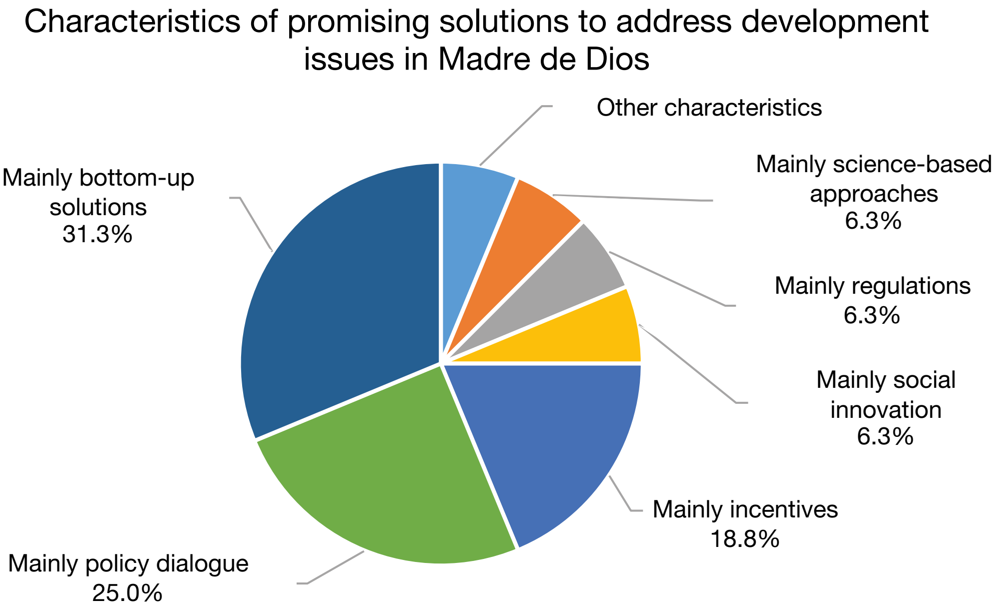


Figure 27. Characteristics of promising solutions to address development issues in Madre de Dios, Peru, according to local stakeholders (N=16). Source: survey of multi-stakeholder workshop participants.

In terms of national-level government priorities concerning sustainable pathways, emphasis is placed on forest management and land restoration, tourism development, agriculture and agroforestry, as well as support for indigenous knowledge and culture. In terms of local-level government priorities, emphasis is placed on agriculture and value chains, followed by forest management, land restoration, and land use planning (Mathez-Stiefel et al., 2020).

8 Knowledge gaps and research needs

This section draws on the discussions of the synthesis workshop with regional experts and key partners from the Wyss Academy South America Regional Hub, held virtually in June 2021 (Annex 3), as well as on information from the literature review.

The identification and implementation of targeted measures and interventions to improve nature–people relations in Madre de Dios are currently limited by a still incomplete understanding of the social-ecological system and its components, and by the uneven availability of supporting data and information across temporal and spatial scales.

A general priority is to achieve a better understanding of the social-ecological system and dynamics of Madre de Dios in its regional context, its interactions with bordering regions, and the underlying drivers of change – including the dynamics of forest frontiers and highland–lowland interactions. For example, expanding the study area to include the regions of origin of migrant populations in the High Andes and neighboring regions in Bolivia and Brazil will provide a more comprehensive picture of complex regional dynamics, and shed light on larger-scale opportunities for sustainable development.

In terms of social components, there is currently insufficient knowledge about people's level of well-being and income generation based on different livelihoods and economic activities in Madre de Dios, as well as local people's visions for the future. Improving such understanding using an inclusive, participatory approach is essential to jointly identify sustainable livelihood options that support ecosystem conservation while guaranteeing economic sustainability and contributing to progress towards the Sustainable Development Goals for local populations (Fisher et al., 2018). For example, analysis of COVID-19's impacts on different stakeholders, their livelihoods, value chains, household incomes, and the overall departmental economy could provide valuable insights into people's choices regarding how to balance income and well-being in a changing and dynamic environment. In addition, it would be important to identify the most promising sustainable economic activities (including non-land-based activities) for society to recover from the COVID-19 crisis in the short-, medium-, and long-term.

At the level of governance, better coordination and collaboration between multiple actors and improved understanding of their interests and power relations are needed for integrated landscape planning and management, as well as for the creation of sustainable initiatives (Rodriguez-Ward et al., 2018). In particular, the role of land tenure, or lack thereof, as a driver of deforestation and forest degradation should be further investigated. For land use planning to be successful and participatory, and to determine the spatial scale of opportunities, detailed spatial information is needed. Citizen science could be a strong tool to engage stakeholders in participatory monitoring of biodiversity change and to enable better planning and timely interventions, for example concerning the production of forest products like Brazil nut in the face of climate change. Decision-making on conservation and restoration efforts could be strengthened with initiatives to monitor forest degradation using remote sensing techniques (Tarazona & Miyasiro-López, 2020).

As multifunctional landscapes and multiple use forest management have been identified as key opportunities for sustainable development of the region, understanding of their benefits and valorization should be improved, including further studies on the integration of selective timber harvesting with NTFP extraction (Rockwell et al., 2015). There is a need for greater knowledge of regeneration and production of valuable native species, and their potential uses for enrichment planting.

Several knowledge gaps exist regarding the complex issue of gold mining and its impacts on the social-ecological system in Madre de Dios. For example, multidisciplinary research is needed to understand the full ecological consequences of increased sediment transport in freshwater systems due to gold mining in the region (Dethier et al., 2019). In addition, the possible impacts of mercury pollution on agricultural crops and Brazil nut need to be investigated. In areas affected by gold mining, there is not enough knowledge about reforestation and remediation techniques, including insufficient understanding of soil degradation and the resilience (or lack thereof) of native tree species to the extreme conditions of mined areas (Román-Dañobeytia et al., 2015). To support the ecological restoration of areas degraded by gold mining at a larger scale, recent studies could be expanded or built upon – including studies involving monitoring of experimental plots focused on native and pioneer species and application of bio-fertilizers (Sanguinetti, 2020); analysis of the survival percentage of different species depending on their wood density (Román-Dañobeytia et al., 2020); and the effects of mining areas and hunting on seed dispersal and regeneration vis-à-vis adjacent forests (Caballero Espejo et al., 2018). In this regard, restoration-related technological packages and business plans could be developed, tailored to different ecological conditions. The potential (economic) benefits of restoration activities could be explored, as well as the enabling factors for successful scale-up of restoration practices.

More spatially explicit biophysical data and information are needed for a better understanding of the social-ecological system and technical innovations towards a sustainable transition. In particular, there is a lack of comprehensive, systematically monitored/generated information on the status and trends of species, ecosystems, and ecosystem services in Madre de Dios. Such data is essential to enable informed management and decision-making. Overall, long-term standardized biodiversity monitoring schemes are currently lacking. An analysis of the International Long-Term

Ecological Research (ILTER) site network identified significant gaps in the Amazon basin, suggesting the need for geographical expansion of the network in this region (Wohner et al., 2021). In particular, data on Amazonian freshwater ecosystems are largely unavailable, hindering the sustainable management of these systems and their aquatic resources (Markham & Sangermano, 2018; Sweeney et al., 2020). Similarly, data on the distribution and biological diversity of Amazonian wetlands is needed to better manage and mitigate growing threats to these ecosystems (Householder et al., 2012). The lack of protective legislation and the absence of recognition of wetland areas under international conventions like Ramsar may in part reflect the scarcity of information to support decision-making (Householder et al., 2012).

Better data at higher resolution are also essential for an improved understanding of the abiotic elements of the social-ecological system. A dense network of weather stations collecting data over long periods of time is crucial for the validation process of climate models under the current climate. Even though the National Meteorology and Hydrology Service of Peru (SENAMHI) established and maintains several weather stations, they are concentrated along the mountains and the western slopes of the Andes, rendering model validation in the rainforest, and in particular in Madre de Dios, almost impossible. In addition to validating models, it is important to improve the understanding of large-scale to regional scale interactions. To date, the effect of large-scale controls on the regional climate – such as the El Niño-Southern Oscillation or the Amazonian forest itself – are not well understood and require further research to identify potential changes under global warming. This includes the dynamics of complex interactions between land surfaces and the atmosphere, which have not yet been fully captured – particularly not by global and regional climate models. This adds an additional level of complexity and uncertainty to climate simulations. Consequently, model-based projection of future and past climate conditions is not simple and, in the best case, several long-term climatologies are needed to evaluate the uncertainties in each period.

There is a growing need to improve monitoring, early warning systems, and training regarding integrated risk and disaster management, including forest fires and floods, as well as damage caused by extreme weather events in affected sectors (Chavez Michaelsen et al., 2020). In particular, the main drivers of increased flood damage risk around main urban centers – that is, climate change (with increasing droughts and torrential rains), poor planning (e.g. expansion of urban areas in flood prone zones), and land use change (deforestation and expansion of gold mining) – require a comprehensive, integrated response (Guevara et al., 2020). More support is necessary to strengthen the knowledge of households, communities, institutions, and sectors to adapt to climate change and adjust their practices to prevent disasters and prepare for extreme events. Integrating indigenous and local knowledge and perceptions would be key to support their engagement (Chavez Michaelsen et al., 2020).

It will be essential to team up with ongoing third-party research projects, practitioners, academia, business, and government institutions from the local to the international level to avoid redundancies and enable synergies that meet current data and information needs and fill knowledge gaps.

9 Conclusion

Sustainability challenges call for transformative changes that harmonize nature conservation and human well-being. The Madre de Dios region in Peru, a biodiversity hotspot, hosts rich natural resources that provide a variety of contributions to people such as climate regulation, Brazil nut fruits, and ecotourism, and offer opportunities for sustainable development of the region. At the same time, the capacity of ecosystems to continue delivering these contributions is threatened by deforestation, unsustainable exploitation of resources, and mercury pollution from gold mining. Climate change may interact with other drivers, such as land use change, exacerbating their possible negative impacts. Mercury pollution not only threatens the environment, but also human health. In addition, gold mining is associated with social conflicts, crime, and illegal trafficking. The underlying drivers of local change include population growth and migration, road construction, increases in the international gold price, and insecure land tenure. Opportunities for sustainable livelihoods in the region include Brazil nut harvesting, agroforestry, certified logging, and ecotourism, all of which would benefit from a multiple-use, systemic, and integrated approach. Addressing issues such as land rights and ensuring equal participation of stakeholders in decision-making processes, integrating biodiversity products in efficient supply chains that generate added value, and developing local capacities could improve income generation of local communities while delivering conservation outcomes.

Appendices

Appendix 1: Climate modelling approach

A key feature in Peru's climate is the complex orography, which calls for a dynamical downscaling approach. This approach makes use of a weather prediction model that explicitly solves atmospheric equations and parameterizes some fine-scale processes such as cloud formation. The regional model provides a physically consistent product on a high spatial resolution, but comes at the cost of a large sample of different scenarios. For this report, the Weather Research and Forecasting (WRF) model is employed, using three nested domains, where the finer nest is located in the respective coarser domain. Further, WRF uses initial and boundary conditions from a global model to obtain horizontal resolutions of 25 km, 5 km, and 1 km for the respective nested domain. The largest domain covers the full northern part of South America, while the second domain zooms into a larger area around Peru, covering the interaction between the highlands and lowlands, and the third one focuses on Madre de Dios. For the current climate, the years 1981–2010 are considered; the future is modelled using the high-emission scenario RCP8.5 for the period 2071–2100.

In order to understand climate and its changes, a dense network of observational data must be available in the first place. In Peru, several observations are available from the National Meteorology and Hydrology Service of Peru (SENAMHI), but most of the weather stations are located along the mountain ranges of the Andes and very few stations are placed on the eastern slopes and in the lowlands of the Amazon forest. These unevenly distributed observations certainly are sufficient to validate climate model simulations on the western slopes of the Andes, but for the flatlands and the eastern slopes, this is a challenging task. Therefore, other data sources need to be considered, such as satellite-based precipitation products: TRMM, IMERG, CHIRPS, and PISCOp v2.1 (Aybar et al., 2020; Funk et al., 2015; Huffman, Adler, Bolvin, & Nelkin, 2010; Huffman et al., 2014, 2007). Even though these products make use of different ranges in the electromagnetic spectra, i.e. visible, infrared or microwave, the final products are based on relationships between cloud thickness and cover and the actual rain, as satellites mainly observe a cloud and its structure rather than precipitation directly. The finest grid of the satellite-based data reaches around 10 km, but as Figure 28 indicates, these data products are not able to represent the peak precipitation intensity at the right locations, i.e. at the steepest slopes, where the air has to rise and, hence, loses most of its contained water. In fact, the peak intensity is still displayed in the rather flat areas, which is not realistic from a physical point of view. This mismatch can be partly attributed to the relative coarse resolution of the data sets. The regional climate model could add value, as it makes it possible to simulate in a physically consistent way processes on a much finer spatial and temporal scale than the satellite-based data. Such simulations are beneficial in particular for areas with complex topography and low-density of observations, as in the case of Peru and Madre de Dios. Additionally, regional climate models further make it possible to extend projections into the future without assuming any stationarity in climate states. Nevertheless, it must be kept in mind that one simulation presents only one of multiple climate states that are possible in the chaotic weather/climate system. Thus, uncertainties arising from model deficiencies cannot be assessed by a single simulation and internal variability is potentially underestimated. To account for this, our simulation is compared to CMIP5 models discussed in more detail in the IPCC-AR5 (IPCC, 2013).

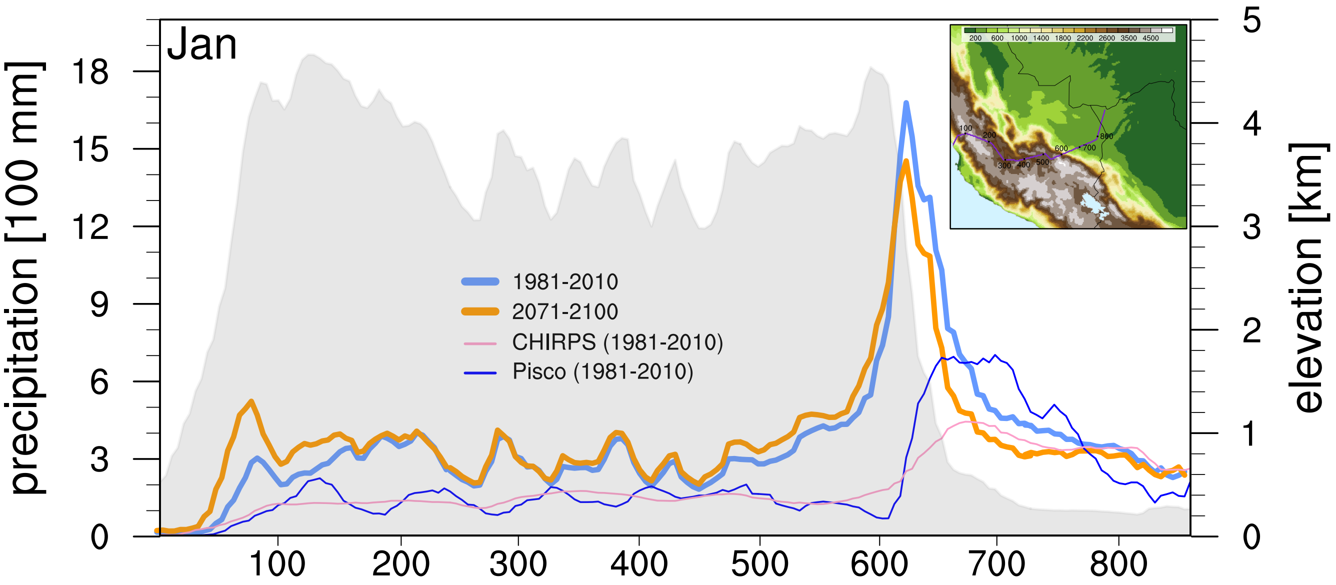


Figure 28. Climatological monthly precipitation sums for January along a transect through the Andes into Madre de Dios. The precipitation measures for the past (1981–2010, blue thick line) and the future (2071–2100, orange thick line) obtained from the downscaled simulation are compared to the two satellite-based datasets CHIRPS (pink) and PISCOp V2.1 (dark blue) for the period 1981–2010. The lines provide precipitation measures in 100 mm per month (left y-axis). The transect is following the purple line in the inset in the upper right corner of the plot. The numbers in the inset denote the distance from the start (west coast) in km and they correspond to the numbers on the x-axis. The grey shading indicates the topography along this transect given in km above sea level (right y-axis). Source: authors' own elaboration.

To obtain a rough estimate of changes in future fire risk, the fire weather index (FWI), based on the Weather Guide for the Canadian Forest Fire Danger Rating System (Lawson & Armitage, 2008), is calculated for the regional climate simulations. The FWI considers 2-m temperature, relative humidity, wind speed and rain and provides some indication on the initialization and distribution of fire. However, one limitation of the FWI is that the availability of fire fuel is not included in its definition. The FWI classifies fire danger into six categories from "very low" to "extreme".

The El Niño and La Niña events are calculated using the Niño 3.4 index. It is calculated based on five-month running means of the sea surface temperature anomalies in the central Pacific (5°N-5°S, 170°W-120°W). El Niño and La Niña events are defined if the index exceeds the threshold of ±0.4°C in at least six consecutive months.

Appendix 2: Stakeholder analysis

During the pilot phase of the Wyss Academy for Nature, together with the Wyss Academy main local partner, Conservación Amazónica (ACCA), a series of methods were used to map and analyze stakeholders relevant to initiatives for nature and people in Madre de Dios and to capture stakeholders' perspectives on the main development issues and trends in the region.

Stakeholder mapping

Based on the expert knowledge of ACCA professionals, we first mapped the actors or stakeholders. In the context of this study, stakeholders were defined as individuals, groups or organizations affected by, interested in and/or capable of affecting biodiversity conservation and human well-being initiatives in Madre de Dios. To conduct the stakeholder mapping, we followed three steps: 1) identification of stakeholders and their interests; 2) differentiation among stakeholders and their categorization; and 3) analysis of the relationships among stakeholders. We started by making a free listing of stakeholders. We then grouped the stakeholders into categories and assessed these categories, their characteristics, roles and interests. Finally, we analyzed the relationships between stakeholders using a "rainbow diagram" that makes it possible to visualize the degree (low, moderate, or high) to which they impact and are impacted by the state of natural resources.

Stakeholder survey

We captured stakeholder perceptions of the main development issues and trends in Madre de Dios by means of a survey, conducted through Survey Monkey, which was sent to 34 people representing 11 different stakeholder categories (two of these people belonged to two stakeholder categories; see Table 6). Of these, sixteen (47%) responded to the survey anonymously. The survey was complemented by in-depth interviews with three conservation and development experts with extensive knowledge of the Madre de Dios context. Responses to open-ended questions were subjected to basic content analysis using QDA Miner Lite software. Analytical categories were predefined based on ACCA professionals' expert knowledge of the Madre de Dios context.

Sector	Actor category	Survey (N=36)	Workshop (N=40)
Direct land users	Indigenous peoples	3	1
	Small- and medium-scale farmers	1	2
	Logging concessionaires and companies	1	1
	Brazil nut concessionaires	1	2
	Subtotal	***6***	***6***
Indirect land users	Ecotourism companies and concessionaires	1	2
	Subtotal	***1***	***2***
Public sector	National government agencies	5	5
	Departmental and provincial government agencies	3	5
	Subtotal	***8***	***10***
Civil society and research	Conservation and development NGOs	8	9
	International cooperation	4	2
	Local and national research institutions	5	4
	International research institutions	4	9
	Subtotal	***21***	***24***

Table 6. Profile of the actors that participated in the study: activity sector, actor category, and number of participants in the survey and in the multi-stakeholder workshop.

Box 3. Survey questionnaire (the questionnaire was translated into Spanish and adjusted to Survey Monkey).

Achieving universal human well-being in the context of finite planetary resources requires imaginative thinking and exceptional action. The Wyss Foundation and the University of Bern thus aim to build pioneering partnerships in regions that embody the hyper-complex challenges and threats of unsustainable and unjust development. We are aware that these same spaces are also at the heart of groundbreaking initiatives to respond to the multiple challenges of climate change, biodiversity loss, and unsustainable land use. Based on our commitment to engaged and transformative science, the future Wyss Centre Bern for Global Stewardship (WCB) invites local partners and stakeholders to a co-design workshop as an initial call to engage in transformative action. As an initial step to this workshop, we ask participants to kindly answer the following questions. This questionnaire will not take you more than 15 minutes. Thank you for your time.

1. **If you had USD 1 Million to promote sustainable pathways for nature and people in Madre de Dios, what would be the idea you would spend it on?**
2. **Imagine the same situation, this time with USD 50,000. What would be the project idea you would spend it on?**
3. **If you were in the responsible government position, what would be your priority in view of sustainable pathways for nature and people in Madre de Dios,**

    a) At national level (kindly name at least one initiative)
    b) At local level (kindly name at least one initiative)

4. **Imagine you had a choice to talk to an influential person/institution about sustainability for nature and people in Madre de Dios.**

   a) Who would you want to talk to?
   b) Why?
   c) What would be the issue you would talk about? (you can name more than 1 issue).

5. **What are the three most pressing problems you encounter in Madre de Dios? – Are any of these problems related to a) climate change, b) biodiversity loss, c) land use change (Yes/No)**
6. **Why have the problems you mentioned not been addressed so far (2 most important reasons).**
7. **What have been issues for conflict in your region lately (last 5 years)? Please name at least 1.**
8. **Please name the most successful initiative for enhancing sustainability for nature and people in Madre de Dios region in the last 10 years.**
9. **Why was it successful?**

   a) well financed
   b) good scientific foundation
   c) solid stakeholder buy-in
   d) broad local participation
   e) strong political support
   f) other reasons, please specify:

10. **If you were to draft solutions to address some of the pertinent problems in your region, what character would that solution have:**

    a) Mainly technology
    b) Mainly scientifically driven approaches
    c) Mainly regulations
    d) Mainly incentives
    e) Mainly policy dialogue
    f) Mainly social innovation
    g) Mainly bottom-up solutions
    h) Mainly top-down solutions
    i) Others, please specify.

Thank you very much for your kind cooperation. Kind regards. The Wyss initiative team

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Multi-stakeholder workshop

The results of the stakeholder mapping and survey were presented in a two-day multi-stakeholder workshop, where they were corrected, enriched, and validated by representatives of various stakeholder categories. The event, jointly organized by the University of Bern and ACCA in Lima in January 2019, brought together 37 representatives from local communities, various levels of administration, civil society organizations, the private sector, and national and international research institutions (three of them belonged to two stakeholder categories; see Table 6). The objectives of the workshop were: 1) to understand the main dynamics of social-ecological systems; 2) to analyze stakeholder perspectives and relationships; and 3) to identify transformation pathways towards conservation and human well-being. The IPBES conceptual framework (Díaz et al., 2015) was used to analyze the direct and indirect drivers of systems change, and their impacts on nature and human well-being in Madre de Dios. The session on transformation pathways started with an exercise on desirable futures for nature and people in Madre de Dios, taking into account the stakeholder mapping that had been validated in the previous session. Finally, a brainstorming exercise generated 182 ideas for potential science–management–society collaboration initiatives, of which eight were analyzed and prioritized in multi-stakeholder working groups as possible transformative pilot projects in the region.

Appendix 3: Madre de Dios synthesis workshop

Workshop description

The Wyss Academy for Nature held an online workshop on 1 June 2021 with invited experts from the South America Regional Hub, researchers from the Wyss Academy, and researchers from three University of Bern centers: the Institute of Plant Sciences (IPS), the Centre for Development and Environment (CDE), and Climate and Environmental Physics (CEP) (see complete list of participants in Box 4). The workshop aimed to harness the knowledge from regional experts and key partners of the Wyss Academy on challenges, opportunities, and knowledge needs for more just and sustainable people–nature relationships in Madre de Dios, Peru. The five South America Regional Hub experts were people with extensive knowledge of the context of natural resource management in Madre de Dios. They represented diverse actor groups including civil society, government, and research institutions, as well as diverse disciplinary expertise such as forestry, political ecology, ecological economics, rural development, and conservation practice. The workshop was facilitated by the Wyss Academy Senior Advisor for the Hub South America and was held mainly in English, although two of the invited experts made their contributions in Spanish.

The workshop was divided into three parts. First, researchers from the University of Bern shared the key findings of an advanced draft of chapters 1–6 of the present appraisal report. Second, in a panel discussion, the five regional experts were invited to briefly present their views on the main challenges and existing dilemmas for nature-and-people relationships in Madre de Dios, as well as on assets and opportunities for nature–people relationships in the region. The panel presentations were followed by a short discussion with the audience. Third, workshop participants worked in two groups (the Hub experts and representatives from different institutions were distributed among the two groups) to jointly identify and agree on the most relevant knowledge gaps and research needs to address the main challenges and to realize the potential of the opportunities identified in the previous sessions.

Box 4. Workshop participants. Name, institution, country, and role in the workshop (when that person had a specific function).

- Juan Loja, ACCA, Peru – panelist
- Sidney Novoa, ACCA, Peru – panelist
- Augusto Mulanovich, Mariposario Tambopata, Peru – panelist
- Jamil Alca, Univ. Agraria La Molina & Ministry of Housing and Sanitation, Peru – panelist
- Evert Thomas, Bioversity International, Peru – panelist
- Amor Torre-Marin, IPS, University of Bern, Switzerland – presenter
- Mark Snethlage, IPS, University of Bern, Switzerland – presenter
- Markus Fisher, IPS, University of Bern, Switzerland
- Thomas Breu, CDE, University of Bern, Switzerland
- Chris Hergarten, CDE, University of Bern, Switzerland – co-facilitator, notetaker
- Kaspar Hurni, CDE, University of Bern, Switzerland
- Christoph Raible, CEP, University of Bern, Switzerland
- Martina Messmer, CEP, University of Bern, Switzerland
- Santos J. González-Rojí, CEP, University of Bern, Switzerland
- Andreas Heinimann, Wyss Academy, Switzerland
- Eva Ludi, Wyss Academy, Switzerland
- Dominic Martin, Wyss Academy, Switzerland – notetaker
- Sarah-Lan Mathez, Wyss Academy & CDE, Univ. of Bern, Switzerland/Peru – facilitator, translator

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Summary report

Feedback on chapters 1–6 of appraisal report: general agreement

All participants agreed with the main findings of the appraisal report. Specifically, participants confirmed the identification of logging, mining, and agriculture as interdependent drivers of overexploitation, pollution, and land use change (in particular, deforestation) in Madre de Dios, and confirmed that these lead to negative impacts on biodiversity and ecosystem services, and consequently also on people. The participants also confirmed that the Interoceanic Highway, immigration from the highlands, and demand for gold are the underlying drivers of local logging, mining, and agriculture expansion.

The discussion also emphasized some areas where further system knowledge is needed. Specifically, the problem of illegal gold mining was debated. While sustainable agricultural activities (e.g. agroforestry, fish farming, Brazil nut harvesting) are often seen as an alternative, participants highlighted that mining will persist given the high financial returns, concluding that more sustainable mining should be a key objective in the region. Consequently, an engaged debate centered around the legalization of informal gold mining in current mining concessions, and whether this might encourage further gold mining outside concessions. While mining is one of the most visible problems in Madre de Dios, participants also insisted on the need to carefully study and monitor land use change and deforestation processes linked to logging and agricultural expansion, including for cattle. They also highlighted the fact that the vast part of the territory of Madre de Dios that is outside mining areas displays major potential for implementation of sustainable conservation and agricultural activities.

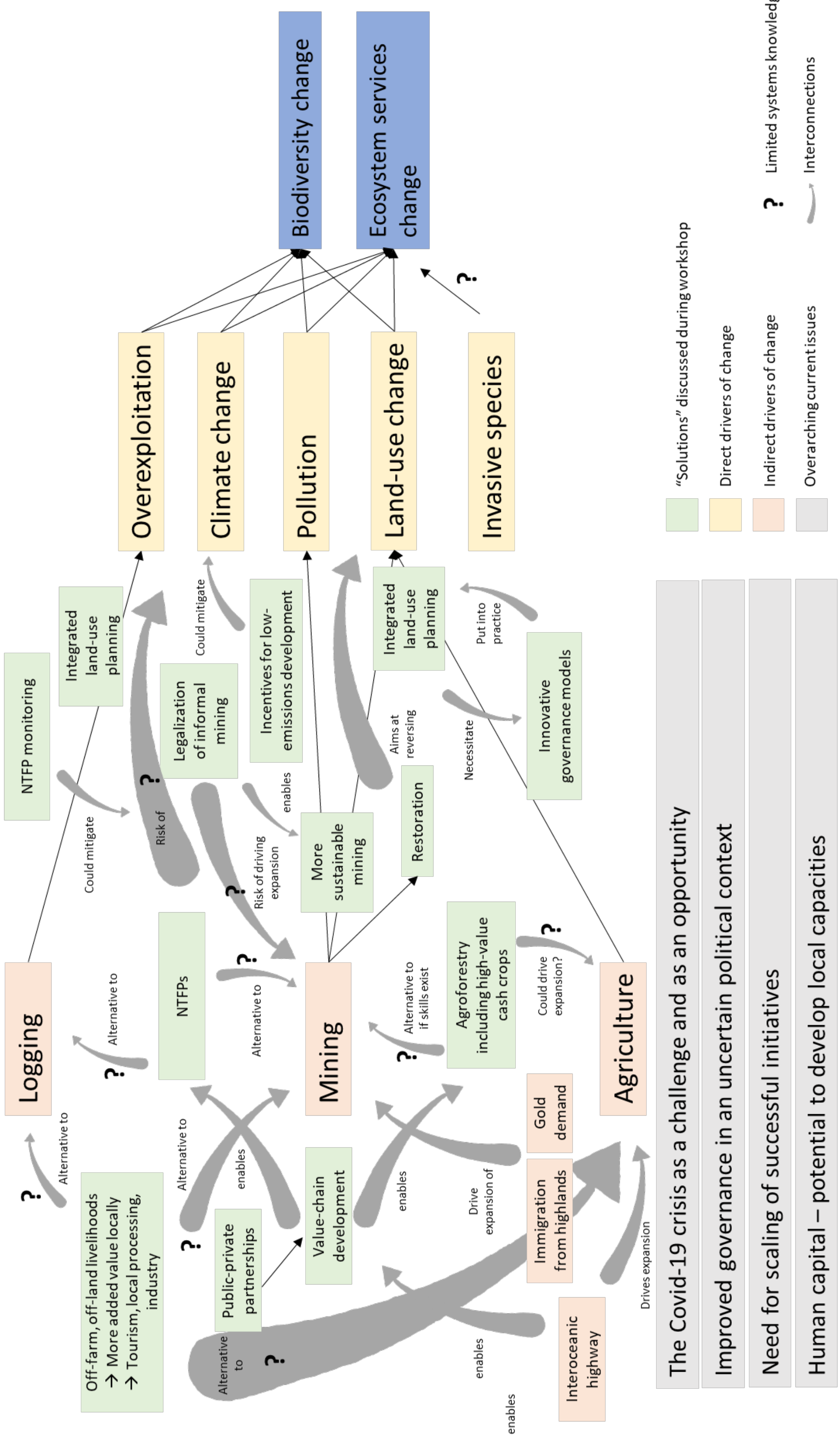
Solutions highlighted: major potential exists

Throughout the workshop, it became clear that many "solutions" exist. Some of them have been tested in small-scale projects, some have been successfully implemented elsewhere in Peru or Latin America, and others are new and appear to hold major untapped potential. Specifically, participants mentioned: 1) better land use planning; 2) off-farm, off-mining livelihoods by adding more value locally (ecotourism, industry, local processing); 3) value chain development for NTFPs and high-value cash crops (e.g. Brazil nut, cacao); 4) scaling up innovative, tested land governance models (e.g. management of the buffer zone of the Tambopata National Reserve, public–private partnerships); 5) the implementation of more sustainable mining (including legalization of informal mining); and 6) restoration of formerly mined sites for the benefit of biodiversity and ecosystem services. Here, a consensus emerged among participants that an integrated implementation of these "solutions" is necessary given their interconnectedness and common implementation hurdles (Figure 29).

Overarching issues: current challenges and opportunities

The participants highlighted four overarching issues that are especially relevant in the current context for all proposed "solutions". First, while the COVID-19 pandemic had a clear negative impact on the local economy and livelihoods (e.g. on trade, tourism, etc.), and consequently led to an increase in anthropogenic pressure on natural ecosystems, the departmental government's efforts to reactivate the economy after the global health crisis represent a chance for progress towards more just outcomes for people and nature. Second, one participant highlighted the fact that there had been an overall improvement of departmental governance in recent years, including improved capacity to enforce control over natural resources and efforts towards formalization of gold mining. However, the political path the country is taking may lead to adverse conditions for environmental initiatives (the workshop happened only a week before the second round of the presidential elections, with both candidates displaying a weak environmental agenda). Further, participants mentioned that oftentimes employees of local institutions and organizations are not from the region of Madre de Dios, hampering the integration of local knowledge and perceptions, while local staff would benefit from training and capacity-building in particular regarding integrated approaches. Lastly, problems in scaling up existing and well-tested solutions were mentioned repeatedly.

Figure 29. Visual representation of the rich debates and discussions that were held during the Madre de Dios Synthesis Workshop. The elements, interconnections, and causalities represented in the figure were identified based on the workshop notes and do not represent a complete picture of challenges and opportunities for nature and people relationships in Madre de Dios.



Appendix 4: List of acronyms

ACCA	Conservación Amazónica / Amazon Conservation
AR5	5th Assessment Report
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMIP5	Coupled Model Intercomparison Project Phase 5
FEMA	Fiscalía Especializada en Materia Ambiental / Specialized Prosecutor for Environmental Matters
FSC	Forest Stewardship Council
FWI	Fire Weather Index
GOREMAD	Gobierno Regional de Madre de Dios / Regional Government of Madre de Dios
IIAP	Instituto de Investigaciones de la Amazonía Peruana / Research Institute of the Peruvian Amazon
IIRSA	Integration of the Regional Infrastructure of South America
ILTER	International Long-Term Ecological Research
IOH	Interoceanic Highway
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
MIDAGRI	Ministerio de Desarrollo Agrario y Riego / Ministry of Agricultural Development and Irrigation
MINAM	Ministerio del Ambiente / Ministry of Environment
MINEM	Ministerio de Energía y Minas / Ministry of Energy and Mines
NGO	Non-Governmental Organization
NTFP	Non-timber forest product
OEFA	Organismo de Evaluación y Fiscalización Ambiental / Agency for Environmental Assessment and Enforcement
PDC	Plan de Desarrollo Concertado / Concerted Development Plan
PEZA	Plan Estratégico de la Zona de Amortiguamiento / Strategic Buffer Zone Plan
PIACI	Pueblos Indígenas en situación de Aislamiento o en situación de Contacto Inicial / Indigenous Peoples in Isolation or Initial Contact
PNCB	Programa Nacional de Conservación de Bosques / National Forest Conservation Programme
RCP	Representative Concentration Pathway
REDD	Reducing Emissions from Deforestation and forest Degradation
RIA	REDD Indígena Amazónico / Indigenous Amazonian REDD
SENAMHI	Servicio Nacional de Meteorología e Hidrología del Perú / National Meteorology and Hydrology Service of Peru

SERFOR	Servicio Nacional Forestal y de Fauna Silvestre / National Forest and Wildlife Service
SERNANP	Servicio Nacional de Áreas Naturales Protegidas por el Estado / National Service of Natural Areas Protected by the State
SPI	Standardized Precipitation Index
WHO	World Health Organization
WRF	Weather Research and Forecasting model
ZEE	Zonificación Ecológica y Económica / Ecologic and Economic Zoning

Appendix 5: Acknowledgments

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Participants to the online synthesis workshop held on 1 June 2021 provided insights to chapters 7 and 8 (see Appendix 3).

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