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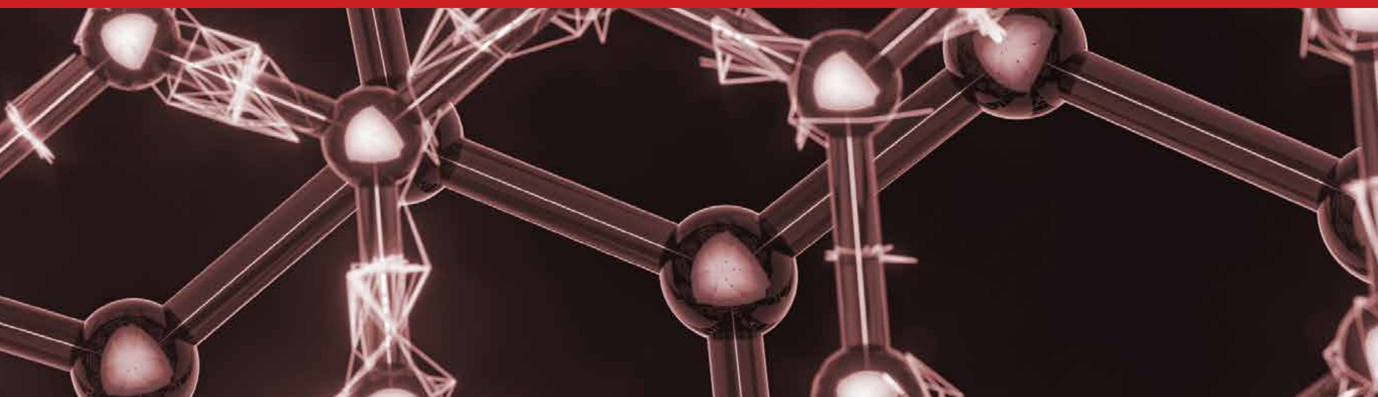
Environmental Sciences, Volume 35

Amazonia

From Pre-history to Future

Edited by Heimo Mikkola



Amazonia - From Pre-history to Future

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Aims and Scope of the Series

Scientists have long researched to understand the environment and man's place in it. The search for this knowledge grows in importance as rapid increases in population and economic development intensify humans' stresses on ecosystems. Fortunately, rapid increases in multiple scientific areas are advancing our understanding of environmental sciences. Breakthroughs in computing, molecular biology, ecology, and sustainability science are enhancing our ability to utilize environmental sciences to address real-world problems.

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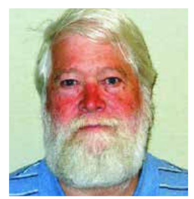
Meet the Series Editor



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Dr. Heimo Mikkola, Ph.D., is an Adjunct Professor of Zoology at Eastern Finland University. He had a major career as an 'Ambassador of Food' with the Food and Agriculture Organisation of the United Nations in Africa and South America. He has authored over 700 papers and books and was nominated as' Champion of Owls' in Houston, Minnesota, USA, in 2014. After retiring from the United Nations, he has edited 14 books for IntechOpen, London. This book is number 15 and the third on Amazonia.

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Preface

The Amazon rainforest has become a global priority in the face of climate change and biodiversity conservation. Old and planned new megaprojects threaten conservation efforts and the Indigenous communities' rights to manage their ancestral lands [1]. The interaction between human infrastructure and wildlife is a crucial aspect of biodiversity conservation.

The construction of new roads in the Amazon has been directly linked to deforestation through fires, illegal gold mining, logging, and unsustainable hunting. The devastating effects of road development are especially evident along the 2600-km interoceanic highway connecting Brazil to Peru [2]. A well-known and leading non-natural cause of wildlife mortality is collision with vehicles [3].

A new highway is now planned from Iquitos to San Antonio in Peru, along the Putumayo River, which marks the border with Colombia. Over a 100 km stretch of this highway would go through the Maijuna–Kichwa regional conservation area. The reasoning given for that new road is to encourage greater use of natural resources, facilitate increased tourism, reduce transportation costs, improve the quality of life of local people, and increase employment [1]. Indigenous communities affected by megadevelopment projects like this highway should have been engaged in prior consultation. Often, Indigenous people maintain several environmental values that are otherwise disappearing. Without Indigenous knowledge, a top-down approach to conservation actions and policies appears to be weak.

There is growing evidence that Amazonia is moving toward subregional biophysical tipping points, with expected forest diebacks and changes in the composition, structure, and functioning of terrestrial and aquatic ecosystems [4].

Furthermore, the most severe impacts of global climate change are affecting Indigenous communities and marginalized rural and urban Amazonians [5]. This has been particularly evident over the past two years, during the record droughts and burning seasons [6, 7], as well as in previous years of record flooding [8]. It is essential to empower indigenous youth to take the lead in addressing climate change matters, as they possess the unique ability to navigate between their local realities within traditional territories, understanding the struggles and local adaptations, as well as the complexities of modern societies worldwide [9, 10].

In this book, we have fresh data on past and present animals and plants in Amazonia. The significance of chemical prospecting in the Amazonian biodiversity and biomass dynamics in land uses. Modern and Indigenous knowledge in the use of medicinal plants are also well covered in the last two chapters. The protection of forest environment is a major challenge in the preservation of knowledge about the use of new and

old medicinal plants. Aquaculture development in Brazil has significant potential to reduce rainforest loss by providing a sustainable alternative to traditional livestock farming, which is a major driver of deforestation.

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Section 1

Introduction

Chapter 1

Introductory Chapter: Amazon News on Past and Present Fauna, Flora and Anthropology

Heimo Mikkola

Motto: "One hectare in the Peruvian Amazon has more species than Finland."

Dr Jukka Salo, Finnish Alto Mayo expert, email 22.12.2024

1. Introduction

Finns have always been eager to study the Amazon area. Reinhold Ferdinand Sahlberg (1811–1874), an entomologist, visited Brazil several times and collected tens of thousands of insects and almost 400 bird and mammal skins. After him, Auvo Pohjakallio and Kalervo Lahtivirta collected birds, insects, plants and reptiles in Brazil [1]. Emeritus Professor Rafael Karsten was a Finnish social anthropologist who studied the South American indigenous people during his six research travels from 1911 to 1947 [2]. Three of his many publications were [3–5]. Karsten was the first person to describe the indigenous processes of warfare and religion scientifically. This previous interest might explain why Finland supported the Biological Diversity project (Biodamaz) in the Amazon region of Peru from 1980 to 2010 [6]. In this project, the Finnish scientists, many from the University of Turku, and the Research Institute for the Peruvian Amazonia, IIAP, combined research aspects with socioeconomic enhancement efforts. So, research became a functional tool for human development needs in Peru [6]. Here, we concentrate on the ancient and latest biodiversity news in the Amazon region.

2. Past fauna

Isotopic palaeoecology studies have given new info on Pleistocene mammals from the Brazilian Amazon [7]. The species studied were *Neochoerus* sp., *Notiomastodon platensis*, *Eremotherium laurillardi*, *Trigodonops lopesi*, *Toxodon platensis*, *Palaeolama major*, *Tapirus* sp. and *Holmesina rondoniensis*.

Neochoerus, sometimes called 'new hog', is an extinct rodent closely related to the living capybara *Hydrochoerus hydrochaeris*. Capybara weighs 35–66 kg, while *Neochoerus* was c. 200 kg. It fed mainly on herbaceous plants in wooded savannas.

Notiomastodon platensis is related to modern elephants and weighed c. 6300 kg. Thus, it represents the largest animal in South America (**Figure 1**). Originally, it had a North American origin and crossed south after the formation of the Isthmus of Panama. Humans hunted *Notiomastodon*, which may have been a factor in its extinction.

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Figure 1.
Notiomastodon platensis *skull in Buenos Aires, Argentina. Creative commons photo.*

Laurillard's Ground Sloth, *Eremotherium laurillardi,* became extinct during the Late Pleistocene (126,000–11,700 years ago). It weighed c. 3500 kg and had a more generalised browser diet in closed canopies to woodlands.

Trigodonops lopesi weighed c. 1900 kg and foraged in wooded savannas. Its relative, *Toxodon platensis*, weighed c. 1800 kg. The first known fossil skull of this mysterious mammal was purchased by Darwin in Uruguay [8]. That skull started wild speculation, as Toxodon was said to be like a cross between the hippo (*Hippopotamus amphibius)*

Figure 2.
Toxodon platensis, a mystery mammal from the Pleistocene Epoch, South America. Unknown artist's work. Available from: https://www.britannica.com/animal/Toxodon/media/1/601253/138124.

and the black rhino (*Diceros bicornis)*, although not closely related to either (**Figure 2**). It was felt to be aquatic, like the dugong (*Dugong dugon)* and Amazonian manatee (*Trichechus inunguis)*, to which it is also allied. Now, it is nested in a separate group of extinct mammals, the Notoungulata [9]. Plant-eating *Toxodon* was the most common large-hoofed mammal during the Pleistocene Epoch in South America. Different feeding strategies obviously reduced the interspecific competition between these large mammals during the late Quaternary [7].

Palaeolama major, Cameliade, weighed c. 280 kg and lived in an open area, feeding on shrubs in the forest border. Ancient *Tapirus* sp. weighed c. 250 kg, and brocket deer *Mazama* sp. (c. 40 kg) were browsers in closed canopies to woodlands [7].

Holmesina rondoniensis weighed c. 227 kg and was a herbivore that grazed on coarse vegetation [6]. It was much larger than any modern giant armadillo, *Priodontes maximum*, which does not attain more than 54 kg [10].

3. Present fauna

The Alto Mayo Landscape covers about 780,700 hectares in Peru, where the Amazon rainforest meets the Andes Mountains [11]. It is the area for which the previously mentioned Biodamaz project created the biodiversity protection programme (Estrategia regional de biodiversidad de Amazonas), which is still implemented by the local authorities. Therefore, it was a great joy in Finland when the Conservation International team reported their findings in 2024 [11].

A research team studied the Alto Mayo region for 38 days in the summer of 2022 and identified over 2000 species, 49 of which were considered to be at risk of extinction. The team noted a lot of agriculture and land conversion going on in the area, heavily influenced by people. Despite that, they still managed to find and document 27 new species, including four mammals, eight fish, three amphibians and 10 butterflies, in addition to dozens of rare and endangered species, many not known from anywhere else in the world [11]. Many more species found are likely new but require further investigation. Some species are not adequately identified due to limited taxonomic information available. Quite advanced research technology was the collection of environmental eDNA from water samples of Alto Mayo. Through these samples, the presence of 261 vertebrate species was recorded, namely 44 fish, 25 amphibians, 69 birds and 78 mammals [11].

3.1 Reptiles and amphibians

The team found 27 amphibian species and 18 reptiles, including a climbing salamander, *Bolitoglossa* sp. It was abundant in a small area of the Alto Mayo white sand forest, where it seems to stay in low vegetation and shrubs. Two new frog species were *Chiasmocleis* sp. and *Pristimantis* sp. Also, two new snake species were discovered, namely *Atractus* sp. and a subterranean blind snake, *Epictia* sp. One of the most dangerous snakes in the area is a fer-de-lance viper. Seven more reptile and amphibian species, potentially new to science, require additional work.

3.2 Fish

Nearly 30 study areas revealed 68 fish species, and eight were new to science. One excitement was a swamp eel belonging to the genus *Synbranchus*. It can breathe air and stay alive for long periods on land, allowing it to move between the water bodies

and survive droughts. Among the fish, a bristlemouth armoured catfish was also new to science. It had a strange bulbous and squishy nose, and it was guessed that the fish was using that massive nose to sense prey hiding in the sandy riverbed. Many water basins were not studied, so the new fish species are still waiting to be found.

3.3 Mammals

The team recorded 50 medium and large mammals (over 1 kg), 35 small non-flying mammals (less than 1 kg) and 45 species of flying bats.

From the bats, a new species was a short-tailed fruit bat, *Carolla* sp., and from small mammals, an amphibious mouse, *Daptomys* sp., that swims with webbed feet, was most interesting. A previously undescribed dwarf squirrel, *Microsciurus* sp., has to be mentioned. During the night, the team saw an arboreal opossum species in the moonlight, but unfortunately, only seven owls, my favourites, are mentioned in the report, and none of them is a rare or new species, as was hoped for [11].

3.4 Birds

Including the owls, the team recorded 536 species of birds. Rare birds were seen during the day, for instance, a Rufous-crested Coquette, *Lophornis delattrei* (**Figure 3**), which is a tiny hummingbird. Due to its small size (2.8 g) and population, it is a rare sight even within its native region.

Figure 3.
Rufous-crested Coquette Lophornis delattrei *in Manu National Park, Peru. Photo: Courtesy of Francesco Veronesi, Italy.*

3.5 Insects

The team concentrated only on butterflies and beetles. Some 218 species of butterflies were observed, including 10 new to science and maybe 24 more pending further identifications. In the local Awajún language, they are called wampishuk and are noted for their large wings and extreme colour variations.

The Awajún name for the dung beetles is toritos or carahuay, and the team found 70 species of these. Two of these *Scybalocanthon* species were previously unknown to science and 45 were undocumented in the region.

Finding these new species were stunning the research team, making it to plea for more sustainable practises in the use of the Alto Mayo Landscape. This could help species persistence in the face of climate change, habitat loss and other threats [11].

4. Flora news

The Rapid Assessment Program (RAP) documented nearly 1000 (out of Peru's 20,000) vascular plants in central Alto Mayo, listing 10 species as threatened with extinction. Three new species to science, namely *Ilex* sp., *Schefflera* sp. and *Stylogyne* sp., await further identification. It has been estimated that 30% of vascular plants remain to be discovered. The team was surprised to find such high plant diversity despite habitat fragmentation caused by anthropogenic activities. The Awajún people take care of many plants as an important source of medicines, building materials and food [11].

5. News also from human anthropology studies

Indigenous knowledge and oral histories of the use of native *Guadua* bamboo species have been studied in Southwestern Amazonia [12]. Results showed that bamboo had an important role in indigenous socio-cosmologies, land use, and resource conservation. Bamboo patches provide a safe place for animals, such as peccaries, armadillos, turtles, diverse birds, agouti, paca, deer, tortoises, the *Plecturocebus grovesi* monkey and the *Callithrix pygmaea* monkey. Also, jaguars, *Panthera onca*, use bamboo thickets as places to hide [12].

Indigenous peoples' ways of protecting bamboo from uncontrolled fire and deforestation and the overall respect of bamboo as a game animal protector and source of fertile lands have primarily contributed to indigenous ecological practices in the Amazon region. Bamboo was instrumental in constructing and developing the Earth Builders' culture [12].

Climate change hypotheses during the Amazonian Holocene often assume that the presence of ancient charcoal from forest fires indicates periods of drier climate in the past. These theories neglect the possibility that such charcoal may result from early human activities [13]. Excavations have produced new evidence of early Holocene human presence in the tropical forest region of Southwestern Amazonia. Hundreds of geoglyphs (geometrical earthworks) with an associated system of roads in the state of Acre, Brazil, challenge existing theories about pre-colonial human-environment interactions. New evidence of human-related ash and charcoal accumulation in Amazonia dates back to c. 10,000 years [13]. People who built geoglyph-type earthworks harvested and consumed wild and domesticated palm fruits, Brazilian nuts,

Bertholetia excelsa, and other identified species in the first millennium of the Common Era [14]. Plant domestication occurred in the pre-colonial Amazonia as complex and nonlinear activities of protecting, supporting and cultivating. This indigenous domestication had a long-lasting impact on Amazonian forest composition. Human and botanical interaction led to observable differences in Brazil nuts and some palm fruits compared to their ancestors [14]. The latest publication I have tells about the discovery of the Tumichucua archaeological site in Beni, Bolivia. That was a prominent part of a previously unknown ancient civilisation. It was building Amazonian geoglyphs and hundreds of ceremonial centres, including the roads, from 700 BC to 900 AD [15]. Surely, the future will bring us more fauna, flora and human-related news from Amazonia, which is largely terra incognita (unknown land).

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Section 2

Aquaculture, Biodiversity and Ecosystem Services

Chapter 2

Aquaculture Could Reduce the Rainforest Loss in Brazil

Heimo Mikkola

Abstract

Many countries in Latin America and the Caribbean are not exploiting their full potential in aquaculture. Brazil is used here as an example because it has the most significant amounts of surface freshwater in the world, and it is a country with a coastal extension of more than 8000 km in its territorial dimension. Brazil is the second-largest aquaculture producer in the region after Ecuador, and the production level has steadily increased, now nearly 0.8 million metric tons. Since 1997, the country's fish supply has experienced an average annual increase of 3.5%. In 2023, the country ranked 26th globally in fish consumption with 224,000 tons, with smaller countries like Japan, the Philippines, Thailand, and Vietnam surpassing it. The fish consumption per capita in Brazil is only 8 kg/year, a figure well below that recommended by the World Health Organization (WHO) and less than 40% of the world average. Then there is alarming news that many fish farmers in Brazil have abandoned the activity. Reasons for this situation are sought in this chapter, as well as some possible solutions. It is felt that further aquaculture development in Brazil has significant potential to reduce rainforest loss by providing a sustainable alternative to traditional livestock farming, which is a major driver of deforestation. Aquaculture could also save the endangered arapaima fish.

Keywords: aquaculture, cultured fish species, fish farmers, arapaima gigas, alternative fish feed

1. Introduction

After the Russian Federation, Canada, the United States of America, and China, Brazil is the world's fifth-largest country with a total area of 8.5 million km^2 [1]. The highest average annual precipitation (2205 mm) is observed in the Amazon region, which accounts for 74% of the internal surface water resources of Brazil [1]. The average internal renewable surface water has been estimated at 5660 km^3/year, the highest amount of surface freshwater resources in the world [1].

With a total length of about 6990 km, the Amazon is the planet's longest river, just before the Nile with 6850 km [2]. Amazon is deep and has the largest drainage area and water flow. It is navigable by ocean-going ships as far as Iquitos in Peru. Entirely within Brazil, the San Francisco River is the largest, flowing for over 1609 km northward before it turns eastward into the Atlantic. The last 277 km of the lower river is navigable by ocean steamers. The Paraná-Paraguay River system drains the

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southwestern portion of Minas Gerais. Brazil's two southernmost states are drained through the Uruguay River [1, 2].

Due to its natural climate conditions and its energy matrix, Brazil is one of the countries with the most potential for aquaculture. It has approximately 13% of the world's renewable freshwater [3, 4].

The conservation of the Amazon Rainforest should be a central focus of public policy across Amazonian countries, underpinning strategies for animal food production management [5]. Presently, extensive livestock farming has proven to be an unsustainable activity in the Brazilian Amazon, significantly contributing to deforestation and exacerbating biodiversity loss [6]. Aquaculture is a viable alternative to these challenges, offering higher economic returns per unit area and improved productivity. Therefore, it presents significant potential for the sustainable production of valuable animal protein in the region [7, 8].

2. Aquaculture

Aquaculture is an efficient way to produce food, offering the best potential to increase fish supplies in the long term. Other production systems, such as beef production, have a low economic return with relatively high investment compared to fish farming. Concerning other agribusiness sectors, aquaculture has the highest capacity to increase world food production [9, 10]. After Ecuador, Brazil is the second-largest aquaculture producer in the Amazon region (**Table 1**), and the production level has steadily increased, as shown in **Table 2**. It is foreseen that the increase will continue after 2022 at the same level, so the present annual aquaculture production must reach about 0.8 million metric tons.

Nile tilapia *Oreochromis niloticus* (**Figure 1**) is the most cultivated species in Brazil, and Common carp *Cyprinus carpio* (**Figure 2**) is the second, and third is Tambaqui *Colossoma macropomum* (**Figure 3**). Since 2010, carp aquaculture has declined, while Tambaqui production has increased. Farming of Tampaqui hybrids has grown considerably, namely Tampaqui and Pacú hybrids. One very popular is a hybrid between female Tambaqui and male Red Pacú, locally called Pirapitinga, *Piaractus brachypomus* (**Figure 4**), which is named Tambatinga, Tamba from mother and Tinga from father. Red Pacú crosses also with other pacú species like Paraná River Pacú *Piaractus mesopotamicus.*

Country/Year.	2020	2021	2022	Difference +/−
Bolivia	3720	3853	3853	+ 133
Brazil	630,200	650,356	690,000	+ 59,800
Colombia	179,351	192,521	204,942	+ 25,591
Ecuador	774,569	896,435	1,123,048	+ 348,479
Guyana	138	142	953	+ 815
Peru	143,830	150,818	140,931	– 2899
Suriname	37	40	45	+ 8
Venezuela	53,609	53,601	53,601	– 8
Latin America & Caribbean	3,780,917	3,848,605	4,260,571	+ 479,654

Table 1.
Aquaculture production trends in Brazil and nearby countries. Production in metric tons [11].

Year.	Production in metric tons
1997	87,879
2000	172,500
2007	290,000
2017	595,000
2020	630,200
2021	650,356
2022	690,000

Table 2.
Annual aquaculture production in Brazil (Sources: [11, 12]).

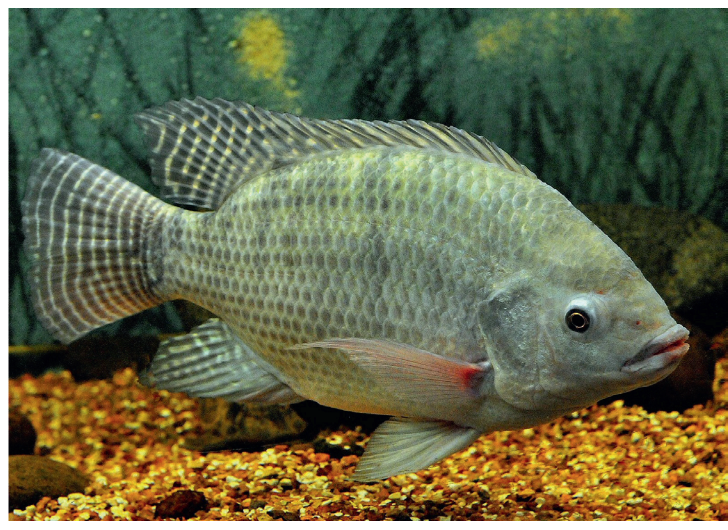

Figure 1.
Nile tilapia Oreochromis niloticus *is a well-adapted alien aquaculture fish in the Amazon Region. Photo: Germano Roberto Schüür/Wikimedia Commons.*

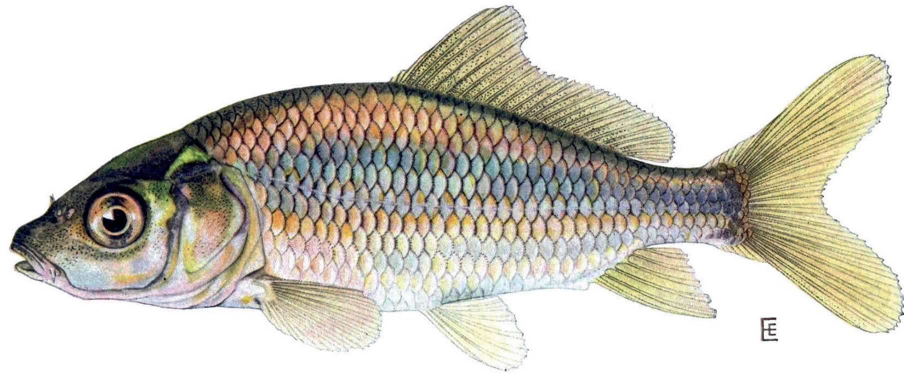

Figure 2.
Common carp Cyprinus carpio *by Ellen Edmondson/Wikimedia Commons.*

Figure 3.
Tambaqui Colossoma macropomum *is one of the most popular native fish species in the Amazon area for aquaculture. Photo: Wikimedia Commons.*

Figure 4.
Red Pacú Piaractus brachypomus *is a popular male fish to produce hybrids for aquaculture. Photo: Wisky/ Wikimedia Commons.*

Tiger catfish or in Brazil Sorubim Tigre of the genus *Pseudoplatystoma* (**Figure 5**) and its hybrids are also worth mentioning [13, 14]. Female Sorubim Tigre crossed with male Sailfin Pim *Leiarius marmoratus* is highly appreciated. That round catfish has no thorns in the fillet and its meat has excellent quality, firm texture, and light color [13, 15].

Arapaima is the largest scale fish in the world (length up to 3 m and weight 200 kg). It is a native teleost in the Amazon basin (**Figure 6**). The local name is Pirarucu in Brazil, Paiche in Peru and Ecuador. It is one of the most promising species for intensive aquaculture development in Brazil and the Region [16]. This enormous fish can fatten in farming over 1 kg per month, making it ready for slaughtering at 14–15 kg [17].

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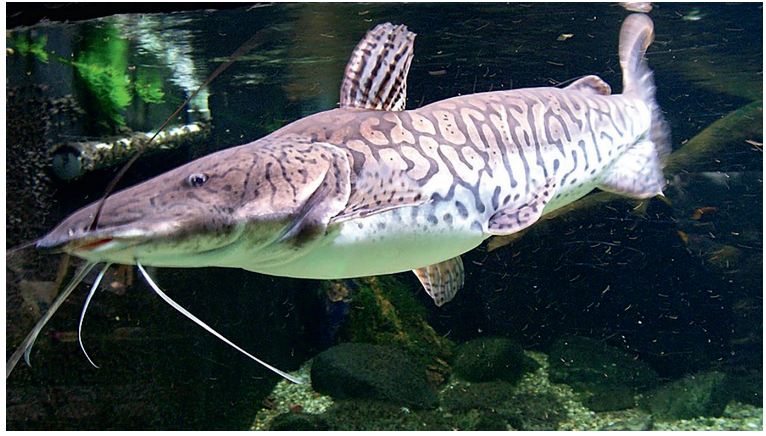

Figure 5.
Tiger catfish or Sorubim Tigre Pseudoplatystoma tigrinum *in Brazil is a very tasty fish. Photo: Floato/ Wikimedia Commons.*

Figure 6.
The largest-scale fish in the world—Pirarucu Arapaima gigas*. Photo: Nasser Halaweh/Wikimedia Commons.*

In 2017, aquaculture's contribution to total fish production was 46%, while marine shrimp culture's share was only 14%. The number of people engaged in aquaculture is not officially known, but it is estimated that the sector involves over 40,000 people [18].

The most promising market nationally and internationally is for the fish produced and originating from the Amazon region [19, 20].

Although the aquaculture production of Brazil is the second largest in the region after Ecuador, the average fish consumption figures of the country are proving that it is not exploiting its full potential. In 2022, human consumption took 89% of the global aquatic animal production. From that, it has been estimated that the average per capita fish consumption in the world was 20.7 kg [21]. **Table 3** shows that Brazil consumes fish less than 40% of the global average, and lags behind neighboring countries like Peru, Guyana, Suriname, Venezuela, and Colombia. It is relevant to highlight that the fish consumption in Brazil is only 8 kg/year/*per capita*, a figure well below that recommended by the World Health Organization (WHO), which states that the population should eat fish at least twice a week, the ideal *per capita* consumption being 12 kg/year [23]. Much higher fish consumption figures are known from the Amazon basin, varying between 15 and 80 kg/person/year, so for many indigenous people, fish is an important food security component [24].

Country	Consumption	Year
Bolivia	2.7	2021
Brazil	8.0	2021
Colombia	8.8	2021
Ecuador	6.5	2021
Guyana	25.4	2021
Peru	26.5	2021
Suriname	17.1	2021
Venezuela	10.3	2021
The World	20.7	2022

Table 3.
*Average fish consumption of the Amazon basin countries in kg/year/*per capita*. Sources of information [21, 22].*

Fish consumption can play a role in ensuring food security, as fish is a highly nutritious source of protein, vitamins, and minerals. However, it remains a challenge not to cause negative impacts on natural ecosystems when trying to meet the growing demand for fishery resources. Aquaculture is fulfilling the protein supply needs, because its growth has exceeded that of other animal protein industries. Aquaculture already represents 51% of the world's total fish production, partly because the share of capture fisheries has declined at the same time [21].

China, Indonesia, India, Vietnam, Bangladesh, the Philippines, the Republic of Korea, Norway, Egypt, and Chile are producing 89.8% of the world's total [21]. Due to its natural resources, Brazil should have been within the top ten, but its national production has remained inferior to that of major global producers.

3. Huge potential, but several producers are abandoning the activity. Why?

Lately, Aquaculture Review published alarming news that many fish farmers in Vigia in the northeastern region of Pará have decided to abandon their fish farms [25]. This is not good for the country's need to develop this activity. The research identified a total of thirty fish farming enterprises, out of which eleven were presently declared inactive, but having been operational between the years 2005 and 2021. Around 55% of fish farmers were between 51 and 60 years old. Their education was very low because none of them had completed elementary school. Of the producers, 82% had been fish farmers for over 5 years, and 73% had decided to give up the activity in the last 3 years. Often seen as a relatively recent activity for most producers, fish farming has been practiced for 15 years in Vigia. Despite all that time, many farmers felt inexperienced in this activity. However, gradually, they were acquiring knowledge to develop fish farming. For all of them, it was a valuable source of subsistence, supplementing family income. None of the farmers had aquaculture as their only source of income, which characterizes the activity as complementary and secondary [25]. In the southeast of Pará, the situation is very different, as 75% of fish farmers earn their income from fish farming [26].

Regarding cultivation structures, fish farming in the interview area in Vigia does not differ from the rest of the state. Most farmers use excavated ponds in their

small- to medium-scale production and rely only on family labour. Therefore, the fish farming facilities are rustic, as the producers have designed and built those themselves. The producers have had limited financial resources to hire outside help or technical support [25].

Limited technical skills, lack of funds for production expansion and access to technical assistance services, high input costs, and the absence of government support were the main reasons to demotivate fish farmers so much that they decided to abandon the activity. The need for regular provision of technical assistance was highlighted, as well as the development of technological innovations and vocational courses. The adoption of these measures would help to train aquaculturists, helping the local communities to make a decisive contribution to food security and generate occupation, employment, and income for the local population [25].

Inactive local producers are eager to return to the activity if a new opportunity arises. However, returning integrated actions by government agencies will be of fundamental importance for the sector's development. Those who wish to return to the activity call for effective participation from the public sector to gain more support in their most demanding technical and fish farming production aspects. Public sector help could make this activity develop beyond a supporting role in rural areas and decisively contribute to food security. In addition, employment and job creation are crucial to increasing the local income. Therefore, the research team recommends integrated measures by addressing the difficulties faced by fish farmers [25].

The development of the aquaculture sector requires the following actions from authorities:

1. Free and high-quality technical assistance guiding and training producers in fish farming production techniques is awaited from EMATER/PA (Technical assistance and rural extension company of the State of Pará).

2. Aquaculture innovations in technology and product development, including production chain-related services, e.g. the design of low-cost feeds with alternative ingredients, should be the task of IFPA (Federal Institute of Education, Science, and Technology of Pará).

3. Regular entrepreneurship courses and business plan development, providing aquaculturists with knowledge enabling them to manage their business more professionally, should come from SEBRAE (Brazilian Service of Support for Micro and Small Enterprises).

4. The product sale promotion through periodic public events, such as live fish fairs, including required fish marketing infrastructure development, which is expected from the Municipal Secretariat of Fisheries and Rural Development.

Fish farmers in the region face significant difficulties in increasing fish biomass because they do not have access or money to buy a balanced feed supply with the correct nutritional value that meets the animals' needs. In addition, commercial feed forms the highest cost for aquaculture production, feed expenses can reach up to 70% of the total production costs [27]. Amazonas, Rondônia, and Roraima State fish farmers have similar feed costs problems [28].

4. Brazil should seek new solutions to feed the fish

African research serves one fish feed option, which Brazil could investigate and adapt to its feed needs. Traditional fish feeds depend on fishmeal and soybean meals and face economic and environmental challenges due to the high price of these meals. In response, black soldier fly larvae meal (hereafter BSFLM) has emerged as a promising, nutrient-dense alternative [29]. BSFLM consistently provides high-quality protein (30–48%), aligning with tilapia's requirements, and is rich in essential minerals and fatty acids. While its lipid content (26–28%) may require processing adjustments, the overall profile supports tilapia health and growth [29].

Nile tilapia (*Oreochromis niloticus*) has become one of the most farmed fish worldwide, being the cornerstone of global aquaculture, mainly due to its overall adaptability, fast growth rates, and resilience to various environmental and farming conditions. This species plays a role even in enhancing global food security [30].

Cage aquaculture offers a good solution for Nile tilapia production [31], especially in such regions where lakes, rivers, and reservoirs provide an ideal environment for supporting high-density fish farming. Cage culture is common, especially around large lakes, like Lake Victoria in Kenya, where most aquaculturists use this way to answer the increasing demand for tilapia [32]. The cage installation is easy and requires relatively low capital investment [33, 34]. Cages are also an efficient way to use space in natural water bodies, making them a practical choice for small- to large-scale fish farmers globally [35].

Even though Nile tilapia's performance in cages is only partly investigated, free water exchange is one of the key advantages of cage culture, which allows oxygen flow and the presence of natural nutrients simultaneously with free waste removal from the cages. Good quality and the natural water flow mimic the wild habitat of fish, potentially reducing stress and improving the growth rates [36]. Cages are also easy to monitor, making the management of stocking densities, feed ratio applications, and fish health follow-up less complicated [29].

The efficient breakdown and dispersion of organic waste are supported by the continuous water flow in cages. This is particularly important when using high-protein feeds like BSFLM. The natural environment provided by cages also allows tilapia to engage in natural feeding behaviors, potentially optimizing feed conversion rate. The natural foraging occurs in cages and complements BSFLM-based diets, as the fish have access to both supplementary feed and natural organisms living in the water, enhancing their overall growth performance and health.

Given the growing interest in sustainable feed alternatives, incorporating BSFLM into cage-based Nile tilapia farming holds promise for reducing reliance on conventional fish meal. At the same time, BSFLM feed maintains or even improves growth rates and feed efficiency. However, research is needed to further assess the specific impacts of BSFLM in cage aquaculture, particularly in terms of long-term fish health, water quality management, and economic viability [29].

Producing BSFLM in adequate volumes to warrant industrial processing will require funding and the building of large-scale insect-rearing facilities, including relevant automation technologies, and the establishment of efficient supply chains, which will have to meet the growing demand for sustainable aquafeed ingredients [29].

Involving research institutions, industry stakeholders, and governmental entities is crucial for advancing research and product development. Collaborative partnership should help to meet the most significant challenges related to regulatory compliance and market integration. Additional research is required to map the role of BSFLM

in diverse environmental contexts. Potential synergistic effects with other feed ingredients should be investigated, so that better nutrient absorption and overall feed performance can be enhanced. It is necessary to align the adoption of BSFLM with global sustainability objectives. It is imperative to focus on mitigating dependence on conventional feed sources and minimizing the environmental impacts of fish farming. BSFLM integration into aquaculture systems could have a role in promoting sustainable fish production intensification and additional food security while concurrently preserving the Amazon region rainforest.

5. Aquaculture should save *Arapaima gigas*

Arapaima, or in Brazil also pirarucu (= redfish due to the color of its scales), formed traditionally a significant portion of the diet of Amerindians living near larger bodies of water [37]. A commercial fishery for pirarucu started as early as the late eighteenth century to satisfy the demand for Bacalhau. Bacalhau (Portuguese) or Bacalao (Spanish) is salted and dried Cod *Gadus morhua* eating which can be traced back to the Dark Ages. They were Basque fishermen who created a market for Cod, especially in Catholic Europe. This high-quality and durable source of animal protein was consumed mainly on religious holidays [38]. Cod's prominence increased during the Portuguese and Spanish eras as a cheap protein given to the slave population working on the Caribbean and South American plantations [38]. Later, Pirarucu was found to be an excellent local substitute for Cod within the Amazon basin. It had firm, white, flaky, practically boneless, and nearly fat-free flesh, which was easy to salt and dry. Pirarucu was processed and then exported out of Brazilian processing centres in Manaus, Santarem, and Belém, the best-known processing centres in Brazil [37].

Ancient descriptions tell that between 1885 and 1893, 1282 tons of dry and salted Pirarucu were sold annually in Belém (a total of 11,540 tons) [39]. Similarly, between 1918 and 1924, some 968 tons/year (7 years total 6775 tons) were landed in the State of Amazonas, and between 1919 and 1921, 5729 tons (1920 tons/year) were landed in Belém alone [40]. Despite these high levels of exploitation, until the early 1960s, pirarucu appears to have been relatively abundant near the main Amazon region processing and export cities, such as Manaus in the State of Amazonas and Santarem and Belém in the State of Pará [41].

Only in the 1970s, did Pirarucu become increasingly rare, and in the 1980s, it was commercially extinct near larger Amazonian cities, and in some areas, it disappeared completely [42]. Stemming from its history of Portuguese colonization, there has been a misconception of the Amazon region that it has an overabundance of natural resources, characterized as inexhaustible regardless of human demand [43]. This led to substantial exploitation of the native fauna, causing severe population declines of several fish species, such as Pirarucu [44]. However, as early as 1975, the world community recognized the plight of *Arapaima gigas* and listed it as an Appendix II fish in CITES (Convention on International Trade in Endangered Species of Fauna and Flora). In the 1990s, aquaculture efforts started but were not halting the illegal fishing of that wanted species. Finally, in early 2001, the government of Brazil was forced to ban all Pirarucu fishing, except in the Mamirauá sustainable developmental reserve [37].

Large-scale exploitation of this native species of the Amazon started in protected areas [45, 46]. The development of industrial fish farming has been facing

technological challenges such as low reproduction control, high costs of fingerlings and feed, and susceptibility to diseases. However, the fact remains that the species has a lot of commercial potential due to its boneless, high-nutritional-value meat and the possibility of using its skin as high-quality leather.

Several studies have been conducted on Pirarucu's digestive physiology based on its feeding habits, and to determine its nutritional requirements during the different stages of development. Alternative ingredients to enhance feeding strategies need to be assessed. Also, their feeding patterns in the farming context need further research [47]. There are still gaps in information and a deficiency in various aspects of nutritional physiology, particularly in the formulation of efficient and balanced feed for this species.

National scientific research has aimed at structuring and developing the pirarucu chain, and the available literature demonstrates growing interest in pirarucu, particularly in studies focusing on biology and technology. Scientific production related to that fish is concentrated in Brazil, particularly in the Northern region [48].

Despite the national interest in pirarucu, a large part of these investigation results is often unknown to the international forum. To fully unlock the potential of this native species, it is crucial to foster global collaboration. Advanced computational methods have been developed due to the increasing number of scientific studies and the need to compile information efficiently to guide public policies and funding agencies. These methods enable data analysis from fundamental studies to guide private strategies and public policies [49]. Particularly important is to continue the genetic studies, which are promising in improving the reproduction and preservation of this prehistoric fish [50].

The most important fact remains—Pirarucu farming is profitable [51]. *Arapaima gigas* has had a profitable production performance in earth ponds, fish presented a weight gain of 11 kg in 390 days and production of 3266 kg/ha. Fingerlings and feed prices were the most expensive elements in the fish farming costs. However, the outcome was that this is a highly profitable business with relatively low investment. An incremental investment of US$3287 brought a profit of US$ 3977/cycle, giving a Net Present Value of US$ 22,149, and an Internal Rate of Return of 32% [48]. This would be one way to increase the income of small-scale producers and diversify their production.

6. Brazil has enormous potential in fish farming in its reservoirs

The total water reservoir and dam capacity in Brazil was estimated to be 700 km^3 in 2010 [52]. This figure includes all hydroelectric dams in the country, other dams bigger than 10 million m^3 in the Northeast, and valuable reservoirs for the water supply of municipalities. The most important dams in the Northeast are Castanhão (6.7 km^3), Eng. Armando Ribeiro Gonçalves (2.4 km^3), Orós (1.94 km^3), Pedra (1.64 km^3), Banabuiu (1.601 km^3), and Coremas-Mãe d'água (1.358 km^3) [52].

Many of the dams in Brazil are used for hydropower. In 2007, the installed capacity of the hydroelectric power stations was 76,757 MW, which is 76.5% of the total power installed capacity in Brazil [52]. The Itaipu power plant, the largest hydroelectric plant in the world (power production is 12,600 MW and dam capacity is 29 km^3 divided equally between Brazil and Paraguay), is located on the Paraná River on the Paraguay-Brazil frontier, not far from Iguaçu Falls. New hydroelectric power stations will be built in several already inventoried places, adding 107,307 MW of installed generating power

in the next few decades. The Brazilian hydroelectric potential is estimated at around 258,686 MW, of which only 21% is being exploited. There are eight hydroelectric dams with a total capacity more than 20 km^3: Castro Alves (92 km^3), 14 de Julho (55 km^3), Serra da Mesa (54 km^3), Tucuri I and II (50 km^3), Sobradinho (34 km^3), Furnas (23 km^3), Ilha Solteira (21 km^3), and Porto Primavera (Eng. Sergio Motta) (20 km^3).

No fish farming potential of these large dams is mapped, but recently, Potential Aquaculture Sites (PAS) for fish net cages in four hydroelectric reservoirs located in the Jamari River basin in the Western Brazilian Amazon (Rondônia State) were investigated [53]. The reservoirs included one of the Hydroelectric Power Plants (HPP Samuel) and three of the Small Hydroelectric Dams (SHDs Santa Cruz Monte Negro, Jamari, and Canaã).

Combined, these reservoirs offer an estimated fish production potential of up to 466.0 tons per year. To define sustainable aquaculture areas in these reservoirs, further studies on carrying capacity and hydrodynamic modeling of organic outputs are recommended. This research highlights an alternative for animal food production without contributing to deforestation of the Amazon Rainforest.

7. Discussion

Traditional livestock farming in the Amazon significantly contributes to deforestation and biodiversity loss. In contrast, aquaculture offers a more sustainable alternative with higher economic returns per unit area. By shifting to aquaculture, Brazil can reduce the pressure on its rainforests and promote biodiversity conservation. However, challenges such as low fish consumption *per capita* (8 kg/year) and the abandonment of fish farming by many farmers need to be addressed.

To fully realize the potential of aquaculture, Brazil needs to adopt sustainable practices, such as using alternative fish feeds and improving water management. Given the growing interest in sustainable feed alternatives, incorporating black soldier fly larvae meal into cage-based Nile tilapia farming holds promise for reducing reliance on conventional fish meal while maintaining or increasing fish growth rates and feed utilization efficiency.

Stronger public policies and support for the aquaculture industry can enhance its role in sustainable development and conservation efforts. It is essential to implement sustainable practices to mitigate the environmental impact of aquaculture, particularly on mangrove ecosystems affected by shrimp farming [54]. While aquaculture productivity rates far exceed those of extensive livestock farming—the predominant source of animal protein in the Brazilian Amazon—aquaculture policies must also emphasize anti-deforestation practices. In this regard, net-cage aquaculture in natural and artificial water bodies offers a sustainable approach to fish production, using non-forested areas such as lakes, rivers, and hydroelectric reservoirs.

Pirarucu stocks have declined drastically in the Brazilian Rivers after the construction of hydroelectric plants, which fishermen have pointed out as the main factor for the decline in the species' population. The lack of adequate fishing management in the country affects the economic well-being of rural communities dependent on fishing. Eventually, this could lead to the disappearance of traditional artisanal fisheries in some areas and consequent rural exodus. Fish farming projects could save the remaining pirarucu stocks as well as increase the income of small-scale aquaculturists and diversify their production. Sustainable fish farming could offer a solution to maintaining the genetic diversity of *Arapaima gigas* [55].

Additionally, continued investment in research and development can help address the challenges faced by the industry and promote innovative solutions. By focusing on sustainable aquaculture, Brazil can leverage its vast freshwater resources to produce food efficiently while conserving its valuable rainforest ecosystems. This approach not only supports environmental sustainability but also offers economic benefits, making it a viable strategy for the future.

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Chapter 3

The Significance of Chemical Prospecting in the Amazonian Biodiversity: Unveiling New Molecular, Pharmacological Entities, and Their Potential Applications in Agrochemistry, Pharma-Industry, and Green Chemistry – A Perspective from Ecuador

Juan Enrique Tacoronte Morales

Abstract

The potential of chemical prospecting in the Amazon, specifically for Ecuador, is assessed with some case studies from an applied green chemistry perspective, highlighting its relevance for discovering new molecular entities with potential pharmaceutical and agrochemical applications. The Amazon biodiversity is not only crucial for ecological balance but also constitutes a rich source of natural compounds and secondary metabolites used by indigenous communities for medicinal and ritual purposes. Chemical prospecting involves the systematic search (structural-functional) for new chemical compounds from natural sources, a critical step in drug discovery and agrochemical development. This process begins with the collection of animal samples, and their metabolomic evaluation, followed by the extraction and identification of bioactive compounds using analytical hyphenated (GC-MS, NMR-HPLC, etc.). These compounds are evaluated for their biological activity, including antimicrobial effects. The essay reports the analysis of defensive secretions of terrestrial invertebrates (Diplopoda) and the preliminary biological activity. However, chemical prospecting for biodiversity faces significant challenges, such as biodiversity conservation and ethical concerns related to intellectual property rights. It is essential to adopt sustainable and collaborative practices to ensure that Amazon's invaluable resources are preserved while unlocking new solutions to global challenges in health and agriculture.

Keywords: Amazonia biodiversity, chemical prospection, secondary metabolites, defensive secretions, Diplopoda, green chemistry, biological activity, Ecuador

1. Introduction

Chemical prospecting is the process of searching for new bioactive molecules in nature, particularly those with potential applications in pharmaceuticals, agrochemicals, and other industrial uses [1]. In the context of Amazonian biodiversity, this approach becomes a crucial tool for discovering chemical compounds that can address public health, sustainable agriculture, and environmental conservation challenges [2]. The Amazon rainforest, with its impressive biodiversity, is a treasure trove yet to be fully explored in terms of its capacity to offer new molecular entities. Natural pharmacology, sustainable agrochemistry, and green chemistry are complementary fields that promote the responsible exploitation of these natural resources to maximize their benefits without compromising environmental health. This essay explores the significance of chemical prospecting in Amazonian biodiversity (terrestrial invertebrate defensive secretions), highlighting its importance in discovering new molecular entities, its relevance to pharmacological development, its potential applications in pathogen control, and its alignment with green and environmental chemistry principles.

1.1 Amazon rainforest: A key resource for biodiversity and natural products

The Amazon rainforest, covering over 6 million square kilometers, is home to an extraordinary array of plant and animal species. With over 390 billion trees representing approximately 16,000 species, it hosts an exceptional level of biological diversity [3]. This biodiversity is not only crucial for global ecological balance but also offers invaluable natural compounds that have been historically used by indigenous communities for medicinal and ritual purposes. Plants, fungi, and animals in the Amazon produce a wide range of chemical compounds that protect them from pathogens, herbivores, and extreme environmental conditions. These compounds often exhibit potent biological activity, making them prime candidates for chemical prospecting [4].

1.2 Biodiversity as a source of bioactive compounds

Amazonian biodiversity is a goldmine for discovering novel bioactive compounds with therapeutic potential. These bioactive compounds can be classified into alkaloids, flavonoids, terpenoids, benzoquinonoids, and glycosides, which have demonstrated anti-inflammatory, antimicrobial, antiviral, and anticancer properties. However, much of the Amazon's chemical biodiversity remains unexplored, underscoring the importance of continued chemical prospecting efforts in the region. Natural products derived from Amazonian animals (edaphic invertebrates) have the potential to be developed into new drugs, agrochemicals, and other industrial materials [5].

1.3 Chemical prospecting in the Amazon: A discovery process

Chemical prospecting involves systematically searching for new chemical compounds in natural sources, followed by their structural elucidation and their

screening for potential biological activity. In the Amazon, this typically begins with the collection of animal samples from the rainforest. These samples are then analyzed to identify chemical entities with potential therapeutic or agrochemical applications [6].

1.4 Green chemistry in chemical prospecting

Green chemistry plays a crucial role in ensuring that chemical prospecting is conducted in an environmentally responsible manner. Green chemistry emphasizes the design of chemical products and processes that minimize the generation of hazardous substances and reduce the environmental impact of industrial processes. In Amazonian chemical prospecting, green chemistry promotes environmentally friendly extraction and synthetic methods that reduce the use of toxic chemicals and solvents. This alignment of green chemistry with chemical prospecting ensures that Amazon's resources are used efficiently and sustainably. By applying these principles, we can ensure that the natural resources of the Amazon are used responsibly, preserving the ecosystem while enabling the discovery of valuable bioactive compounds [7].

1.5 Environmental chemistry: Ensuring sustainable prospecting practices

Environmental chemistry focuses on understanding the behavior and impact of chemicals in the environment, guiding the sustainable use of natural resources. In Amazonian chemical prospecting, environmental chemistry principles help mitigate the ecological impact of harvesting natural compounds or secondary metabolites isolated from edaphic invertebrates. For example, sustainable non-invasive collection methods, such as defensive secretions, can help minimize the destruction of populations in ecosystems. Additionally, environmental chemistry ensures that any agrochemicals or pharmaceutical products derived from Amazonian compounds do not cause long-term environmental damage.

1.6 Pharmaceutical applications of Amazonian biodiversity

The Amazon rainforest has already contributed to several significant pharmaceutical discoveries, highlighting the immense potential of its biodiversity for drug development [8].

New molecular entities for drug development

1. *Anticancer agents*: Amazonian plants produce a variety of alkaloids, terpenoids, and other bioactive compounds with anticancer properties. For example, camptothecin extracted from *Camptotheca acuminata* has been developed into the chemotherapy drug Topotecan, used for treating ovarian cancer. Other compounds from plants, such as *Maytenus* species, exhibit anticancer activity by inhibiting the proliferation of cancer cells.

2. *Antimicrobial and antiviral compounds*: The Amazon is home to numerous plants, microorganisms, and animals that produce compounds with strong antimicrobial and antiviral activities. For example, berberine, found in several Amazonian plants, has broad-spectrum antibacterial and antifungal properties. Other compounds like curcumin from turmeric have demonstrated antiviral properties, particularly against herpes simplex virus.

3. *Anti-inflammatory and analgesic compounds*: Many Amazonian plants contain compounds that exhibit anti-inflammatory and pain-relieving properties, such as saponins, flavonoids, and terpenoids. These compounds could be developed into non-steroidal anti-inflammatory drugs (NSAIDs) or pain management medications, offering safer and more effective alternatives to traditional treatments.

1.7 Agrochemical applications: Harnessing Amazonian biodiversity for sustainable agriculture

In addition to pharmaceuticals, chemical prospecting in the Amazon has significant implications for agrochemicals. With the growing global demand for food and the challenges posed by pest resistance, the discovery of new agrochemicals is critical. Natural compounds from the Amazon can provide environmentally friendly alternatives to synthetic pesticides, herbicides, and fungicides, contributing to more sustainable agricultural practices [9].

1.7.1 Natural pesticides and herbicides

Many Amazonian plants produce compounds that naturally deter herbivores or inhibit the growth of competing plants. For example, pyrethrins, found in *Chrysanthemum* species, are already used as natural insecticides. Other Amazonian species may offer similar compounds, providing eco-friendly alternatives to traditional pesticides that are toxic to humans and wildlife. By discovering such compounds, we can develop safer agrochemicals that reduce environmental contamination and improve agricultural sustainability [10].

1.7.2 Plant growth regulators

Several Amazonian plants produce compounds that regulate plant growth by mimicking or modulating plant hormones such as auxins and gibberellins. These compounds can be used to enhance crop yields, promote faster growth, and improve resistance to environmental stressors. For example, gibberellic acid, which is derived from fungi in the Amazon, is already used commercially to improve fruit production in crops like grapes and rice [11].

1.8 Educational vision: Integrating green chemistry, biodiversity, and sustainability in education

Education plays a vital role in promoting the sustainable exploration of Amazonian biodiversity. Universities and research institutions should offer programs that integrate chemical prospecting with sustainability and green chemistry principles. By educating future generations of scientists about the importance of ethical and responsible bioprospecting, we can ensure that Amazon's resources are protected while benefiting from their potential applications in medicine and agriculture. Interdisciplinary programs that combine bioprospecting, pharmacology, agrochemistry, and green chemistry can foster a holistic understanding of how to balance innovation with sustainability. This knowledge can empower citizens, community members, and students to pursue careers that contribute to both scientific advancement and environmental conservation [12].

In this context, we will analyze a case of chemical prospecting of the Amazonian biodiversity of Ecuador, oriented to the search for biologically active secondary metabolites isolated from the defensive secretions of millipedes.

2. Biodiversity chemical prospection of the invertebrate edaphic fauna of the Amazon. Case study: Defensive secretions of millipedes

Millipedes, terrestrial arthropods belonging to the class Diplopoda, comprise approximately 12,000 described species [13] distributed across various eco-geographical zones worldwide, with an estimated diversity of 80,000 species [14]. Neotropical species, both continental and insular, are distinguished by their substantial size and comparatively understudied chemical ecology, particularly concerning allomones and defensive secretions. This contrasts with the extensive body of literature on Insecta and Arachnida [15].

Millipedes exhibit significant spatial biodiversity, thriving as epiphytobionts, troglobionts, edaphobionts, and generalist detritivores [16]. They play a crucial role in the organic evolution of soils and the transformation of detritus in tropical and temperate forests [17]. When threatened, these invertebrates respond by coiling into a protective spiral with the head oriented inward or by ejecting a defensive-repugnatorial secretion from repugnatorial glands located in the diplosegments (pleurotergites) of the body. This secretion is released through dorsolateral ozopores and acts as a repellent [18].

The chemical composition of millipede defensive secretions varies significantly depending on the family and species, displaying high specificity. These secretions are an extraordinary source of biologically active secondary metabolites, including esters, alkaloids, benzoquinones, fatty acids, cyano derivatives, unsaturated alcohols, and (E)-alkenals [19, 20]. Eco-chemotaxonomic studies of these compounds can facilitate the complex task of taxonomic identification of species and geographic subspecies in their natural habitats. Such studies also enhance our understanding of the chemical-behavioral relationships and microevolutionary processes within the edaphic fauna of eastern Ecuador and other Neotropical regions [21]. Furthermore, they provide new "molecular" perspectives for the rational conservation of rare and/or endangered species.

Repugnatorial secretions may represent an ecologically sustainable source of biologically active secondary metabolites—novel structural and pharmacological entities with the potential for scaling and possessing microbicidal activity [22]. This study reports the preliminary investigation of the defensive secretion of the Rhinocricus sp. millipede, endemic to the Ecuadorian Amazon (Diplopoda, Spirobolida, Rhinocricidae). These millipedes inhabit the leaf litter of tropical forests in the eastern zone (Francisco de Orellana, El Coca, Palmar del Rio) of Ecuador and exhibit characteristic microbicidal activity.

3. Materials and methods

Individuals of this species reach an average length of 15–18 cm, a diameter of 1.4 cm, and an average weight of 20–28 grams. Adult specimens (10 individuals, **Figure 1a,b**) were manually collected at Empresa Palmar del Rio (00°19' S latitude and 77°04' W longitude) in El Coca, Francisco de Orellana, located 175 km east of Quito (voucher specimen 0001, Centro de Biología, Universidad Central del Ecuador, Tacoronte J.E., 2016).

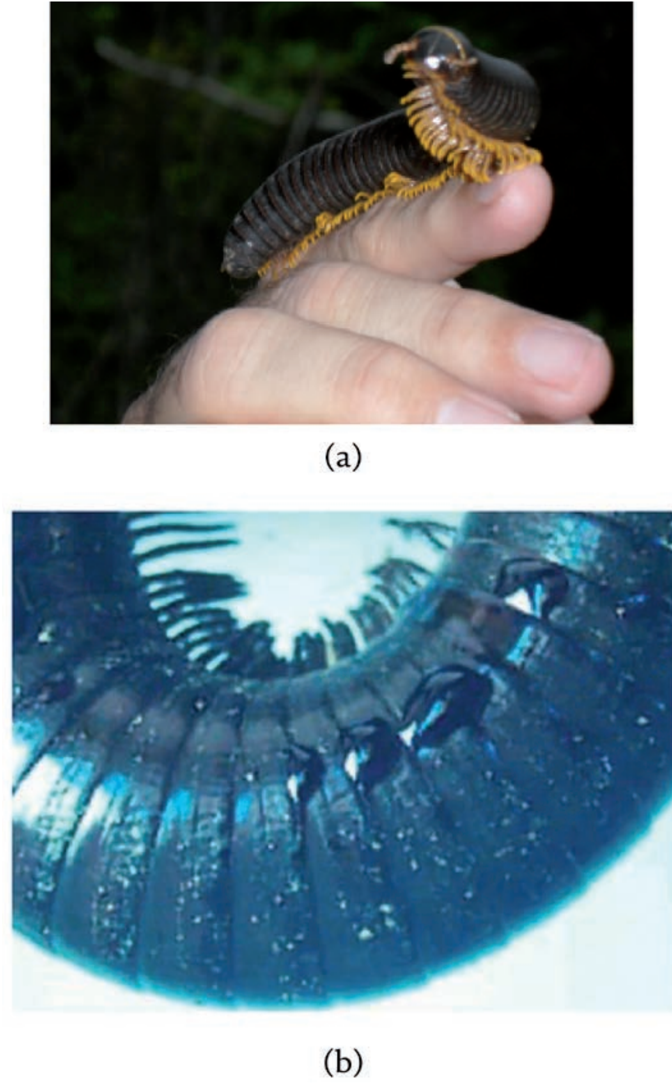

Figure 1.
(a) Ecuadorian endemic millipede, Rhinocricidae, genus Rhinocricus *sp. (b) Voucher specimen of millipede species* Rhinocricus *sp. with ejected defensive secretion.*

To obtain the defensive secretion—ejected from the ozopores located on the dorsolateral part of the body, characterized by a brown-yellowish coloration, irritant effect, and pungent "phenolic" odor—the individuals were stimulated by applying pressure to the posterior part of their bodies. The secretion obtained (approximately 600 μg per individual) was absorbed onto Whatman No. 4 filter paper and refrigerated at −4/−10°C. The filter paper was then extracted with cold diethyl ether (5 × 2 mL), and the extracts were concentrated under a stream of nitrogen gas before being used for subsequent analyses. After the disturbance and extraction of the repugnatorial secretion, the millipedes were released directly back into their collection area. Contact of the secretion with the skin was avoided to minimize the risk of burns and allergic reactions [23].

FTIR spectra were recorded using a Philips Analytical PU 9600 spectrophotometer in the range of 450–4500 cm^{-1} using KBr pellets. ^1H and ^{13}C NMR spectra were acquired using a Bruker ACF-250 spectrometer at 25°C with 0.3 M solutions in $CDCl_3$. Chemical shifts (δ) were reported in ppm. Tetramethylsilane (TMS, δ = 0.0 ppm) was used as an internal reference for ^1H NMR spectra, and the central peak of $CDCl_3$ at 77.03 ppm was used for ^{13}C NMR spectra. All chemical reagents were purchased from recognized suppliers (Merck Germany, Quito, Ecuador), and their purity was assessed using gas chromatography (GC) and FTIR.

For Gas Chromatography Coupled to Mass Spectrometry (GC-MS) analysis, a Hewlett-Packard 6890 gas chromatograph (Palo Alto, CA, USA) with a 5973 quadrupole detection system (GC-MS) was used. The separations were carried out through a capillary column of Ultra 2 type (J & W Scientific, Folsom, CA, USA), 12 m long and 0.22 mm in internal diameter. As a carrier gas, He was used at a flow of 1 mL/min. Temperature ramp: 60°C with increments of 10°C/min up to 300°C (isothermal 5 min.). Run time: 30 min. Injection volume 2 μL at a temperature of 280°C, in split mode (1:10 ratio). The ionization source was IE at 70 eV operating at 230°C. Acquisition mode: Full Scan. Range of m/e 40–700.

The following databases were used for structural characterization: NIST98 (National Institute of Standards and Technology, Gaithersburg, MD, USA), PMW_TOX2 (Wiley Library and Pfleger Maurer Weber (PMW), National Metrology Institute of Japan (NMIJ, Tokyo, Japan), and National Institute of Advanced Industrial Science and Technology (AIST, Tokyo, Japan). In addition, the databases that report the chemical composition of the invertebrate defensive secretions (https://www.pherobase.com, accessed 16 October 2020) and their GC-MS (libraries for

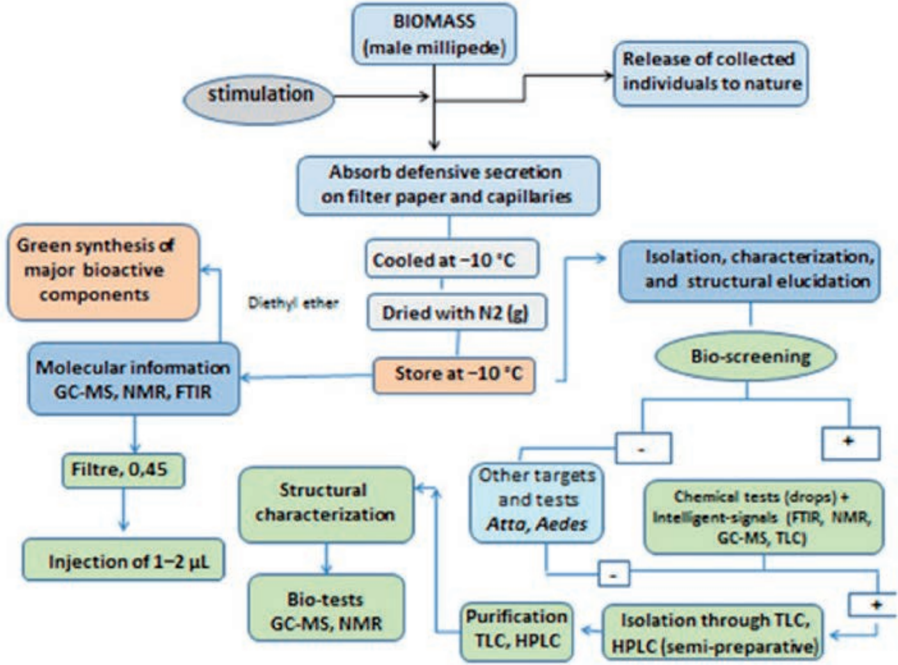

Figure 2.
General analytical methodology for defensive secretions of millipedes.

the rapid identification of metabolites in complex biological samples, Max-Planck Institute of Plant Molecular Physiology, Postdam, Germany) were considered. Using the reported sources and m/e data from the GC-MS, the most likely structures and their fragmentation mechanisms are postulated. Identification of the components was based on a comparison of GC retention data and mass spectra. Each component was quantified using n-hexadecane as an internal standard (**Figure 2**).

The disc diffusion method [24] was used for the microbicidal activity assay. The defensive secretion solution (0.5–100–1000 μg/mL) was added to filter paper discs (5 mm diameter), which were then placed on Petri dishes containing nutrient agar (Mueller-Hinton Agar-H_2O 0.8%). The inoculum of the fungal and bacterial species to be analyzed was aseptically added to the opposite end of the disc. The plates were incubated for 72 h at 37°C, and the minimum inhibitory concentrations (MICs) were calculated. Chloramphenicol (30 μg) was used as a positive control, and ethyl acetate was used as a negative control. The susceptibility of the microorganisms to the defensive secretion was determined by the formation of an inhibition zone after 18 h of incubation at 36°C.

4. Results and discussion

The application of the eco-sustainable methodology outlined in **Figure 2** facilitates a chemical-ecological approach to bioprospecting, positioning biodiversity as a strategic resource for the isolation and generation of high-value secondary metabolites and derivatives. The initial analytical study of this secretion, using the rhodanine test in aqueous ammonia [25] and the KI test, suggested the presence of para-quinones. This was corroborated by the observation of a blue-violet coloration when treating the ethereal solution of the defensive secretion with ethyl cyanoacetate/ammonia [26]. Di-, tri-, and tetra-alkyl or alkylmethoxy-substituted para-quinones have been previously reported as defensive substances in other diplopod species [27], causing severe allergic and toxic effects on ocular mucous membranes and the epidermis, as well as exhibiting microbicidal effects.

The ethereal solution (10 mL) was percolated through a column of calcium phosphate ($CaHPO_4$ impregnated with 2% $AgNO_3$ via a wet method, 30 cm length x 1.0 cm diameter), using a mixture of n-hexane/ethyl acetate 85:15 v/v (100 mL) as the solvent. The resulting eluates (110 mL) were analyzed by thin-layer chromatography (TLC) using both silica gel-polyester plates with a UV detector (5 × 5 cm, run time 15 min) and silica gel-calcium phosphate plates on glass, activated with fluorescein at 254 nm (2 × 5 cm, run time 30 min). A compound with Rf 0.5 was detected using n-hexane/ethyl acetate 50:50 v/v as the eluent and ammonia as the chromogenic agent. Similar results (Rf 0.47) were obtained using TLC plates with silica gel G impregnated with a 3% aqueous solution of oxalic acid and eluting with benzene-ethyl acetate (10,2 v/v). The oily residue obtained, dark brown in color, was subjected to spectrophotometric analysis.

Analysis of the FTIR spectrum (**Figure 3**) revealed intense bands at 1660–1580 cm^{-1} ($\nu C{=}O$ 1654 and 1665 cm^{-1}, $\nu C{=}C$ 1587 cm^{-1}), attributable to substituted para-benzoquinones (1654 cm^{-1}). In the 1320–1100 cm^{-1} region, medium intensity bands (1313 cm^{-1}, 1196 cm^{-1}) were observed, corresponding to valence and deformation vibrations in the C−CO−C group. In the 1200–1020 cm^{-1} region, an intense band at 1108 cm^{-1} was distinguished, attributed to asymmetric valence vibrations of the C−O−C group, typical for ethers, as well as at 1013 cm^{-1}, corresponding to

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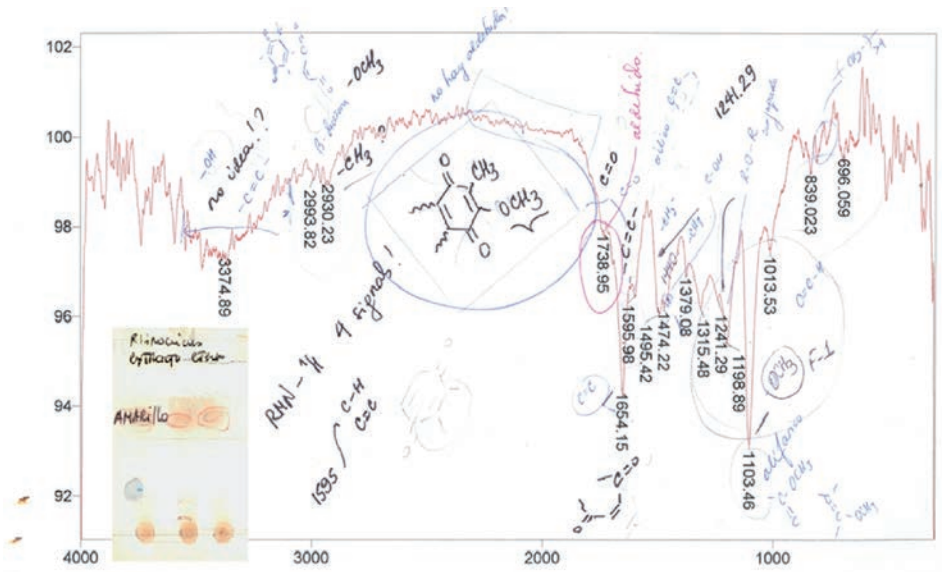

Figure 3.
FTIR Spectrum of major compound isolated from Rhinocricus *sp. defensive secretion.*

symmetric valence vibrations of the same. These observations were corroborated by the presence of bands at 2990 cm^{-1}, 2930 cm^{-1} (asymmetric valence vibrations of -OCH_3), and 1475 cm^{-1} (asymmetric and symmetric deformation vibrations of -OCH_3). A signal at 1380 cm^{-1} corresponded to symmetric deformation vibrations of –CH_3 (C-H), and at 2950 cm^{-1} to valence vibrations of the (CH_3−) group. These data suggest the presence of a di-substituted para-benzoquinone.

The ^1H and ^{13}C NMR spectra (**Figure 4a,b**) corroborate the proposed structure as a 2,3-disubstituted p-benzoquinone. For the 2,3-disubstituted p-benzoquinone derivative, four well-differentiated signals were observed in the ^1H NMR spectrum: a singlet at 1.87 ppm (3H), typical for methyl groups CH_3 (olefin-oxo-substituted molecular environment); a singlet at 3.92 ppm (3H), attributable to O−CH_3; a doublet at 6.53 ppm (1H); and a doublet at 6.75 ppm (1H), attributed to an α,β-conjugated dicarbonyl olefinic system, characteristic of 2,3-disubstituted benzoquinones. The ^{13}C NMR spectrum showed eight signals between 11.22 ppm and 188.34 ppm, corroborating the existence of the proposed cyclic α,β-unsaturated dicarbonyl system (see **Figure 1**): 188.34 ppm (C-1); 129.40 (C-2); 156.15 ppm (C-3); 175.52 ppm (C-4); 136.45 ppm (C-5); 137.85 ppm (C-6); 11.22 ppm (C-7); 59.48 ppm (C-8).

The proposed structure for the major component of the defensive secretion of the Ecuadorian millipede *Rhinocricus* sp., derived from Fourier-transform infrared (FTIR), preliminary GC-MS, and proton and carbon nuclear magnetic resonance (^1H/^{13}C NMR) spectroscopy analyses, is detailed in **Figure 5**. This natural benzoquinone has been described in spirobolid diplopod species from the mega-edaphofauna of the central-western zone of the Cuban archipelago, in the African continent for the genera Metiche and Archispirostreptus [28, 29].

Millipedes are known to biosynthesize phenolic compounds, organic acids, and terpenoids, which, within these multicomponent defensive mixtures, may exhibit potential antibacterial activity under natural conditions [30]. Antifungal activity has also been described for the repugnatorial secretions of certain millipede species

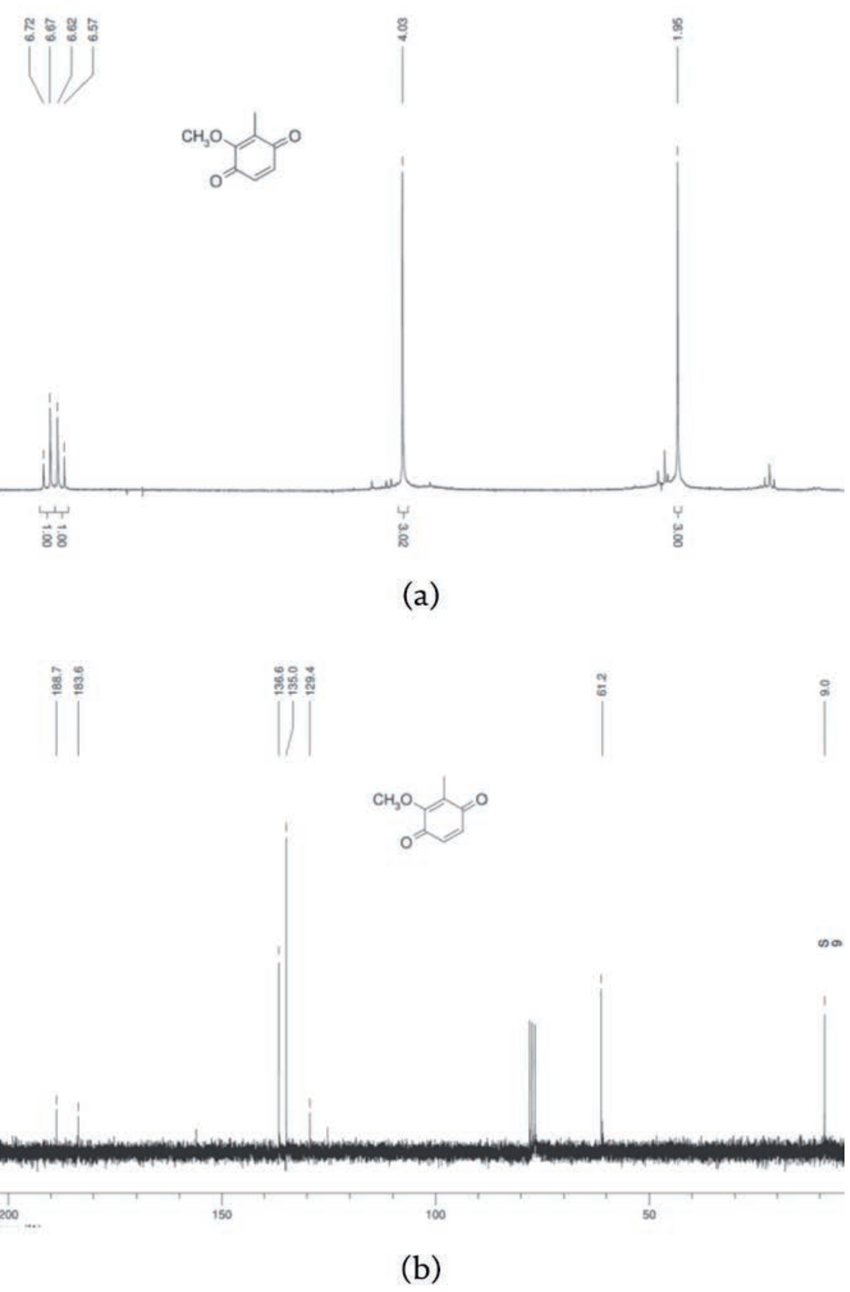

Figure 4.
(a) An NMR Spectra (1H and 13C, 250 MHz, deuterated chloroform) of the major compound from Rhinocricus *sp. defensive secretion. (b). ^{13}C-NMR Spectra (1H and 13C, 250 MHz, deuterated chloroform) of the major compound from* Rhinocricus *sp. defensive secretion.*

within the family Xystodesmidae [31]. Furthermore, millipedes have been utilized as active ingredients in traditional medicine, both in extract and powder form, for treating epidermal pathologies, fevers, and bone pain [32, 33].

The microbicidal activity observed for this defensive secretion of benzoquinonoid nature, against both Gram-positive and Gram-negative bacteria and fungi, is detailed

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Figure 5.
Structure of the derivative isolated from the defensive secretion of Rhinocricus *sp.: 2-methyl-3-methoxy-para-benzoquinone.*

in **Table 1**. Notably, the major methoxylated benzoquinonoid component exhibits strong microbicidal action against microorganisms such as Candida, Trichophyton, and Staphylococcus species. A preliminary explanation for the detected microbicidal biological activity of the defensive secretion from this Ecuadorian Amazonian endemic rhinocricid, considering the basic benzoquinonoid structure of the major component as a conjugated enedione-type 1,4-benzoquinone, involves the reversible formation of semiquinone anion radicals and variations in the coplanarity of the benzoquinone-substituent system [34].

The knowledge gained from studying the chemical composition and biological activity of these secretions has also highlighted the potential to design and scale up a formulation based on derivatives of this nature obtained through a sustainable synthetic route (green chemistry). This formulation could be used as a potential antifungal agent for veterinary or human applications, as well as extending its potential use as an agrochemical with lower harmfulness to the environment and biota compared to traditionally known and used pesticides.

Currently, studies on bioactivity, structure-activity relationship (SAR), and synthetic micro-scaling in eco-sustainable conditions (green chemistry) of this derivative are underway.

Pathogen	MCI (μg/mL)
Fosecae pedrosoi	60,0
Candida albicans	30,0
Microsporum gypeseum	78,0
Microsporus canis	56,3
Trycophytun metagraphyte	27,0
Epidermophyton flocossun	68,0
Trycophytum rubrum	44,0
Staphylococcus aureus	38,0
Escherichia coli	70,0

Table 1.
Minimum inhibitory concentration (MIC) of the defensive secretion containing the described major benzoquinonoid component.

5. Conclusions

Chemical prospecting in the Amazon rainforest represents an exciting frontier for discovering new bioactive compounds with potential applications in pharmaceuticals and agrochemicals. By integrating green chemistry and environmental chemistry, we can ensure that these discoveries are made sustainably, minimizing environmental impact while maximizing the benefits of Amazonian biodiversity. As we explore the rainforest's chemical riches, it is crucial to adopt sustainable practices that preserve the ecosystem and ensure that the benefits of these resources are accessible for generations to come. Moreover, integrating sustainability and green chemistry principles into education will empower future scientists to conduct responsible research, paving the way for innovations that support both human health and environmental preservation.

The preliminary study of the defensive secretion from the Ecuadorian endemic millipede *Rhinocricus* sp., one of the most significant millipedes due to its importance in the biomass of the endemic edaphic fauna of the Republic of Ecuador, reveals that it is predominantly composed of 2-methyl-3-methoxy-para-benzoquinone. This finding expands our knowledge of chemotaxonomy, chemical evolution, and the chemical ecology of these Ecuadorian terrestrial invertebrates.

The detected biological activity, typically antimicrobial, allows us to value these repugnatorial secretions as a potential source of bioactive structures for the sustainable development of new formulations for microbial growth control.

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Conflict of interest

The author declares no conflict of interest.

Notes/thanks/other declarations

All tables, figures, and schemes presented in this document are entirely the author's own work.

Adult specimens of the species under study were collected at Empresa Palmar del Rio (latitude 00°19' S and longitude 77°04' W), El Coca, Francisco de Orellana, 175 km east of Quito.

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Voucher specimens are located at the Centro de Biología, Universidad Central del Ecuador, Ciudadela Universitaria, Gato Sobral y Leyton, and at the Technical University of Esmeraldas, Ecuador (Dr. Tacoronte J.).

The analytical-compositional study of the defensive secretion and the evaluation of the biological activity were carried out in the dependencies of the Centro de Biología (microbiology lab) and in the dependencies of the Empresa Proinstra Analitika, Quito.

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Chapter 4

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

Winston Franz Ríos-Ruiz and Luis Alberto Ordóñez-Sánchez

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

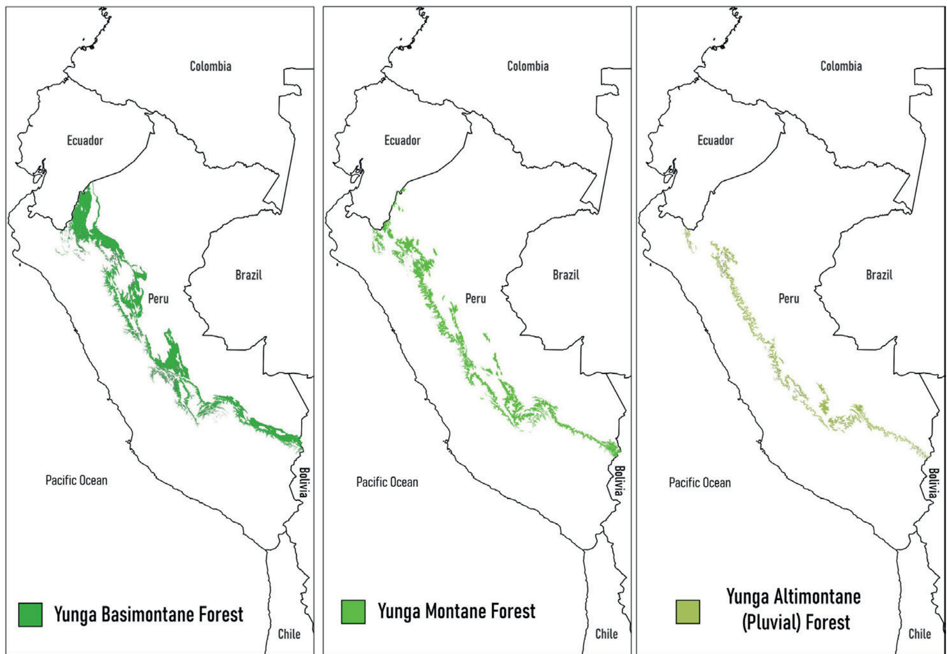

Figure 1.
Maps of Peru depicting the Upper Amazon, comprising the Yunga Basimontane Forest, the Yunga Montane Forest, and the Yunga Altimontane (Pluvial) Forest. (Modified from Ref. [5]).

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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Section 3

Validation and Use of Medicinal Plants

Chapter 5

Traditional Healing in the Amazon Region

Matea Stiperski Matoc, Zoran Stiperski and Tomica Hruška

Abstract

The biodiversity of the Amazon region is the source of a rich palette of traditional healing methods. Indigenous knowledge about the benefits of plants reflects the plant diversity and richness of the Amazonian environment. Traditional communities have developed extensive knowledge to treat their health problems, as they do not have access to modern medicine. Numerous plants have been shown to have pharmacological bioactivity and benefits. Copaiba oil is traditionally used as an anti-inflammatory agent to treat ulcers, scars and leishmaniasis. Terpenes have an antiparasitic effect. Traditional cultures have developed numerous therapeutic solutions for diseases. Magical-religious beliefs are an important part of the treatment of diseases. Treatment methods often include dietary nutrition, healing ceremonies and purification rituals. The spread of medicinal plants and treatment methods depends not only on geographical distribution but also on the cultural acceptance of local communities. The selection of certain medicinal plants by the local population is a complex interplay of culture, ecology and pharmacology. In the past, medical ethnobotanical clinical research has transferred various knowledge from traditional communities to laboratories and pharmacies.

Keywords: traditional healing, traditional cultures, plant diversity, medicinal plants, pharmacological bioactivity, medicinal ethnobotany, the Amazon

1. Introduction

In all developing countries, around 80% of the population use medicinal plants as their primary source of healthcare and sometimes as the only treatment available [1]. The remoteness and slow integration into modern life, as well as the added richness of biodiversity in the Amazon region, have opened up the possibility and need for traditional healing methods. Western medicine has slowly and gradually become established. Illness in the traditional sense is not only seen as a physical condition, but also as a mental imbalance, social conflict or environmental disharmony. Healing therefore involves physical medicines (plants), rituals, chants and the involvement of the community. Shamans are central figures. They act as healers, spiritual mediators and keepers of knowledge. They acquire their knowledge through apprenticeship. Hundreds of plant species are used for treatments, visionary diagnoses and spiritual healing. The knowledge of these plants includes preparation methods, dosage, synergistic combinations and spiritual application. Rituals often include chanting, drinking

psychedelics, smoking and invoking plant spirits. The ceremonies may deal with the causes of illnesses believed to be due to the intrusion of spirits, envy or the loss of the soul. The indigenous peoples of the Amazon do not distinguish between nature and the sacred. Plants, animals, rivers and landscapes have spiritual powers. Healing is often about maintaining or restoring harmony between humans and these non-human beings. Illnesses are interpreted within a cosmological framework: dreams, omens and shamanic visions influence the diagnosis. The healing practises are regionally specific and characterised by the local flora, cosmology and socio-cultural history of the individual indigenous groups. Traditional medical knowledge is passed on orally, through practices and through dreams or visions, often within the family or from elders to the younger generation. Deforestation, mining, missionary work and the dominance of Western medicine are threatening the survival of the traditional healing systems of many indigenous communities. Efforts are being made to integrate indigenous medicine into national healthcare systems, for example, in intercultural clinics in Peru or Brazil. There is a biomedical interest in the plants of the Amazon region.

2. A holistic view of health

Traditional medicine in the Amazon region emphasises a holistic approach. The holistic approach in traditional Amazonian medicine refers to an integrated healing system that views the body, mind, spirit and environment as interconnected. In this worldview, health is not simply the absence of disease, but a state of balance between the individual, the community, nature and the spiritual world. The indigenous peoples of the Amazon see themselves as part of the ecosystem, not separate from it. Western medicine is often seen as "healing the body," while traditional practices also include spiritual and social elements such as rituals or community healing gatherings [2]. Illnesses have physical symptoms that can have spiritual or emotional causes, such as envy, loss of soul or spiritual intruders. The Ese'eja, a tribe of hunters, fishers and gatherers in south-east Peru, perceive health and illness through a prism that combines physical, spiritual and social dimensions [3]. Plants are not seen as inert substances, but as spiritual beings with their own intelligence and personality. The forest is not just a pharmacy; it is a living, sacred being. Traditional healing systems help people to alleviate physical ailments, but also to establish a connection with their ancestors. Certain illnesses such as kankë (cancer) are attributed to spiritual causes, indicating a mixture of physical and metaphysical understanding of the causes of illness [4]. Disease can arise from social disharmony, and healing can involve restoring social balance, not just treating the individual. In Chazuta, medicinal plants are used as part of a traditional medicine that takes a holistic view of health and illness, combining the use of plants with lifestyle advice and spiritual practices [5]. In traditional Amazonian medicine, healing is an act of reconnection with oneself, the community, the land and the spiritual world. This holistic framework reflects a worldview in which health is sacred, relational and ecological.

3. Use of medicinal plants

Numerous studies have analysed the medicinal plants used in traditional medicine in the Amazon region. Their spatial distribution at a local level, the ratio of indigenous and exotic species, the importance of individual plant parts and the degree of frequent use for various ailments and diseases have been analysed. Ethnobotanical

inventories show that tribal pharmacopoeias often contain dozens, if not hundreds, of plant species with known medicinal value [6–10]. One hundred forty-five species of medicinal plants were found in the Sangay gardens in the Ecuadorian Amazon. Medicinal plants accounted for about 30% of the total number of plant species found in these gardens, which emphasises their importance for local health practices. A large proportion of the medicinal plants (64%) were indigenous species, while the remaining 36% were exotic, introduced species. The most commonly used plant parts for medicinal purposes were the leaves (53%), followed by the stems (13%), fruits (11%) and other parts such as roots and bark [11]. A study documented 197 species of medicinal plants used by communities in Imbituba, Santa Catarina, Brazil. A significant proportion (60%) of these plants are cultivated in home gardens, while 36.5% are harvested in the wild in local ecosystems such as sand dunes, forests and wetlands [12]. The abundance of medicinal plants in home gardens in the Ecuadorian Amazon is illustrated by a study in which 145 species of medicinal plants and 104 pharmacological properties were identified in 138 gardens [11].

The predominant habitats for medicinal plants are high forest, flooded forests, regenerating forests and seasonally flooded forests, in which 59% of medicinal plant species occur. Of all species, tree species are the most commonly used (47%). Medicinal plants are often cultivated in home gardens (37% of species) and are mainly used to treat paediatric or female diseases. Exotic species are used less frequently in traditional medicine; only 20% of all documented medicinal plants are exotic species [13]. The study recorded 945 reports on the medicinal use of 289 plant species collected in Chazuta in the Peruvian Amazon. Herbal medicines were mainly used to treat musculoskeletal disorders (29.7% of all reports of medicinal use), gastrointestinal complaints (13.4%) and skin diseases (12.9%) [5]. The most commonly used autochthonous or naturalised plants were *Cymbopogon citratus*, *Arrabidaea chica* and *Mentha pulegium*. In the Juruena Valley in the Brazilian Amazon region, gastrointestinal complaints, followed by respiratory diseases, were at the top of the list of medicinal plant treatments [14]. The forest floor of the Amazon is full of medicinal plants and herbs with reparative properties. Mi'e (rainforest strawberry) is used to treat injuries and open wounds, the roots of the añaëka plant to treat snake bites and the seeds of the huatiduria to combat the influence of evil spirits on the body. *Tradescantia zanonia* and *Monolena primuliflora* have become the most important medicinal plants of the Kichwa community in the Ecuadorian Amazon region [15].

In a study conducted in the Colón Putumayo region of the Colombian Amazon, 38 species of medicinal plants were documented. *Chamaemelum nobile* showed the greatest benefit in local traditional medicine. All respondents fully agreed that they used medicinal plants to treat six ailments: anxiety, nasal congestion, insomnia, hair loss, muscle pain and skin spots. Some plants were used exclusively to treat one type of illness, while others were used for multiple health problems. *Chamaemelum nobile* (known as Roman chamomile) has the most benefits and is used to treat ailments such as anxiety, insomnia and digestive problems. *Mentha spicata* (mentha mint) is often used for gastrointestinal complaints, colds and as a sedative. Aloe vera is often used to treat skin diseases, burns and inflammations. *Cymbopogon citratus* (lemon grass) is used for fever, colds and as a sedative. *Lippia alba* (bush grass or lemon balm) is known for its relaxing properties and is often used for anxiety and muscle pain. *Rosmarinus officinalis* (rosemary) is used to treat muscle pain, respiratory problems and to improve memory and concentration [16].

The study documented 467 medicinal plant taxa used by the Cashinahua (Huni Kuin) along the Curanja River in the Ucayali region of Peru. Of these, 79 were not or only rarely cited for medicinal use or phytochemical analysis. The study showed that

the leaves were the most frequently used part of the plant, accounting for 93.6% of cases. The most frequently cited therapeutic activities were related to pregnancy and labour complaints (13.8%), followed by poisoning, infections and infestations [17].

Here are some examples of the use of medicinal plants in the Ecuadorian Amazon. *Cymbopogon citratus* (lemongrass) is used to treat digestive problems and fever. *Zingiber officinale* (ginger) is used to treat respiratory problems and as an anti-inflammatory agent. *Saccharum officinarum* (sugar cane) is used to treat kidney diseases. The juice is consumed directly. It is often grown in home gardens for medicinal and nutritional reasons. *Citrus aurantium* (bitter orange) is used to treat colds and indigestion. The dried peel is used. The bitter orange is an exotic species used in traditional medicine. *Piper aduncum* (bell pepper) is used for its antiseptic properties and to treat skin infections. It is an indigenous species that is widely used [11].

Copaiba oleoresins are used in traditional medicine for their medicinal properties, including anti-inflammatory, antimicrobial and healing properties. They have antiparasitic activity, including against Leishmania species, suggesting potential in the treatment of parasitic infections. Copaiba oleoresins are thought to have analgesic effects due to their ability to modulate inflammatory mediators and pain pathways. Copaiba oleoresins promote wound healing, probably due to their anti-inflammatory and antimicrobial properties that facilitate tissue repair and prevent infection [18].

It is worth noting that many diseases are not known and are not treated in the traditional way. Diseases that can be treated surgically are not part of traditional medicine. Traditional medicine includes various diseases of the gastrointestinal tract, respiratory problems, open wounds, various inflammations, snake venoms, mental illnesses and the like (**Figures 1** and **2**).

Figure 1.
Forest in the Peruvian Amazon near the Tambo River, a tributary of the Ucayali River. Photo taken in 2011. Picture by the author Zoran Stiperski.

Figure 2.
Restoration of vegetation after deforestation in the Amazon region near the Tambo River, a tributary of the Ucayali River. Photo taken in 2011. Picture by the author Matea Stiperski Matoc.

4. Healing rituals and ceremonies

The indigenous people of Amazonia use various herbal preparations to connect with nature and communicate with spirits outside our world [19]. Psychedelics from nature are used in various forms of religious and cultural life [20–22], such as at entry into adulthood, in various seasonal rituals, and in preparation for war [23]. In ritual, the boundaries between the patient, the shaman-doctor, the medicine and the environment disappear. Shamans believe that a person's physical health improves by improving their spiritual health and vice versa [24].

Healing rituals are the essence of the holistic approach to traditional healing in the Amazon region. By performing rituals, the Amazonian people enter the "spirit world," which is an essential part of the medicinal use of medicinal plants in Chazuta in the Peruvian Amazon [5]. At the centre of the healing are "teacher plants" such as ayahuasca and purgahuasca (extracted from *Banisteriopsis caapi*), which are believed to promote self-awareness and emotional healing. The Ese'eja are a tribe of hunters, fishermen and gatherers of indigenous origin who live in south-east Peru. Their culture is closely linked to religious beliefs. They believe that illnesses can be caused by bad luck, distraction, laziness or evil forces. The evil forces come through the direct actions of a harmful shaman or through interactions with the devil. Malevolent spiritual forces are one of the main causes of illness. At the centre of their healing practices is the use of ayahuasca (*Banisteriopsis caapi*), a psychoactive vine that plays a central role in shamanic rituals. Ayahuasca ceremonies are used to diagnose illnesses and facilitate healing. During these rituals, the shamans invoke the spirit of ayahuasca to gain insight into the patient's condition and guide the healing process [3].

The shaman does not necessarily have to be a good botanist. His main concern is to manage a network of personal relationships that includes all kinds of living beings. Within this network, the cause of the illness is to be found, a belief shared by shamans and ordinary people. Various psychoactive substances (e.g., tobacco, ayahuasca and datura) and numerous medicinal plants are used for vapour baths, collective ceremonies and individual séances [25]. Contrary to popular belief, knowledge of a wide variety of medicinal plants is not necessarily typical of a shaman [26]. Great shamans may only know a few types of medicinal plants. The greatest shaman of Yuru had one of the lowest scores in identifying medicinal plants among his native population: between 70% and 75% of the average adult [27].

The indigenous ethnomedicine of the Amazon region is generally based on numerous forms of treatment. A key question concerns the nature of "good medicine." When assessing the value of medicinal plants, the Western approach focuses on the chemical efficacy of the plants themselves, whereas the Ashéninka pay much more attention to the relational aspects. The relational dimension also includes the plants themselves as a kind of person. This has implications for Ashéninka shamanism and herbalism [25]. The partial overlap between herbalism and shamanism results from the division into "natural" diseases, which are treated with herbs, and "supernatural" diseases, which are treated shamanically in some parts of the Amazon region [28].

When a foreign body, such as a thorn, enters a person's body, it is understood as a material support for the disease and not as its cause. It is assumed that the illness is based on relationships or, as in this case, on conscious or unconscious aggression. Someone has sent the thorn into the patient's body. This may be a harmful entity from the forest, for example, a ghost or an animal, but more often a relative or neighbour is seen as the culprit [25]. The search for the culprit is a real problem for the Ashéninka shaman. Violence within the ethnic group is strictly forbidden. The usual pattern of behaviour of the Amazons is characterised by constant hostility and war between neighbouring local groups, while internal disputes are strictly forbidden. War is only waged against outsiders [29, 30].

The Ashéninka believe that if you are bitten by a poisonous snake, you have to find and kill the snake before you can use the medicinal plant physically; otherwise, the medicine is absolutely useless. The reason for this is that by killing the snake, we destroy the will with which the snake wanted you dead. This is expected to have some physical effect on the material medical substance, but first of all, it must involve the restoration of the right relationship. Before this crucial step, the restoration of the right relationship, the most effective antidote literally does not materialise [25]. The body has an innate will. Predators or snakes are full of murderous intentions, and the prey feels a physical will to flee or fight. Many animals hunger for certain types of human souls, souls as an aspect of the body. Some plants are filled with certain psychotropic wills and energies, some with healing, poisonous or nourishing substances [31].

A common healing practice throughout the Amazon and even in the Native American world is for the shaman to blow tobacco smoke or spit tobacco juice on the parts of the patient's body that he believes to be the cause of the illness. There are many variations among shamans. The smoking or spitting of tobacco may be accompanied by a particular chant. Sometimes they use wild medicinal plants as leaf baths. The constant use of tobacco and other psychoactive plants gives the shaman an extraordinary diagnostic ability to "see" the cause of the illness [25]. The ritual follows a specific, simple form under the guidance of a religious practitioner or shaman who respectfully establishes contact with the good spirits [32]. We recall that according to the traditional experience of the Matsigenka, health is not only an individual, purely physical and biomedical matter, but also a social, relational one [33].

Figure 3.
Hamlet along the Tambo River, Amazon, Peru. Photo taken in 2011. Picture by the author Matea Stiperski Matoc.

A widespread form of treatment is the steam bath. In the Ucayali region, this special technique is borrowed interethnically from the Ashéninka, Matsigenka [34] and Yaminahua. The steam bath is not the exclusive domain of the shamans, but is used by specialised women with a certain affinity and shamanic talent. The added value of the shamans consists in a better selection of leaves for the bath and a higher diagnostic accuracy in divination [25].

The method for treating mental illness involved the ritual ingestion of *Nicotiana rustica* (mapacho) under the guidance of an experienced Amazonian healer. Post-treatment evaluations showed clinically relevant improvements in several mental health indicators, including reductions in depression, anxiety, stress and somatic symptoms. Participants reported increasing calmness, mental clarity and overall well-being over the course of the week-long treatment and described the experience as deeply embodied and emotionally transformative. In Amazonian medicine, tobacco is considered a “teacher plant” that is said to impart knowledge and guidance when used ceremonially, which emphasises its spiritual and therapeutic significance. In addition to nicotine, *Nicotiana rustica* contains β-carboline alkaloids, which may contribute to its psychoactive effects and therapeutic potential (**Figure 3**) [35].

5. Passing on traditional medical knowledge

Local medical systems rely on plant diversity and traditional knowledge [36]. The loss of traditional knowledge has a negative impact on the survival of some plant populations [37], with potentially serious consequences for biodiversity and human well-being [38, 39].

A decline in traditional knowledge of medicinal plants can be observed among the younger generations. Traditional knowledge about the use of medicinal plants is influenced by ethnicity and generational age, with younger generations cultivating fewer species and having less knowledge about their properties. The erosion of traditional knowledge among younger generations poses a threat to the preservation of the diversity of medicinal plants and associated cultural practices [11].

The remoteness and limited access to Western medicine, as in the eastern and central Peruvian Amazon, contribute to the preservation of traditional knowledge of herbal medicine [17]. In the past, the Amazon was only sparsely populated, mostly by hunter-gatherers and primitive farmers. The settlements were small, scattered and isolated from each other in vast forests. The largest South American civilisations and empires developed in the Andes, on the Pacific coast and in the lowlands of the southern part of the continent, while the Amazon was bypassed. European colonisers rarely entered the Amazon region [40]. The use of medicinal plants in the Ecuadorian Amazon is among the highest in South America, partly due to the lower availability of conventional health care at the regional level [41]. Malaria is a disease that primarily affects communities that have limited biomedical support and therefore rely on traditional healing rituals [13].

Traditional medical knowledge is primarily passed on vertically (from parents to children) and indirectly (from elders to younger members of the community) [15]. Women have played a key role in the conservation of agrobiodiversity, as they are the main transmitters of traditional knowledge about medicinal plants within the family [11]. The type of learning also influences knowledge. People who learnt from elders named different plants than those who learnt through courses or books.

Figure 4.
Ceremonial hall of the Nopoki University, dedicated to the education of the indigenous population of the Amazon region in Atalaya, Peru. Photo taken in 2011. Picture by the author Zoran Stiperski.

Figure 5.
Ashaninka—Instituto Superior Technologico Publico (Public Higher Technological Institute), Puerto Ocopa, Peru. Photo taken in 2011. Picture by the author Zoran Stiperski.

However, many young indigenous people have grown up without access to the knowledge of their elders about medicinal plants. Sometimes their parents did not pass on the stories, other times they were discouraged from doing so by a dominant Western culture that does not value or cannot imagine indigenous knowledge. But as the older generations die off, young indigenous leaders and artists are realising their responsibility to protect traditional knowledge and pass on the stories of their ancestors to future generations. The traditions that their ancestors upheld are alive and well, and without the collective efforts of citizens, this sacred memory will be lost.

But sometimes young people take a renewed interest in the old traditional knowledge of Amazonian medicine. With the help of photos and audio commentaries, young indigenous people try to convey the importance of medicinal plants, to pass on traditional knowledge about plants to the future and to awaken the spirit and curiosity of young people. The elders of indigenous peoples have passed on a wonderful healing culture to younger generations; the artwork of young people can help to carry it forward (**Figures 4** and **5**) [42].

6. Local adaptation

The study was conducted in Colón, Putumayo, a community in the Sibundoy Valley in the Colombian Andes known for its rich biodiversity and cultural heritage. Participants included the rural population of Colón, indigenous communities such as the Quillacingo and Pasto, and Afro-descendants, all of whom have knowledge of

Figure 6.
Radio station from Atalaya serves as a transmitter of important knowledge and information for the indigenous population of the Amazon region. Photo taken in 2011. Picture by the author Matea Stiperski Matoc.

medicinal plants. The ethnobotanical knowledge of the community is deeply rooted in ancestral traditions, cultural practices and family farming systems [16].

The study examines the role of Amazonian home gardens as a reservoir of traditional knowledge and biodiversity, particularly in relation to medicinal plants, in the community of Sangay in the province of Morona Santiago, Ecuador. The study refers to two large ethnic groups: the indigenous Shuara and the immigrant Mestizos, both of whom have a rich heritage of traditional knowledge. Certain plant species have specific cultural meanings, leading to differences in the ranking of medicinal plants between the Shuar and the Mestizo communities [11]. *Cymbopogon citratus* (lemon grass) is used to treat digestive problems and fever. It is widely used in the Shuar and Mestizo communities [11]. Cultural preferences in the Ecuadorian Amazon influenced the selection of medicinal plants; the Shuar community cultivated 114 medicinal plant species, while the Mestizo and other groups cultivated 78 and 32 species respectively (**Figure 6**) [11].

7. Syncretism between traditional and Western medicine

Some researchers argue that there is considerable overlap between traditional and Western knowledge and that the two are not necessarily in conflict [43–45]. Traditional and complementary-alternative medicine are increasingly respected by national governments and health care providers [46]. The Peruvian National Programme of Complementary Medicine and the Pan-American Health Organisation recently compared complementary medicine with allopathic medicine in clinics and

hospitals of the Peruvian social security system. A total of 339 patients—170 were treated with complementary-alternative medicine and 169 with allopathic medicine—were observed for 1 year. Treatments for osteoarthritis, back pain, neuroses, asthma, stomach ulcers, tension and migraine headaches and obesity were analysed. The results showed with a significance of 95% that the costs for the use of complementary-alternative medicine were lower than the costs for the use of Western therapies. In addition, the effectiveness of complementary-alternative medicine was greater than the effectiveness of conventional treatments for each of the criteria examined—clinical effectiveness, user satisfaction and reduction of future risks—including fewer side effects, better patient and physician perceptions of effectiveness and 53–63% greater cost-effectiveness of complementary-alternative medicine compared to conventional treatments for selected conditions [47].

The Tsimane people in the Bolivian Amazon regard indigenous and Western medicine as two independent fields of knowledge, although they mix pharmaceutical and herbal treatments in their daily practice. The Tsimane and their doctors consider Western medicine to be trustworthy, powerful and effective, but they also believe that the medical knowledge of the indigenous people helps to preserve their way of life and protect the ecosystem. A Tsimane can use ibuprofen to relieve pain, but he can also drink a decoction made from the bark of the "ochosho" tree, which the Tsimane believe relieves inflammation. For severe infections or high fevers that do not respond to herbal treatments, antibiotics are sought in a Western hospital. The community generally considers Western medicine to be more effective in emergencies or for unknown illnesses. Traditional healers use a locally known herbal tea made from guava leaves as a starting point for treatment, for example, for diarrhoea in children, but turn to Western medicine when traditional treatments have failed. Some villagers are reluctant to be immunised or hospitalised because they are afraid of hurting themselves or because they distrust unfamiliar procedures [2].

Some authors have emphasised the positive attitude of traditional healers towards Western medicine and their willingness to cooperate with physicians [48–52]. There is a therapeutic pluralism in which traditional medicines are used alongside modern medicine, reflecting a complementary approach to health care. Some community members have noted a decline in the use of medicinal plants and attribute this to the convenience and perceived efficacy of medicines [12]. Research in Bolivia [52] suggests that collaboration between ethnomedicine and biomedicine is possible and could benefit local people and their environment, while a lack of collaboration can lead to a lack of understanding of biomedicine and its misuse [53, 54]. Amazonian medicine as practised in Peru today reflects a mixture of traditions that have been altered by centuries of colonial and post-colonial influences, and is no longer the indigenous science that it originally was [55].

The Takiwasi Centre in the Peruvian Amazon has developed a treatment programme that synergistically combines traditional Amazonian medicine with modern psychotherapy for the treatment of substance use disorders. Current Amazonian medical practise and its application in Takiwasi treatment are understood as a kind of hybrid system [56] or third space [57], that is, a construct that has evolved from the interaction of different cultural systems. The programme includes traditional healing methods such as cleansing rituals, nutritional practices and healing ceremonies led by experienced practitioners and adhering to established ritual protocols. It is a successful cross-cultural dialogue between traditional and modern medical systems that illustrates the potential benefits of such collaboration in the treatment of complex health problems such as substance use disorders [58].

The syncretism of traditional and Western medicine is illustrated by the example of a 37-year-old woman with mood, anxiety and attention disorders and a chronic somatic condition who underwent a week-long treatment with traditional tobacco in the Peruvian Amazon. It emphasises the value of integrating indigenous knowledge systems into modern health practices and suggests that traditional Amazonian treatments can offer complementary approaches to mental health [35].

The healers of the Amazon Trio traditionally treated 75 different disease conditions, demonstrating a sophisticated understanding of the various ailments in their cultural context. The study documents 127 anatomical terms that reflect a detailed indigenous anatomical lexicon used in diagnosis and treatment. The integration of traditional and biomedical concepts is evident in the case of Marareya (malaria), when the Trio healers adapted biomedical terminology to their own language and understanding [4].

8. The challenges of the modern world

A major challenge in the context of traditional medicine is the preservation of knowledge about traditional healing methods, knowledge about medicinal plants and the protection of forest communities. The establishment of protected areas is seen as a strategy to preserve biodiversity and traditional knowledge. Local communities have made proposals for these protected areas to resist the pressures of urbanisation and to maintain access to natural resources that are important for their livelihoods. These findings highlight the complex relationship between ethnobotanical knowledge, cultural practises and conservation efforts in coastal regions of Brazil [12].

Understanding the use of medicinal plants in the Chazuta Valley in the Peruvian Amazon can provide strategies for the sustainable management of ethnopharmacologically rich forests in indigenous communities [5]. Ethnobotanical studies are necessary to understand traditional ecological knowledge as a link between ecosystem services and human well-being [59]. The link between ecosystems and knowledge, the Tsimane emphasise that their medicinal knowledge is linked to the forest, which they fear is being degraded [2].

The therapeutic potential of some widespread species has been scientifically confirmed, making them promising prototypes for new medicines. However, the ethnomedicinal use of some species has not yet been scientifically confirmed, which represents an unexplored area for future biological and pharmacological research in the Juruena Valley for the treatment of various human diseases [14]. The potential discovery of new active molecules is probably the main reason for the broad interest in tropical ethnomedicine [60–63].

The use of medicinal plants was documented in five coastal communities on the Rio Jauaperi on the border between the Brazilian states of Roraima and Amazonas. Based on interviews with 62 informants, a total of 119 botanical species were documented, illustrating the rich ethnobotanical knowledge in these communities. The value of medicinal plants emphasises the need to protect the environment. The Xixuaú community has proven that it is able to protect the environment by utilising numerous forest species for its medicinal practices [13].

9. Conclusions

Traditional medicine is practised all over the world, where it is remote and isolated from Western medicine, especially in areas of exceptional biodiversity such as

the Amazon. A holistic approach to treating illness involves the connection between the individual, the community, nature and the spiritual world. Illness is the result of disharmony, and healing restores the necessary balance. Indigenous peoples have a veritable pharmacy in their immediate environment with an abundance of medicinal plants growing in their backyards and in the surrounding forests. Indigenous peoples can often list hundreds of different types of medicinal plants. Healing rituals are at the heart of holistic treatment in traditional Amazonian medicine. The first step of the ritual is diagnosis, followed by healing. The shaman is the key figure in all traditional medicine. In addition to the shamans, the people themselves, especially women, often perform rituals and are familiar with some methods of traditional medicine. Psychoactive substances are used in the ritual healing of illnesses. The practices of traditional medicine vary greatly from place to place, depending on tradition, culture and the availability of medicinal plants. The form of traditional medicine depends on numerous cross-cultural influences, both from the indigenous ethnic groups of the Americas and from colonial, missionary and modern Western influences. It is noticeable that younger generations are less familiar with traditional medicine knowledge, especially in areas with a greater presence of Western medicine. Knowledge of traditional medicine is passed on orally from elders to younger generations, from parents to children. More recently, knowledge has also been acquired through courses or books. The indigenous population of the Amazon region is mostly in favour of Western medicine and often turns to it when traditional medicine does not bring positive results or when confronted with an unknown and complicated disease. Today, the syncretism of traditional and Western medicine is being promoted in various places. The preservation of knowledge and the use of traditional medicine not only preserves ancient, useful knowledge but also the biodiversity of the Amazon region.

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Chapter 6

Application of the Theory of Signatures to Validate the Use of Medicinal Plants in the Riverside Area of the Cities of Mazagão and Macapá, State of Amapá, Amazonia, Brazil

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Abstract

The Theory of signatures can explain how traditional knowledge was formed or perpetuated to the present day. Based on the optical characteristics of plants, the appearance of a particular plant resembles some organ in the human body, indicating that this plant can be used in treating and curing diseases associated with this organ in which the plant resembles. Therefore, this chapter aimed to analyze the relationship of plants with organoleptic optical properties with the use attributed by traditional communities and pharmacological validation through scientific literature. The plants were selected through ethnobotanical research in a riverside region in Amapá State. Photographic records were made to compare the part of the plant with the organ of the human body. After botanical identification, they were subjected to a review of scientific literature to prove the applications of traditional uses. *Results*: The plant species *Arrabidaea chica, Astrocaryum murumuru, Bauhinia splendens, Costus spicatus, Croton urucurana, Eleutherine bulbosa, Melissa officinalis, Phlebodium decumanum, Phyllanthus amarus* and *Zingiber officinale* were identified. *Conclusions*: The species *Costus spicatus, Croton urucurana, Melissa officinalis, Phyllanthus amarus, and Zingiber officinale have* had their main traditional uses proven through registered scientific studies, corroborating the existence of a relationship between the morphological aspects of plants and the indication of use in traditional Amazonian medicine.

Keywords: traditional medicine, ethnobotany, medicinal plants, plant morphology, autochthonous resources

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1. Introduction

The cultivation and management of medicinal plants date back to the most remote times of humanity, with records dating back to 4000 BC [1]. In Brazil, the use of medicinal plants by indigenous communities has always occurred. With the arrival of Portuguese doctors, who were unable to bring medicines used in Europe, the knowledge of medicinal plants was used in conventional medicine [2]. With the arrival of people of African descent in Brazil, more knowledge was used in Brazilian culture since these people used plants and herbs in rituals and to cure diseases. Thus, there was a union of knowledge between indigenous, Europeans, and Africans, which contributed to the great diversity of traditional knowledge in Brazil [3].

Ethnobotanical studies focus on exploring the processes and justifications for the traditional use of medicinal plants [4, 5]. Multidisciplinary research is emerging to investigate secular knowledge and how it was formed, some of these studies use organoleptic properties, such as smell, taste, and optics [6].

The Theory of Signatures, which emerged in the Middle Ages, with the physician and alchemist Paracelsus, who preached *similia similibus curantur* ("*similar, similar cure*") [7], can explain how traditional knowledge was formed or perpetuated to the present day. The Theory is based on the optical characteristics of plants: the appearance of a particular part of the plant resembles some organ of the human body, indicating that this plant can be used in the treatment and cure of diseases associated with this organ in which the plant resembles. It can be attributed to the General Theory of Representations (Semiotics), where the construction of the meanings of each element of human nature occurs, generally related to the image that the element transmits [8].

Even today, researchers from different parts of the world analyze the contributions of the Theory of signatures to traditional populations. Leonti et al. [6] expose that the Theory of signatures is an essential mnemonic device for the indigenous people of southern Veracruz, Mexico. Bennett [9] also supports the idea that the Theory of signatures is a mnemonic device. Populations with low schooling used to pass on the knowledge of medicinal plants acquired clearly and practically to the next generations, being an instrument to facilitate memorization. However, ethnobotanical research in the Amazon is still focused on the defining aspect, with no record of investigations of organoleptic properties.

The State of Amapá, located in the Brazilian Amazon, is considered the most preserved state in Brazil, in which 70% of its area is home to Conservation Units, Indigenous Lands, and Quilombolas [10]. The rainy period occurs from January to June, and the drought period from July to December [11]. The vegetation, according to IBGE [12], is classified as Alluvial Dense Rainforest. According to Rabelo [13], there is a Várzea Forest in the region with daily floods due to tidal variation.

Amapá also has a great diversity of traditional populations (indigenous, quilombolas, riverside people, descendants of Africans, and peasants), creating a unique diversity of knowledge about medicinal plants from the Amazon [10].

This chapter aimed to analyze the relationship between plants with organoleptic optical properties, the use attributed by traditional communities, and the validation of the pharmacological effect in scientific literature.

2. Study area

The Amazon stands out for its humid tropical climate [11], favoring its enormous diversity of fauna and flora. As it is a biome that is difficult to access, it has a great diversity of traditional secular knowledge about medicinal plants, passed from generation to generation. The place of study was the region of the District of Fazendinha (0.0217220, N -51.0853921 O) and the riverside area of the Vila Nova River (−0.096039 N -51.268450 O), in the Municipality of Mazagão, State of Amapá, an island in the eastern Amazon, which houses the mouth of the Amazon River (**Figure 1**).

3. Plant selection

The project was approved by the Ethics Committee of the Federal University of Amapá-UNIFAP under protocol number CAAE - 31830720.0.0000.0003 and review number: 4.073.014.

A list of medicinal plants popularly used in Amapá was built after the compilation of two ethnobotanical studies in the State of Amapá. The list has 130 medicinal plants. After research at the Photo Library of the Virtual Herbarium of the Botanical Garden of Rio de Janeiro (JABOT), ten plants were identified with similar shapes to organs of the human body or physiological functions (**Table 1**).

The collection of botanical material was carried out in November and December 2020 for identification purposes. The exsiccates were deposited at the Herbário Amapaense of the Institute of Scientific and Technological Research of the State of Amapá to identify botanical species (HAMAB-IEPA) by Dr. Patrick de Castro Cantuária.

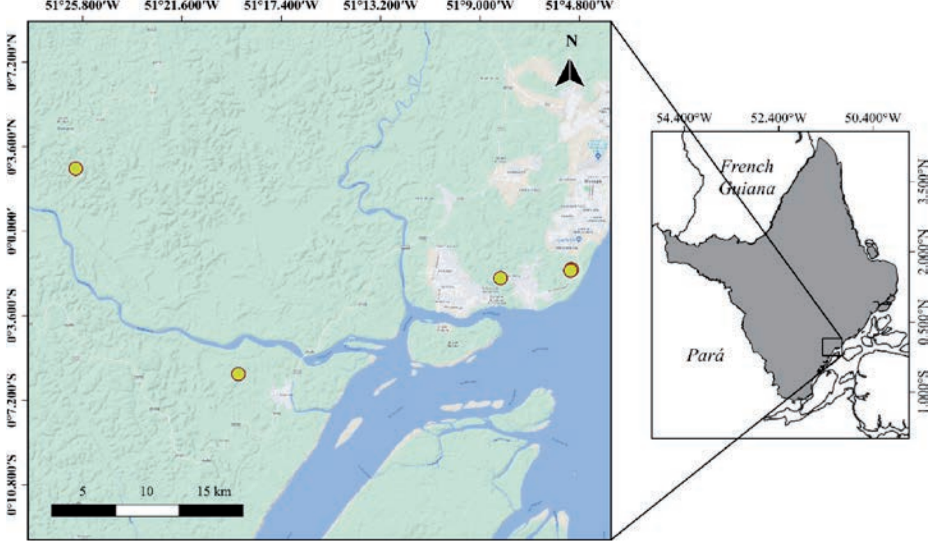

Figure 1.
Location of the area where the plant species were collected.

Herbal deposit number	Scientific name	Popular name	Popular indication	Appearance	Imagem planta	Plant image Related organ image
HAMAB 019281	*Arrabidaea chica*	Pariri	Anemia, diarrhea, wound washing, jaundice	Blood		
HAMAB 019289	*Astrocaryum murumuru*	Murumuru	Inflammation in the eyes	Eyes		
HAMAB 019282	*Bauhinia splendens*	Ladder of tortoise	Joint pain, rheumatism, and syphilis	Intestine		
HAMAB 019282	*Bauhinia splendens*	Ladder of tortoise	Joint pain, rheumatism, and syphilis	Clitoris		
HAMAB 019283	*Costus spicatus*	Canafiche, canarana	Inflammation in the uterus and ovaries, vaginal discharge, urinary tract infection, and syphilis	Urethra		

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Herbal deposit number	Scientific name	Popular name	Popular indication	Appearance	Imagem planta	Plant image Related organ image
HAMAB 019288	*Croton urucurana*	Christ's blood	Hemorrhage, wound healing, antitumor, and diarrhea.	Blood		
HAMAB 019284	*Eleutherine bulbosa*	Marupá, marupázinho	Verminous healing of skin wounds	Hemorrhoid		
HAMAB 019285	*Melissa officinalis*	Cidreira, cidreira herb, Lemon balm	Headache, digestive problems, anxiety, and nervousness	Heart		
HAMAB 019286	*Phlebodium decumanum*	Guaribinha	Cough, hoarseness, and bronchitis	Guariba monkey		
HAMAB 019287	*Phyllanthus amarus*	breaking stone	Urinary tract pain (urinary tract infection)	little Rock		

Herbal deposit number	Scientific name	Popular name	Popular indication	Appearance	Imagem planta	Plant image Related organ image
HAMAB 019290	*Zingiber officinale*	Ginger	Gastrointestinal system, anticancer, anti-cough, anti-inflammatory.	Stomach		

Table 1.
List of plant species identified with the macroscopic characteristics of the parts used and the correlations with parts of the human body.

According to Fidalgo and Bononi [14], the samples were processed in the field and identified with their vernacular names, with labels containing the collection number and specific information for each sample. Photographic records of the species were made, and the geographical coordinates of the area with the Global Positioning System (GPS) apparatus were recorded.

4. Obtaining photographic records

The photographic records were taken from September to December 2020 to record the flowers of the Amazonian Spring. The collections took place in Macapá, in the district of Fazendinha, and the municipality of Mazagão, in the riverside area of the Vila Nova River, with the help of a specialist in traditional medicinal plants.

5. Bibliographic research

The scientific support for the traditional use of the identified plant species was based on searches on three platforms: Web of Science, CAPES Journals, and Google Scholar (articles published between 1945 and 2021). The word pharmacology and scientific name of the identified species were used in the searches. The articles that describe some pharmacological actions of the species were selected. In vivo, in vitro, and clinical studies articles were included. The data were tabulated in Excel spreadsheets, analyzed, and divided into categories.

6. Theory of signatures and plants from Amazon

Arrabidaea chica plant, popularly known as “Pariri” or “Crajirú” in the eastern Amazon region, is used by traditional populations as body paint, sunscreen, mosquito repellent, in wound healing, intestinal colic, skin conditions, blood disorders, and leukemias [3]. Its leaf tea is red as blood and is widely used for anemia [15].

Astrocaryum murumuru is a palm widely used in the Amazon. Its fruit tea is used for inflammation in the eyes [15], and its fruit butter is also used in the cosmetics industry for the manufacture of creams, soaps, and shampoos [16]. The fruit of the palm tree “Murumuru,” when cut in half, looks like eyes, as shown in **Table 1**.

Bauhinia splendens, known as “Ladder of tortoise” or “Herb of Jabuti,” is commonly used for joint pain, rheumatism, and syphilis. The bark of its stem is also used against pathogenic bacteria [17], and its leaves are used for vaginal infections [18]. It can be noted that its flower has a shape that resembles the clitoris and its tangled stem that resembles the large intestine, being used to cure diseases in both organs (**Table 1**).

Costus spicatus is popularly known in the Amazon as “Canafiche.” In other regions of the country, it is known as “Cana do Pântano” or “Cana-do-Brejo.” It is popularly used for pain and inflammation, relief of urinary tract infection, and expulsion of kidney stones. Its anti-inflammatory, antimicrobial, and diuretic action has already been scientifically proven [19, 20]. The shape of its stem resembles the human urethra.

Croton urucurana, popularly known as “Blood Tree,” “Blood of Christ,” or “Dragon Blood,” is a tree whose bark is cut, releasing a viscous red sap similar to blood. This sap is used in traditional medicine as hemostatic, wound healer, analgesic, anti-inflammatory, and anti-rheumatic agent [21].

Eleutherine bulbosa, popularly known as "Marupá," is a tropical herb. Its red bulbs resemble hemorrhoids and are traditionally used for pain and regularization of menstruation, intestinal disorders, and deworming [22].

The *Melissa officinalis* plant, the famous "Lemongrass," well known among medicinal plants, is popularly used for headaches, nervousness, anxiolytics, and heart problems. Its leaf is shaped like a heart [23].

Phlebodium decumanum is known in the eastern Amazon as "Guaribinha," as its root is the same as the guariba monkey *(Alouatta guariba).* Its root tea is used for "guariba cough," as long periods of cough are known in the eastern Amazon, in addition to hoarseness and bronchitis.

Phyllanthus amarus, popularly known as "Quebra-Pedra," as its name suggests, is widely used for the genitourinary system, for kidney stones and gallstones, also used for stomach problems, colic, hepatitis, hypertension, jaundice, Analgesic, antidiabetic, anti-inflammatory, and many other uses, varying from country to country [24]. Its small leaves and seeds resemble small stones, reminiscent of kidney stones.

The rhizomes of the plant *Zingiber officinale* (ginger), depending on its evolution, sometimes are identical to the stomach and one of its most significant benefits is for digestive problems. Studies show that the Chinese have used ginger for more than 2000 years for gastric problems and nausea, being a popular therapy for seasickness [23]. Ginger is a plant that has been extensively studied because of its various uses, anticancer, anti-inflammatory, antitussive, anticoagulant effects, cardiovascular effects, and the gastrointestinal system [25].

7. Vegetable species with a reddish color

It is noted that reddish-colored plants are popularly used for blood disorders. Leonti et al. [6] report in their studies that decoction teas or reddish plant seeds are used to treat bleeding and menstrual problems. It is observed that in addition to Pariri tea (*Arrabidaea chica*) and blood tree (*Croton urucurana*), the flowers of the Escada de Jabuti (*Bauhinia splendens*), used to treat vaginal infections by Indigenous people, also present a reddish color [18].

8. Astringent plant species

Remedies for the gastrointestinal system, such as diarrhea, vomiting, stomach pains, and hemorrhoids, are generally astringent (bark and root), as is the case with the stem of the species Escada de Jabuti (*Bauhinia splendens*), from the root (bulb) of the Marupá plant (*Eleutherine bulbosa*) and Ginger root (*Zingiber officinale*). Leonti et al. [6] demonstrated that the Popoluca indigenous people also use bark and roots to treat diarrhea and dysentery.

9. Names of plant species

Some plant species already have their uses identified by their names, as is the case of the stone-breaking plant (*Phyllanthus amarus*), used for kidney stones, the blood tree plant (Croton urucurana), used for blood disorders, and the Guaribinha plant (*Phlebodium decumanum*), used for the well-known "guariba cough" (intense cough) in the Amazon.

10. Formats of plant species

The popular Lemongrass has already been studied by Dafni and Lev [26]. Its leaves, which resemble the heart, are used for heart problems, depression, and insomnia. Murumuru is still a poorly studied palm, with many descriptive studies. The Canafiche plant, which has a urethral appearance, is widely used for urinary infections and kidney stones. As it is a diuretic plant, it is widely used for the urinary system [27].

11. Popular culture and medicinal plants

Posey [28] reports that beliefs and knowledge can sometimes seem contradictory to Western sciences. However, these contradictions are the primary cultural principles to be investigated to understand how traditional populations see the natural world and how these communities classify nature, both in the natural world and the symbolic and social world.

The Theory of Signatures is seen as primitive and of no relevance to modern society. However, Leonti et al. [6], in their research with the indigenous people of Popoluca, Mexico, demonstrated that a multidisciplinary approach could go beyond expectations and discover new information about how traditional communities classify the world. In this community, a local healer reports that the shape of the plant is used to attribute its use and that healing occurs when it is believed to be in its shape and is, therefore, essential for maintaining local medical traditions.

So far, studies on the correlations between the organic characteristics of plants and human organs in the Amazon are scarce and almost nonexistent. The Theory of Signatures is a mechanism for maintaining local traditions or even for passing on information between generations, perpetuating traditional knowledge to the present day.

12. Pharmacological actions of plant species

Of the 10 plant species described in this study, nine present studies prove their pharmacological effects. For *Astrocaryum murumuru*, no scientific studies have been found that proved its traditional uses. The pharmacological effects of the species *Arrabidaea chica*, *Bauhinia splendens*, *Costus spicatus*, *Croton urucurana*, *Eleutherine bulbosa*, *Melissa officinalis*, *Phlebodium decumanum*, *Phyllanthus amarus*, and *Zingiber officinale* are described in **Table 2**.

The species *Arrabidaea chica* is popularly used for anemia. However, it was demonstrated by Oliveira et al. [29] that this action had not been scientifically proven because, after treatment interruption, there is no significant influence on hematological parameters. Among the other pharmacological actions that have been proven are antihypertensive, diuretic, antioxidant, antitumor, anti-inflammatory, antimicrobial, antiparasitic, healing, and anti-angiogenic activities [30–37].

Bauhinia splendens is popularly used for vaginal infections and against pathogenic diseases. The results by Silva et al. [38] indicated the efficacy of the hydroethanolic extract against *Staphyloccocus aureus* and *Salmonella typhimurium*. The analgesic and anti-inflammatory action in mice was also evaluated by Cechinel Filho et al. [39]. Its antinociceptive action was proven in mice by Filho et al. [17]. The data showed that the plant has significant analgesic action in several pain models.

Species	Popular Name	Pharmacological action	Scientific studies
Arrabidaea chica	Pariri	Antianemic	Oliveira et al. [29]
		Antihypertensive	Cartágenes et al. [30]
		Diuretic	Amaral et al. [31]
		Antioxidant	Dos Santos et al. [32]
		Antitumor	Ribeiro et al. [33]
		antimicrobial	Mota [34]
		anti-inflammatory	Oliveira et al. [35]
		Healing	Jorge [36]
		Antiparasitic	Rodrigues et al. [37]
Astrocaryum murumuru	Murumuru	UD*	UD*
Bauhinia splendens	Ladder of jaboti	Antimicrobial	Silva et al. [38]
		anti-inflammatory	Cechinel Filho et al. [39]
		Analgesic	Cechinel Filho et al. [39]
		Antinociceptive	Filho et al. [17]
Costus spicatus	Canafiche, cana do brejo	Antibacterial and antioxidant	Uliana et al. [40]
		Anti-inflammatory	Silva et al. [41]
		Nephroprotective, diuretic, antilithiasis activity	Moreno et al. [27]
		Hemolytic effect	Silva and Parente [42]
		Antinociceptive and anti-inflammatory	Quintans Junior et al. [43].
Croton urucurana	Christ's blood, for Sangue	Antimicrobial and antioxidant	Simionatto et al. [44]
		Antidiarrheal	Gurgel et al. [45]
		Antiulcer	Cordeiro et al. [46]
		Anti-inflammatory and antinociceptive	Cordeiro et al. [46]
Eleutherine bulbosa	Marupá	Antimicrobial	Padhi and Panda [47]
		Antioxidant and probiotic	Munaeni et al. [48]
		Antihypertensive	Bahtiar and Chumala [49]
		Antifungal	Alves et al. [50]
Melissa officinalis	Lemongrass	Antioxidants	Bayat et al. [51]
		Antihyperglycemic	Weidner et al. [52]
		Antihyperlipidemic	
		Antimicrobial	Mimica-Dukic et al. [53]
		Antiepileptic	Bhat et al. [51]
		Antidepressants	Lopéz et al. [54]
		anxiolytic	Cases et al. [55]
		Antinociceptive	Birdane et al. [56]
		Anti-inflammatory	
		Antispasmolytic	Sadraei et al. [57]
		Neuroprotective activity	Lopéz et al. [54]; Akhondzadeh et al. [58]
		Cardiovascular effect	Akhondali et al. [59]
		Anticancer	Weidner et al. [60]

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Species	Popular Name	Pharmacological action	Scientific studies
Phlebodium decumanum	Guaribinha	Anti-inflammatory	Punzón et al. [61]
		Anticancer	Gridling et al. [62]
		Natural supplement	Díaz-Castro et al. [63]
		Antipsoriase	Das et al. [64]
		Antioxidant and anthelmintic	Das et al. [65]
Phyllanthus amarus	Stonebreaker	Gastroprotective	Raphael and Khuttan [66]
		Antiulcer	Shokunbi and Odetola [67]
		Antifungal	Agrawal et al. [68]
		Analgesic	Iranloye et al. [69]
		Anti-inflammatory	Iranloye et al. [69]
		Antinociceptive	Santos et al. [70]
		Antioxidant	Karuna et al. [71]
		Antispasmodic	Ajala et al. [72]
		Antiviral	Ravikumar et al. [73]
		Contraceptive	Rao and Alice [74]
		Diuretic and antihypertensive activity	Srividya and Periwal [75]
		Hepatoprotective activity	Wongnawa et al. [76]
		Hypoglycemic and hypocholesterolemic activities	Mbagwu et al. [77]
		Radioprotective effect	Harikumar and Kuttan [78]
		Antispasmolytic	Mans et al. [79]
Zingiber officinale	Ginger	Antithrombotic and anti-inflammatory	Thomson et al. [80]
		Hypoglycemic, hypocholesterolemic, and hypolipidemic activity	Al-Amin et al. [81]
		Anti-inflammatory, antipyretic, and Analgesic	Ojewole [82]
		Gastroprotective action	Bryer [83]
		Radioprotective effect	Jagetia et al. [84]
		Antioxidant	Kim et al. [85]
		Antimicrobial	Ficker et al. [86]
		Anticancer	Shukla and Singh [87]
		Antiarthritic	Funk et al. [88]

**UD: undefined.*

Table 2.
Pharmacological actions of plant species recorded in the ethnobotanical survey.

Costus spicatus is traditionally used for urinary infections. Moreno et al. [27] investigated the nephroprotective and antilithiatic effects, and the study indicated a significant nephroprotective effect. The authors suggest the possible efficacy of traditional use. Other investigations on its pharmacological properties have been studied, such as the antimicrobial, antioxidant, anti-inflammatory, hemolytic, and antinociceptive effects [40–43].

Croton urucurana is traditionally used for bleeding, diarrhea, and wound healing. Gurgel et al. [45] investigated its antidiarrheal action, which presented actions on pathologies associated with diarrhea. Its anti-hemorrhagic effect was tested and the hydroethanolic extract showed a significant effect in inhibiting the hemorrhagic activity of Bothrops jararaca venom. It also has analgesic, antiulcer, anti-inflammatory, antinociceptive, antimicrobial, and antioxidant actions [44, 46, 89].

Eleutherine bulbosa, traditionally used for worms and wound healing, has been studied for its antifungal and antimicrobial activity by Alves et al. [50] and Padhi et al. [47], which proved their beneficial actions. Marupá was also investigated for its antihypertensive, antioxidant, and natural probiotic actions [48, 49].

The herb *Melissa officinalis*, known as lemon balm, has heart-shaped leaves that are used as a tranquilizer, anxiolytic, and antidepressant. Cases et al. [55] carried out a clinical study in stressed volunteers with mild to moderate anxiety disorders with hydroethanolic extract of *M. officinalis* leaves, and after 15 days, the manifestations of anxiety decreased by 18%, and insomnia decreased by 42%. Akhondzadeh et al. [58] evaluated the efficacy of *M. officinalis* extract in patients with mild to moderate Alzheimer's disease. After four months of treatment, the extract produced a significantly better effect than placebo and positively affected patients' agitation. The pharmacological effects of *M. officinalis* have also been tested as an antidepressant, antiepileptic, antispasmodic, anti-inflammatory, antinociceptive, antioxidant, hypoglycemic, hypolipidemic, antimicrobial, anticancer, neuroprotective, and cardiovascular effect [51–54, 56–60, 90].

Phlebodium decumanum is traditionally indicated for severe cough. Its anti-inflammatory action was evaluated in the study by Punzon et al. [61], in which the extract showed inhibitory activity on the production of tumor necrosis factor. Guaribinha has also been investigated for its antipsoriatic, anticancer, natural supplementation, antioxidant, and anthelmintic actions [62–65].

Phyllanthus amarus was evaluated for its diuretic, hypotensive, and hypoglycemic effects in the study by Srividya and Periwal [75] in humans, where the urine volume and urine sodium concentration increased in 24 hours, a decrease in blood pressure in hypertensive women also occurred. The blood glucose level was significantly reduced. *P. amarus* was also evaluated for its antifungal, analgesic, anticancer, antiulcer, gastroprotective, anti-inflammatory, antinociceptive, antioxidant, antispasmodic, antiviral, contraceptive, aphrodisiac activity, hepatoprotective activity, hypoglycemic and hypocholesterolemic activity, radioprotective effects and antidiarrheal and anti-amnesia effects were proven [66–74, 76–79, 91–94].

Zingiber officinale was investigated for its gastroprotective activity. The study by Bryer [83] provided evidence on the use of ginger in the treatment of vomiting and nausea during pregnancy. The study by O'Mahony et al. [95] evaluated the bactericidal activity of ginger, being effective against Helicobacter pylori, which can cause peptic ulcers and the development of gastric and colon cancer [96]. The plant was also investigated for its anti-inflammatory, antithrombotic, hypoglycemic, hypocholesterolemic and hypolipidemic activity, antipyretic, analgesic, radioprotective, antioxidant, antimicrobial, anticancer, and antiarthritic effects [80–82, 84–88].

13. Conclusion

Ten plant species were identified that show organoleptic correlation of optics of some part of the plant with a human organ: *Arrabidaea chica, Astrocaryum murumuru, Bauhinia splendens, Costus spicatus, Croton urucurana, Eleutherine bulbosa, Melissa*

officinalis, Phlebodium decumanum, Phyllanthus amarus, and *Zingiber officinale*. The best-known plants, *Arrabidaea chica, Melissa officinalis Phyllanthus amarus,* and *Zingiber officinale,* have more studies that prove their traditional applications. *Astrocaryum murumuru* does not present any published study record on its pharmacological actions attributed to popular medicine, demonstrating the need for more pharmacological research on the Amazonian plant biome.

Costus spicatus, Croton urucurana, Melissa officinalis, Phyllanthus amarus, and *Zingiber officinale* present their main traditional uses proven through scientific studies, corroborating the existence of a relationship between the morphological aspects of plants and the indication of use in traditional Brazilian medicine.

Finally, this study demonstrates the need for a multidisciplinary investigation to ascertain whether the Theory of signatures is used in traditional Brazilian medicine, whether in medicinal plants or as a device for memorizing medicinal plants and transferring traditional knowledge. The Amazon is one of the most biodiverse biomes globally and has a unique diversity of traditional knowledge that is being lost. Because of this factor, there is a need to investigate and document the knowledge and how it has been passed on from generation to generation for centuries.

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Author's contributions

E.B.F. performed the fieldwork and wrote the manuscript on the results obtained. L.A.J., R.C.R.K., P.F.S., A.P.S.R., and A.S.A.B. performed the fieldwork. J.C.T.C. coordinated and supervised the research project and contributed significantly to design and revision of the manuscript.

Declaration of competing interest

The authors declare that they do not have any conflict of interest.

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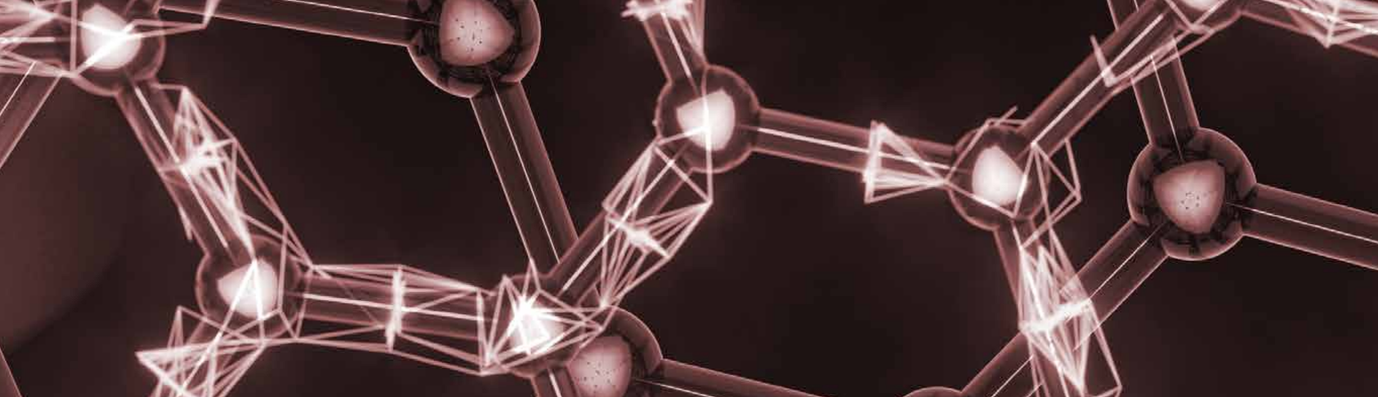

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Six chapters of this book describe recent findings on past and present wildlife and flora in the Amazonia. The significance of chemical prospecting in Amazonian biodiversity and biomass dynamics, as well as its impact on land uses, is presented in two chapters. Indigenous and modern perspectives on the use of medicinal plants are also well covered, and it is concluded that the protection of forest ecosystems is a major challenge in preserving knowledge about traditional healing methods. The potential discovery of new active medicinal molecules explains the broad interest in tropical ethnomedicine. Aquaculture development in Brazil has significant potential to reduce rainforest loss by providing a sustainable alternative to traditional livestock farming, which is a major driver of deforestation.

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