Chapter

Biomass Dynamics in Land Uses of the Upper Amazon: Perspectives for Sustainability

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Abstract

The sustainable management of biomass in the Upper Amazon is essential for environmental conservation and agricultural productivity. Strategies such as sustainable crop management, the expansion of forested areas, and erosion control have been shown to improve soil fertility, mitigate climate change, and strengthen ecosystem resilience. The use of beneficial microorganisms and nitrogen-fixing legumes supports the recovery of degraded soils, while the implementation of agroforestry and silvopastoral systems optimises carbon storage and ecological stability. The efficient utilisation of agricultural and forestry residues, through their conversion into inputs to enhance soil quality, reduces pollution and promotes the regeneration of degraded soils. Additionally, biological pest and disease control fosters more sustainable agriculture by minimising the use of agrochemicals. In this context, public policies such as the conservation of buffer strips, the regulation of agrochemical use, and rainwater harvesting ensure biomass sustainability and the protection of natural resources. The integration of these strategies and policies is crucial for balancing agricultural production with environmental conservation, ensuring the sustainability of agroecological systems in the Amazon region.

Keywords: ecosystem services, agroforestry systems, climate change, Montane rainforest, Yunga

1. Introduction

The Amazon, one of the most biodiverse and ecologically vital regions on the planet, is home to the world's largest tropical rainforest, covering approximately 5.8 million km^2, and the most voluminous river, which carries around 220,000 m^3/s of water along a 4000-kilometre course from the Peruvian Andes to the Atlantic [1]. Its ecological structure is highly diverse and can be classified into different vegetation types based on latitude, altitude, hydrology, and floristic composition [2–4].

Within this complexity, the Upper Amazon, also known as the Montane Rainforest or Yunga, is located on the eastern slopes of the Peruvian Andes, at altitudes ranging from 600 to 3800 metres. This region is characterised by the presence of humid montane and premontane forests with high biodiversity and a significant degree of endemism [5, 6]. The environmental conditions, marked by constant mist and

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high humidity, support the development of a wide variety of adapted plant species. Additionally, the sloping terrain and steep gradients shape the ecological structure and dynamics, regulating the hydrological cycle, storing carbon, and providing habitat for numerous species [7].

However, in recent decades, the Upper Amazon has undergone rapid landscape transformation due to the expansion of agricultural and livestock activities, logging, and other land-use changes [8, 9]. The reduction of above- and below-ground biomass affects carbon and nutrient fluxes, compromising ecological resilience by decreasing carbon storage, altering water regulation, and weakening soil stability, thereby increasing the region's vulnerability to extreme climatic events [10].

To assess the impact of these changes and develop sustainable management strategies, various monitoring tools have been employed, including remote sensing, permanent plots, and biomass estimation models. These methodologies have provided accurate data on landscape evolution and its effects on ecosystem services, offering crucial insights for conservation policy and sustainable management planning [11, 12].

Given this context, understanding the interaction between different land uses and biomass is essential for designing strategies that promote sustainability in the Upper Amazon. This chapter aims to examine the impact of landscape transformations on biomass and their implications for environmental sustainability and climate change. It will explore how variations in land use affect carbon storage capacity and the provision of ecosystem services, highlighting both opportunities and challenges for sustainable management. The information presented will contribute to the development of management strategies that balance the utilisation of natural resources with the ecological conservation of this strategic region.

2. The Peruvian upper Amazon

The Peruvian Upper Amazon, located on the eastern slopes of the Andes, encompasses the regions of Amazonas, San Martín, Huánuco, Pasco, Junín, Ayacucho, Cusco, and Puno. This area is the source of major rivers such as the Marañón, Mayo, Abiseo, Huallaga, Ene, Pachitea, Perené, and Tambo, playing a crucial role in the national hydrography. According to Holdridge's classification [13], the region comprises six life zones and five transitional zones, with ecosystems shaped by climatic conditions and surrounding vegetation.

According to the Ministry of the Environment [5], the Upper Amazon, also known as Yunga, hosts three types of ecosystems. The Yunga basimontane forest, located between 600 and 1800 metres above sea level, features vegetation that blends Amazonian and Andean species, with a moderate presence of epiphytes, covering 6.37% of the national territory (8,237,633.88 ha). The Yunga montane forest, found between 1800 and 2500 metres above sea level, has varying floristic richness, with a notable abundance of epiphytes, lichens, bromeliads, and tree ferns, covering 3.50% of the national territory (4,528,359.89 ha). Above 2500 metres and up to 3800 metres above sea level, the Yunga pluvial elfin forest presents vegetation rich in epiphytes and dwarf forests dominated by Ericaceae, Solanaceae, Asteraceae, Polemoniaceae, and Rosaceae. This ecosystem covers 1.84% of the national territory (2,377,288.52 ha) (**Figure 1**).

The rapid landscape transformation, driven by the unregulated expansion of agricultural, forestry, urban, and road infrastructure activities, has placed significant pressure on ecosystems. While agricultural areas include annual crops and agroforestry systems, non-agricultural spaces are allocated to pastures and other uses. This

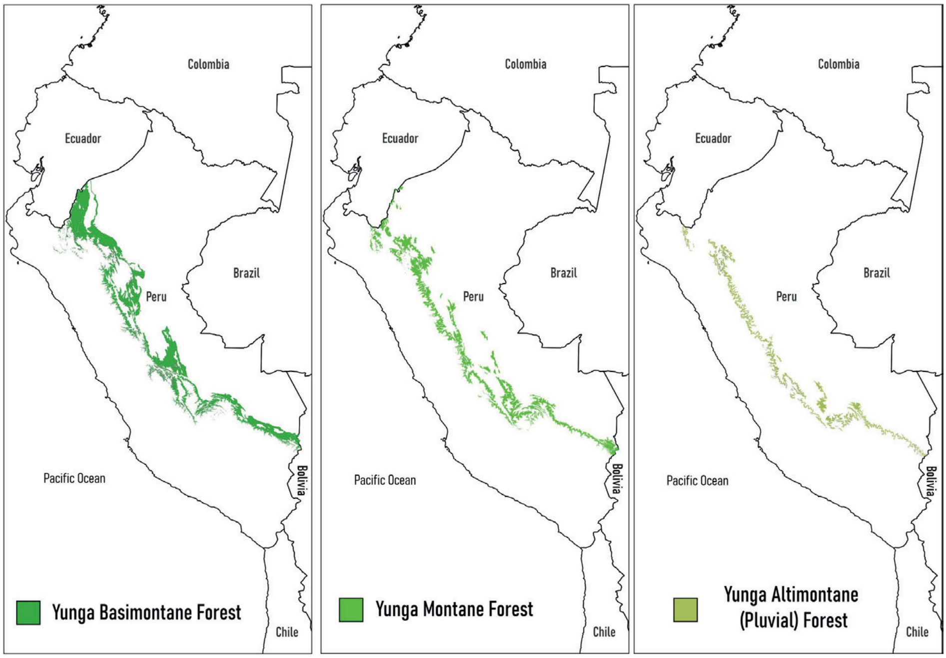

Figure 1.
Maps of Peru depicting the Upper Amazon, comprising the Yunga Basimontane Forest, the Yunga Montane Forest, and the Yunga Altimontane (Pluvial) Forest. (Modified from Ref. [5]).

intervention has led to the degradation of ecosystem services, affecting water regulation, carbon storage, and biodiversity conservation [14].

3. Biomass dynamics in different land uses

Carbon storage and dynamics in the Upper Amazon are determined by different land uses and management strategies. Primary forests hold the highest carbon reserves (485 t C ha^{-1}), followed by 50- and 20-year-old secondary forests (234 and 62 t C ha^{-1}, respectively). The conversion of forests into croplands reduces carbon storage by more than 80% and contributes to greenhouse gas emissions. In contrast, agroforestry systems with coffee and cacao have proven to be a viable alternative, capturing between 19 and 47 t C ha^{-1}, depending on species diversity and soil conditions. Additionally, leaf litter biomass enhances soil quality and facilitates nutrient cycling [15].

Cacao-based agroforestry systems have also demonstrated high carbon sequestration potential, with values ranging from 26.2 to 45.07 t C ha^{-1}, depending on the system's age. Live tree biomass accumulated between 12.09 and 35.5 t C ha^{-1}, while litter biomass ranged from 4 to 9.97 t C ha^{-1}. Furthermore, systems with higher carbon flux generated income through the sale of CO_2 equivalent credits, highlighting their potential both environmentally and economically [16].

In high-Andean ecosystems, forests also play a key role in carbon storage. In the Alto Huayabamba Conservation Concession, these forests were found to store an average of 167.11 ± 25.8 Mg ha^{-1} of biomass, with 83.5% in live biomass and 16.5% in necromass, underscoring their importance as carbon sinks in high-mountain ecosystems [17].

In both rural and urban areas of the Upper Amazon, carbon storage is also influenced by land use. In the community of Churuzapa, Lamas, dry biomass, total carbon, and soil density were evaluated in plots managed by local farmers. A significant correlation (0.786) was found between carbon environmental valuation and the community's socioeconomic status, highlighting the importance of these ecosystem services in rural sustainability [18].

Similarly, in Yantaló, carbon storage in urban orchards was estimated, covering 35% of the locality's surface (21 ha). The average dry biomass per orchard was 0.527 t, with 38% of carbon sequestration attributed to plant biomass and 62% to soil. In total, Yantaló sequesters 1196 t of carbon, with an estimated environmental value of $26,305 per year [19].

Soil carbon storage is another key aspect of biomass dynamics. A study in coffee plantations and secondary forests in San Martín found that the average soil organic carbon (SOC) was 69.19 t ha^{-1}, reaching up to 225.28 t ha^{-1} in the secondary forest of Jepelacio. A positive correlation was identified between SOC, altitude, and $CaCO_2$ content, suggesting a direct link to soil fertility. However, the proximity of agricultural soil carbon values to the critical degradation threshold emphasises the need for conservation strategies to prevent soil carbon loss and agricultural productivity decline [20].

Silvopastoral systems (SS) also represent a sustainable alternative for carbon sequestration. A study in the high jungle evaluated SS with *Cedrelinga cateniformis*, *Eucalyptus* spp., and *Inga edulis*, finding that the system with *C. cateniformis* had the highest carbon reserves. Overall, the soil was the main carbon reservoir, surpassing plant biomass, underscoring its relevance in sustainable management strategies. Additionally, soil chemical properties, such as phosphorus and aluminium content, can influence the efficiency of these systems as carbon sinks [21].

Finally, integrating local knowledge is key to the sustainable management of soil carbon in the Upper Amazon. Smallholder farmers' practices, such as fallow land management, crop rotation, and tree incorporation in agricultural systems, have proven essential for maintaining soil fertility and reducing erosion. The perception of soil as part of the forest ecosystem has fostered strategies adapted to local conditions, promoting the resilience of productive systems to climate change and environmental degradation [22].

4. Sustainable biomass management: Strategies and policies for environmental conservation

Agricultural and forest biomass plays a crucial role in environmental sustainability by contributing to carbon storage, soil conservation, and the regulation of the hydrological cycle. Its proper management not only mitigates the effects of climate change but also enhances ecosystem resilience and agricultural productivity. To optimise these benefits, it is essential to implement sustainable management strategies supported by public policies that ensure its conservation and efficient use.

4.1 Strategies for sustainable biomass management

4.1.1 Sustainable crop management

The adoption of agricultural practices that optimise productivity and soil health is essential for the sustainability of farming systems. Research conducted in the Cumbaza River sub-basin, in the provinces of Lamas and San Martín, as well as in the district of Cuñumbuque, has shown that arbuscular mycorrhizal fungi are a crucial component of the soil in degraded areas [23, 24]. Moreover, their combination with plant growth-promoting bacteria and nitrogen-fixing legumes has proven to be an effective strategy for the restoration of degraded pastures, particularly through agro-silvopastoral management [8, 25].

4.1.2 Expansion of forested areas and conservation of forest cover

Reforestation and ecosystem conservation through the use of cover legumes and phosphate-solubilising bacteria significantly contribute to carbon sequestration, promoting soil resilience and the restoration of degraded landscapes [26, 27]. These practices, in addition to mitigating climate change, enhance soil fertility by increasing the availability of essential nutrients for plant growth. In this context, the implementation of conservation strategies is crucial to ensuring the stability of forest ecosystems and maintaining the ecosystem services they provide. To this end, Peru's regulatory framework, through Law No. 29763, the Forestry and Wildlife Law, establishes that at least 30% of rural areas with forest cover must remain intact, thereby safeguarding ecological functionality and preserving biodiversity within these ecosystems [28].

4.1.3 Soil management and erosion control

In the high jungle or Yunga and Andean regions, erosion control is a priority to prevent soil degradation and the loss of fertility. The rugged topography and intense rainfall characteristic of these ecosystems increase the risk of water erosion, affecting soil stability and the availability of essential nutrients for vegetation. Studies on soil erosion estimation using the RUSLE model in the mid-upper Mira River basin in the Ecuadorian Andes have shown that water erosion is strongly influenced by slope gradient, vegetation cover, and soil management practices [29], which are also key factors in the high jungle and Andean regions of Peru.

The implementation of conservation practices such as terraces, live and dead barriers, and vegetative ground cover has proven effective in reducing runoff and retaining sediments, contributing to the restoration of these fragile soils [30]. The Regulations of the Forestry and Wildlife Law (Supreme Decree No. 018-2015-MINAGRI) mandate the implementation of conservation strategies to ensure soil stability and the sustainability of agroecological systems in the high jungle. In this context, the incorporation of species adapted to the edaphoclimatic conditions of this region, such as *Erythrina poeppigiana, Centrocema macrocarpum, Guazuma crinita,* and *Calycophyllum spruceanum,* has been shown to be an effective strategy for improving soil structure and mitigating erosion in the long term [25].

4.1.4 Improvement of rice cultivation

The integration of agroecological practices in strategic crops such as rice, maize, and beans enhances agricultural sustainability by optimising resource use, reducing emissions, and strengthening biodiversity. The afforestation of field edges in rice paddies contributes to soil conservation, regulates the microclimate, and expands available habitats. The use of biofertilisers based on plant growth-promoting bacteria increases nutrient uptake efficiency and crop yields [31–33], while also improving soil quality and enhancing the resilience of agricultural systems against abiotic and biotic stresses [34], promoting more sustainable production.

4.1.5 Optimisation of banana cultivation

In the Amazon, banana cultivation (*Musa* spp.) is essential for food security and the local economy, but its productivity is compromised by soil degradation and loss of fertility. In Espírito Santo, Brazil, the impacts of organic conilon coffee cultivation in association with different tree species and bananas on the carbon balance were evaluated. Conilon coffee in agroforestry systems reduced soil temperature (5.52%), increased moisture (17%), and improved the carbon balance, particularly with *Gliricidia* and *Inga* (4.70 and 3.56 Mg ha^{-1}). Additionally, it increased soil carbon and nitrogen, enhancing soil quality and agricultural sustainability [35].

Furthermore, the application of organic fertilisers, such as compost and beneficial microorganisms, optimises soil structure and nutrient absorption [36]. Good agricultural practices are essential for ensuring food safety, and protecting both human health and the environment. Practices such as selective pruning and crop residue management help regulate soil moisture, reduce pests, and minimise agrochemical use. In this context, SENASA establishes guidelines and recommendations for their implementation in primary production, ensuring safe food for consumers [37].

4.1.6 Sustainable pasture management

In the Peruvian Amazon, 70% of deforested forests are allocated to grazing, leading to soil degradation. Silvopastoral systems offer a sustainable alternative by integrating native trees with livestock farming, promoting biodiversity and improving soil quality, thereby contributing to ecological stability and productivity [38]. In San Martín, an evaluation of soil microbiological indicators in an agroforestry system revealed that treatments with beneficial microorganisms and agroforestry components increased microbial biomass, basal respiration, and enzymatic activity, highlighting their potential for soil conservation and sustainable management in grazing areas [25].

Meanwhile, in Puerto Bermúdez, Oxapampa, the establishment of forage grasses and legumes was assessed, identifying *Andropogon gayanus* and *Brachiaria dictyoneura* as the most outstanding grasses, while *Stylosanthes guianensis* exhibited the best performance among the legumes. Soil acidity negatively affected the legumes, suggesting the need for fertilisation strategies to optimise their growth [39]. These findings underscore the importance of sustainable pasture management in enhancing forage productivity without compromising soil health.

4.1.7 Diversified agroforestry systems

Diversified agroforestry systems in the Peruvian Amazon represent a key strategy for the sustainability of agroecosystems by integrating production and conservation. The diversity of cultivated species directly influences economic, ecological, and sociocultural stability, fostering more resilient and productive systems. Greater diversity leads to a stronger positive impact on agroecosystem sustainability [40].

Cocoa agroforestry systems in San Martín store carbon, with higher reserves in 12- and 20-year-old systems (>40 t C ha^{-1}). Five-year-old systems have lower carbon accumulation but higher annual flux, generating economic benefits through CO_2 credits, thereby contributing to climate change mitigation [16]. Similarly, silvopastoral systems in the high jungle combine productivity with carbon sequestration, with soil serving as the primary carbon reservoir. Notably, the system with *Cedrelinga* *cateniformis* (Tornillo) exhibited the highest carbon stocks, highlighting the crucial role of these systems in environmental sustainability and carbon capture [21].

Promoting these systems requires technical assistance, economic incentives, and applied research to optimise their impact.

4.1.8 Efficient use of agricultural and forestry residues

The Amazon, a key ecosystem for biodiversity and climate regulation, faces growing challenges due to the consumption of non-renewable energy and its environmental impacts. The efficient management of agricultural and forestry residues emerges as a fundamental strategy to mitigate these effects, promoting sustainable practices that contribute to conservation and ecological balance [41]. In this context, the valorisation of agricultural residues through processes such as pyrolysis enables the conversion of by-products, such as coffee husks, into biochar. This practice not only reduces environmental pollution and improves soil fertility but can also generate new sources of income through carbon sequestration and the replacement of fossil fuels [42].

Similarly, in Juan Guerra, San Martín, nitrogen fertilisation and green manures in rice cultivation were evaluated. *Canavalia ensiformis* reduced diseased tillers (2.82%), while *Crotalaria juncea* improved panicle fertility (91.88%). No significant differences in yield were observed, but CanE-FN100 achieved 8.36 t/ha. The nutritional quality of the rice remained unchanged [43]. Efficient management of agricultural and forestry residues enhances sustainability, soil fertility, and disease control in crops. Its implementation requires research, appropriate policies, and community participation to maximise environmental and economic benefits in the Amazon.

4.1.9 Biological cont3rol of pests and diseases

Biological control in Latin America is gaining importance due to its impact on sustainable agriculture. It reduces the use of agrochemicals, conserves natural resources, and creates market and employment opportunities. To maximise its benefits, greater interaction among key stakeholders and multidisciplinary studies are required [44]. In the Upper Amazon, the use of beneficial microorganisms and natural extracts has proven to be an effective strategy in crops such as cacao (*Theobroma cacao*), rice (*Oryza sativa*), and coffee (*Coffea arabica*) [45–47]. Control strategies based on knowledge of insects, coffee, and their environment are sustainable, innovative, and do not require insecticides, with potential applications in other coffee-producing countries [48].

4.2 Public policies for biomass sustainability

4.2.1 Conservation of riparian buffer strips

Riparian buffer strips are bands of land adjacent to water bodies that are essential for protecting aquatic ecosystems and maintaining soil stability. These areas act as natural filters, retaining sediments and pollutants from agricultural, livestock, and urban activities, thereby minimising their impact on aquatic ecosystems [49].

From a legal perspective, Law No. 29338, the Water Resources Law, establishes the need to conserve these zones to ensure the sustainable use of water and prevent the degradation of water resources [50]. According to this regulation, riparian buffer strips must be kept free from activities that could alter their ecological function, such as deforestation, unplanned infrastructure construction, or agricultural expansion without mitigation measures.

Various studies have shown that conserving these strips contributes to regulating river flow, preventing floods, and reducing the risk of flooding in vulnerable areas [51].

4.2.2 Rainwater harvesting

The efficient collection and storage of rainwater is a crucial strategy for mitigating water shortages in various regions. The Water Resources Law (Law No. 29338) promotes the construction of infrastructure such as infiltration ditches and reservoirs to optimise water resource use [52].

A notable example of this practice is the ancestral water harvesting system implemented in the high Andean community of Huamantanga (Lima, Peru), where *amunas*, infiltration channels designed to capture rainwater and recharge aquifers, are used. A study by Ochoa-Tocachi et al. [53] found that this technique increases water availability by up to 33% during the dry season, benefiting both agriculture and human consumption.

In Ecuador, water sowing and harvesting have also been established as a sustainable water management strategy. Herrera-Franco et al. [54] analysed its impact in the Manglaralto community, where its implementation has improved access to drinking water and strengthened climate resilience. This approach, aligned with the Sustainable Development Goals, highlights the importance of recovering and adapting ancestral knowledge to address current challenges related to climate change and water scarcity.

4.2.3 Regulation of agrochemical use

The use of agrochemicals in agriculture has been essential for pest control and increasing productivity. However, their indiscriminate use can have negative impacts on human health and the environment. Therefore, the regulation of these inputs is crucial to ensuring safe and sustainable agricultural practices. In Peru, Supreme Decree No. 001-2015-MINAGRI regulates the use and commercialisation of pesticides, while the General Environmental Law No. 28611 establishes principles for the prevention and control of chemical substances in agriculture [55].

5. Conclusions

The sustainable management of biomass in the Upper Amazon is essential for ecosystem conservation and agricultural productivity. Agroecological practices such as sustainable crop management, the use of beneficial microorganisms, and the integration of agroforestry and silvopastoral systems enhance soil fertility, increase carbon sequestration, and mitigate the effects of climate change. The restoration of degraded landscapes through reforestation and the conservation of forest cover contribute to ecological stability and biodiversity, while proper soil management and erosion control ensure the sustainability of productive systems and the availability of water resources. Additionally, the efficient use of agricultural and forestry residues reduces pollution and strengthens biogeochemical cycles, while biological pest and disease control minimises the use of agrochemicals, promoting crop resilience. In this context, public policies aimed at biomass conservation—such as the regulation of agrochemical use, rainwater harvesting, and the protection of riparian buffer zones—are crucial for balancing agricultural production with environmental conservation. The integration of technical and regulatory strategies is therefore essential to ensure the sustainability of biomass in the Upper Amazon and its contribution to food security and climate change mitigation.

Conflict of interest

The authors declare no conflict of interest.

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