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Towards sustainable aquaculture in the Amazon

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Aquaculture in the Amazon holds the potential to meet increasing food demands while offering economic opportunities in a region facing deforestation and biodiversity loss. However, expanding aquaculture in this biodiverse region comes with complex environmental and social trade-offs. This Review explores how aquaculture can support sustainable development by minimizing its environmental impact, promoting equitable livelihoods and enhancing food security. It also highlights key challenges, such as greenhouse gas emissions and land-use changes, that need to be addressed for aquaculture to thrive sustainably in the Amazon.

Aquaculture has outpaced wild fisheries as the world's predominant source of aquatic foods[1]. The growth of aquaculture has been especially remarkable in biologically diverse regions with persistent undernourishment and underdevelopment, such as the Amazon[2]. While the expansion of aquaculture in the Amazon offers opportunities to enhance the region's food security, livelihoods and economic development, it also carries substantial environmental risks such as greenhouse gas (GHG) emissions, pollution and biodiversity impacts[3]. Further, aquaculture production occurs alongside other foods, such as cattle and wild fisheries, and the social–environmental trade-offs are relative. Thus, understanding aquaculture's potential to foster sustainable and inclusive development as a component of broader food systems is pivotal for aligning food production with sustainable development goals related to zero hunger, life below water and responsible consumption and production[4].

Beef and wild-caught fish are the predominant animal-derived foods in the Amazon. Cattle production has resulted in large-scale deforestation and carbon emissions, while overexploitation of fisheries has led to aquatic biodiversity change[5]. Thus, aquaculture has garnered considerable attention as a more sustainable alternative that can improve food production with lower environmental impacts and provide concrete and widespread social and economic benefits[5,6]. However, similar to aquaculture globally, the environmental and social impacts of Amazonian aquaculture production are not well characterized[7]. These uncertainties are compounded by the diversity of species farmed and management practices employed in the Amazon, as well

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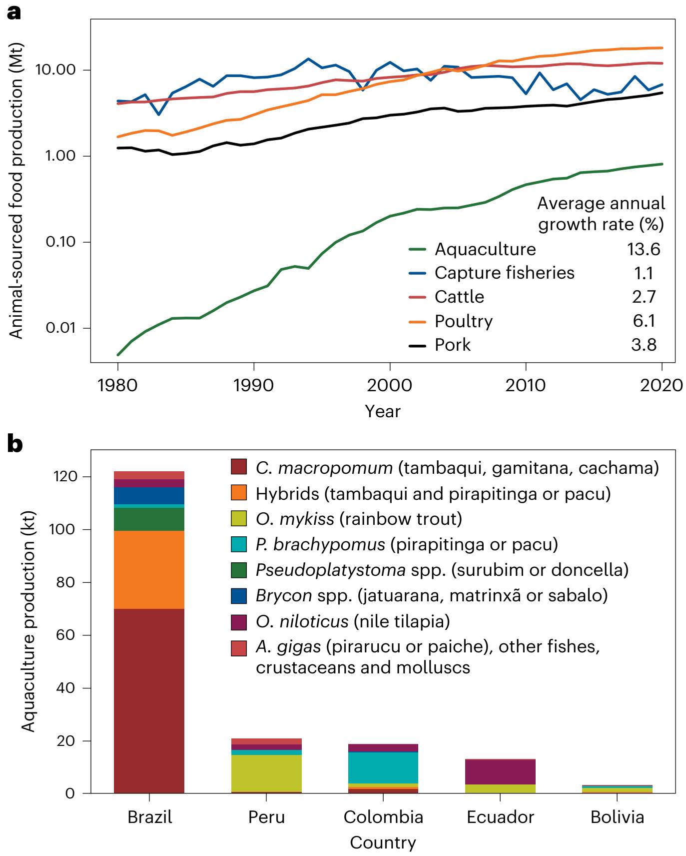

Fig. 1 | Aquaculture is the fastest-growing animal-sourced food system across the five Amazonian countries. a, Animal-sourced food production from 1980 to 2022 in Bolivia, Brazil, Colombia, Ecuador and Peru. **b**, Total aquaculture production and main species produced in the Amazon region of the five countries in 2021. Data from refs. 1,15,21,23,75,76.

as technological, logistical and market challenges[8]. It is also unclear whether farmed fish are similar in nutritional value and accessibility to other animal-sourced foods[9,10].

In this Review, we present an overview of expanding aquaculture in the Amazon, highlighting challenges and opportunities for its sustainable growth. We first analyse the development and current state of Amazonian aquaculture. We then discuss potential environmental impacts and analyse how aquaculture affects regional well-being through livelihood access and human health, key factors in assessing its contribution to sustainable food systems. We underscore the need for strategic approaches that balance aquaculture's growth with ecological preservation to ensure its sustainable expansion in the Amazon. We conclude by offering insights into the future of sustainable aquaculture in the Amazon with implications for global aquaculture development.

Overview of aquaculture in the Amazon

Aquaculture has a long history in the Amazon, with archaeological evidence of fish farms dating to AD 500[11,12]. Contemporary Amazonian aquaculture production began in the 1980s mainly with the founding of the Instituto de Investigaciones de la Amazonía Peruana in Peru and Embrapa Amazônia Ocidental in Brazil[13]. These public institutions fostered new cultivation technologies, from hatchery development to hormonal treatments[13]. Since then, Amazonian aquaculture production has grown exponentially (Fig. 1a). Of Amazonian countries, Brazil is the largest aquaculture producer, and its expansion has largely been supported by governmental and multilateral incentives[13] (Fig. 1b). In other Amazonian countries (Peru and Ecuador), freshwater aquaculture has been overshadowed by mariculture along their coasts, despite efforts to expand within the Amazon basin proper[1,14].

A diversity of species are farmed in the Amazon, with native species predominating because of cultural and market preferences as well as regulatory constraints. Farming of *Colossoma macropomum* (common names: tambaqui, gamitana or cachama) accounts for nearly half of aquaculture production in the Amazon, followed by *Piaractus brachypomus* (pirapitinga or pacu), *Pseudoplatystoma* spp. (surubim or doncella), *Brycon* spp. (matrinxã or sábalo) and *Arapaima gigas* (pirarucu or paiche) (Fig. 1b). The most commonly cultured non-native fishes include *Oncorhynchus mykiss* (rainbow trout), mainly at higher elevations in the Andean Amazon, and *Oreochromis niloticus* (Nile tilapia), which together accounted for 15% of total production in 2021 (Fig. 1b). However, this percentage is probably underestimated since many producers under-report production of non-native fishes such as Nile tilapia, which is illegal in certain Brazilian states. Crustaceans such as freshwater shrimp and molluscs are also produced, but at a much lower volume than fish[2,15] (Fig. 1b).

The regional distribution of species produced in the Amazon varies and reflects different market and environmental drivers. In the lowland Amazon, *C. macropomum* dominates cultivation, particularly in the Brazilian states of Roraima, Rondônia, Amazonas and Pará, where it is produced primarily on a semi-intensive scale (Fig. 2). Growth of *C. macropomum* production drives the overall rate of aquaculture expansion in the Amazon, and its production now has critical roles in regional food security and economic activity[16]. This growth is driven by its market appeal as *C. macropomum* has a desirable taste profile and can be raised in a variety of aquaculture systems and environmental conditions[17,18]. Expansion of *C. macropomum* cultivation has paved the way for a rising trend in creation and production of hybrid species, exemplified by *C. macropomum* × *P. brachypomus* (tambatinga, pacutana) which exhibits enhanced growth rates, disease resistance and adaptability to a wider range of farming conditions[15,19].

Non-native rainbow trout is the most commonly farmed fish in the Bolivian and Peruvian Amazon, with ~20 kt being produced annually (Fig. 1b). Rainbow trout farms are typically located at high elevations in the Andean Amazon (>2,500 m above sea level). Production in Peru doubled from 2012 to 2022, with 90% of product sold in domestic markets[20]. Relatively rapid growth rates and appropriate climatic conditions assure consistent fish production year-round, thereby maintaining steady food supplies and mitigating potential food shortages due to seasonal variations[21]. Thus, this non-native species has a critical role in Andean Amazon economies and food security[22].

Aquaculture in the Colombian Amazon, while constituting less than 10% of national fish production, has seen significant growth, from 9,300 tons in 2013 to 19,150 tons in 2020[23] (Supplementary Table 1). Despite this expansion, Colombia's primary centre of fish production remains outside the Amazon region in the department of Huila (~65% of the national output). The main species cultivated in the Colombian Amazon are *P. brachypomus*, *C. macropomum* and *O. mykiss*. Despite this recent boost, aquaculture in the Colombian Amazon region remains limited to extensive production, focusing primarily on *O. niloticus* production in recent years[24].

Environmental impacts of aquaculture expansion

The expansion of aquaculture in the tropics has been heralded as a sustainable solution to meet the rising demand for protein[25], yet this growth comes with environmental challenges. In the Amazon, aquaculture expansion raises ecological concerns, primarily around carbon emissions[26,27], land-use change[28], biodiversity impacts[29] and nutrient discharge to nearby water bodies[30]. The sector's reliance on feed production, the conversion of natural habitats for aquaculture purposes and the introduction of non-native species pose significant risks to local ecosystems. The nuanced interplay between the perceived benefits of Amazonian aquaculture expansion, such as lower GHG emissions

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	Subsistence and small-scale systems		Medium- and large-scale systems
Species	*A. gigas*, *O. niloticus* (mono or polyculture)	*C. macropomum*, *O. mykiss* (mono or polyculture)	*P. brachypomus*, *Brycon* sp., *Pseudoplatystoma* spp. (monoculture)
Regions	Amapá (Brazil); Pando, Beni (Bolivia); Meta (Colombia); Pastaza (Ecuador); Amazonas, Huánuco, Ucayli (Peru)	Acre, Roraima, Tocantins, Pará Amazonas (Brazil); Napo (Ecuador); Cusco, San Martín, Loreto (Peru)	Rondônia, Mato Grosso, Goiás (Brazil); Pasco, Junín (Peru)
Ponds	Irregular, small, low fish density		Regular, variable sizes, pond types for production stages (for example, fry stage)
Landscape	Within cattle ranch, small crops and forest	Built in waterways	Sharp forest edges, large crops and cattle ranch, well-defined roads
Technology	Limited access to technology and infrastructure, natural food sources		Industrial feed, aerators, fertilizer, antibiotics

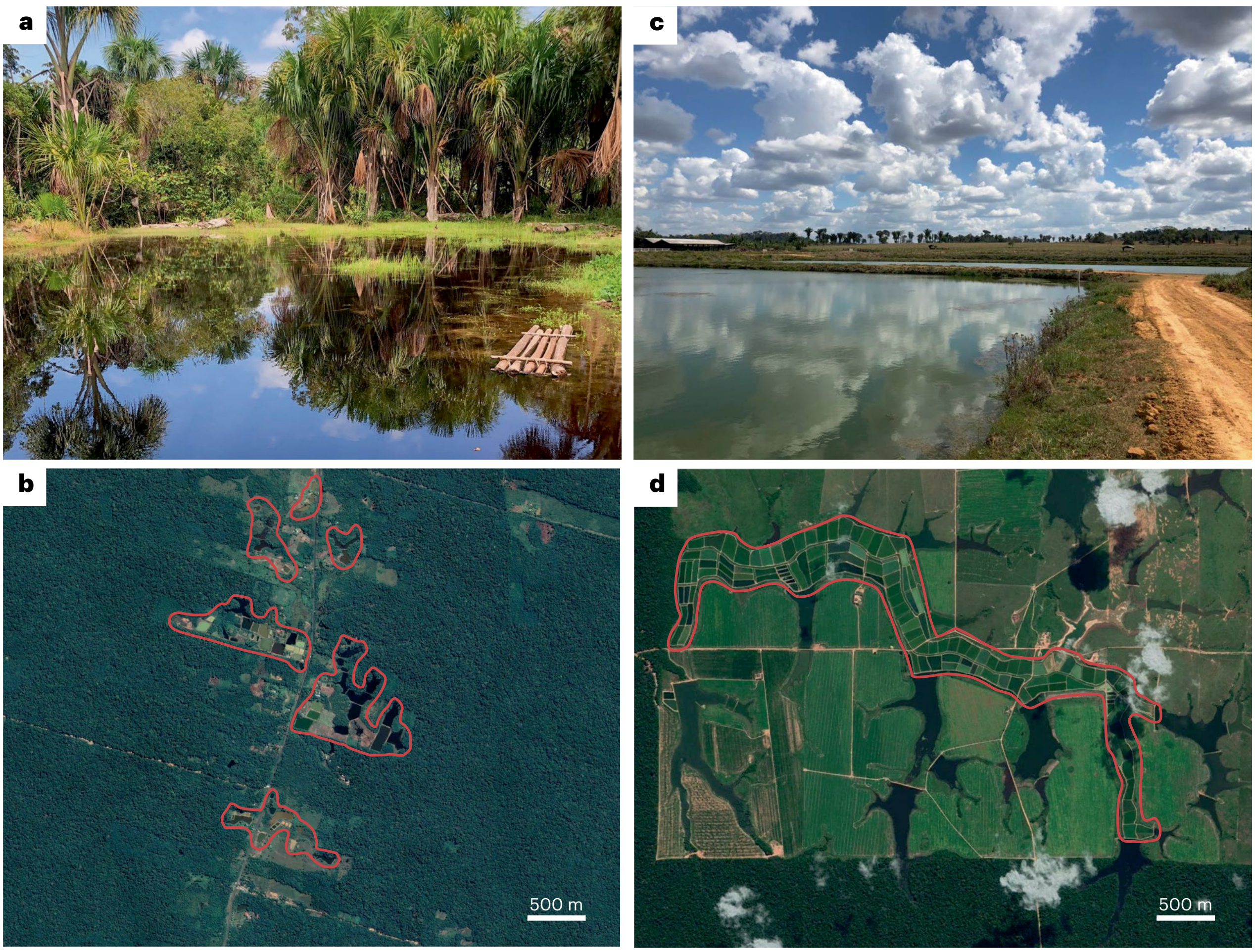

Fig. 2 | Aquaculture in the Amazon fits two typologies: extensive, which tends to be developed in subsistence and small-scale systems, and semi-intensive, developed in medium- and large-scale systems. a,**b**, Extensive aquaculture in the Amazon involves low-density fish production in small ponds with low intervention, relying mainly on natural food sources, leading to lower productivity. **c**,**d**, Semi-intensive aquaculture employs controlled, high-density ponds often supplied with water diverted from rivers, and fish are fed with industrial feed, resulting in higher yields in a smaller area. The red lines in the satellite images (**b**,**d**) circle the complex of ponds in each system to enhance visualization. Credit: satellite photographs in **b**,**d**, Google, ©2024 Maxar Technologies, CNES/Airbus.

compared with cattle production, and the inherent trade-offs, including environmental degradation and social impacts, requires careful examination.

GHG emissions

GHG emissions in aquaculture derive from indirect sources, such as feed production and land-use change, and direct sources such as emissions from ponds and fossil fuel consumption during production, processing and transportation activities. As with other food systems, quantifying indirect GHG emissions from aquaculture generally uses life-cycle assessment; however, such assessments may not always incorporate location-specific conditions due to lack of data availability, and both indirect and direct GHG emissions from aquaculture might be higher in the Amazon compared with other regions of the world. For example, while aquaculture feed is sourced through globally distributed supply chains, substantial amounts of fish feed inputs derive from crops within the Amazon region[31], potentially contributing to additional GHG emissions through deforestation for agricultural products. In some Amazon regions, land clearing for pond construction may also exacerbate deforestation and associated GHG emissions. Moreover, the vast spatial scale of the Amazon coupled with limited transportation infrastructure may lead to higher fossil fuel use in moving aquaculture

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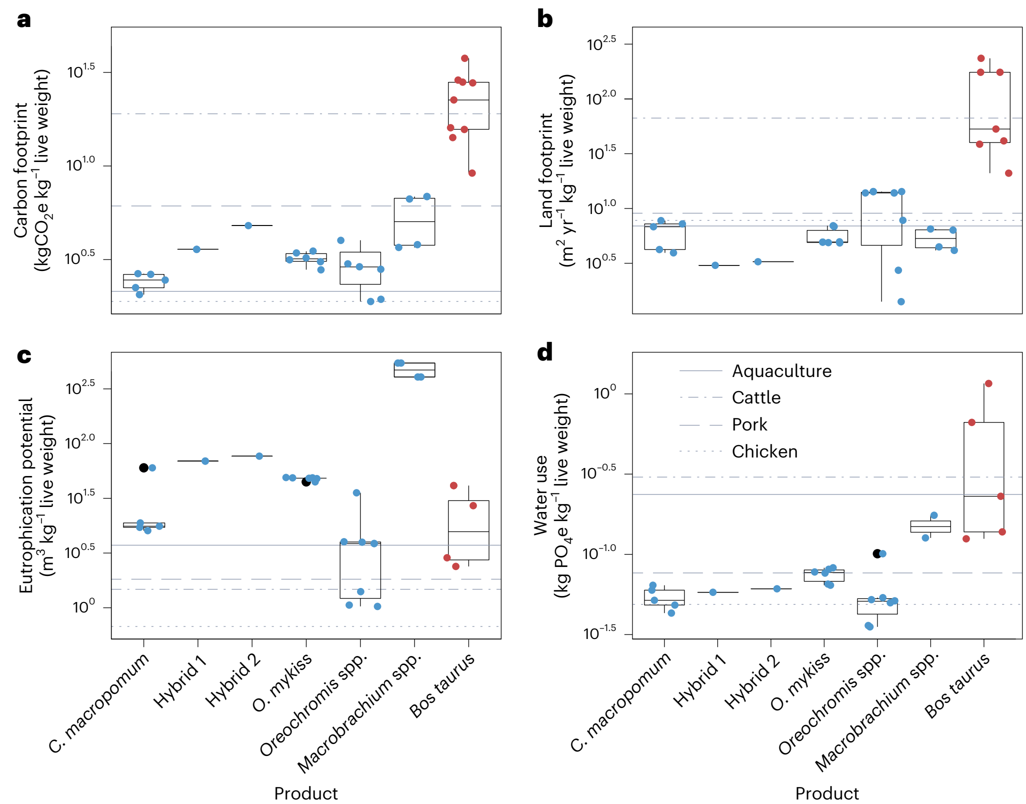

Fig. 3 | Life-cycle assessment suggests aquaculture generally has lower GHG emissions and requires less land compared with traditional livestock, suggesting a smaller environmental footprint for farmed fish species. **a**–**d**, Carbon footprint (**a**), land footprint (**b**), eutrophication potential (**c**) and water use (**d**) in the Amazon region of seven aquaculture and cattle ranching products. Values represent the footprint per kilogram of live weight produced. The blue and red dots represent the results from life-cycle assessments published in the literature for aquaculture and cattle production, respectively. The box represents the interquartile range, with the median as a line inside. Whiskers show data within 1.5 times the interquartile range, and black dots represent outliers. Hybrid 1 is the patinga hybrid *Piaractus mesopotamicus* × *P. brachypomus*, and Hybrid 2 is the surubim hybrid (*Pseudoplatystoma* sp. × *Leiarius marmoratus*). The grey reference lines are the global average carbon footprint (from ref. 3) (**a**), land footprint (**b**), eutrophication potential (**c**) and water use (from ref. 77) (**d**) of aquaculture, chicken, pork and cattle. Data for the Amazon region from refs. 37,78–82.

inputs and products throughout the region. Notably, life-cycle assessments do not yet include direct emissions from ponds[26,27].

Direct GHG emissions from aquaculture ponds may be enhanced by climatic and environmental conditions in the Amazon. Diffusive and ebullitive release of GHGs from aquaculture ponds are driven by decomposition of labile organic material derived from feed inputs[32,33], which can be converted to carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) via microbial activity in sediments and animal digestive tracts[34]. Aquaculture ponds in the Amazon combine conditions that promote CH_4 and N_2O production in sediments, such as high temperatures, water-column thermal stratification and anoxic environments[35], so we might expect higher rates of GHG production and emission relative to aquaculture ponds in cooler climates[36].

Existing information on indirect and direct GHG emissions suggests that species utilized in Amazonian aquaculture generally exhibit higher GHG footprints compared with the global aquaculture average (Fig. 3a). However, the most widely produced Amazonian aquaculture species (*C. macropomum*) has the lowest GHG footprint across all species for which emissions data are regionally available and is similar to the global aquaculture average (Fig. 3a). This global average is primarily from mariculture, which has species such as salmonids with a low food conversion rate, and consequently reduced GHG footprints. Regardless, despite having higher food conversion rate and GHG footprints compared with the global aquaculture average, the overall GHG footprint of Amazonian aquaculture remains lower than that of pork and is three to ten times lower than that of cattle.

Land-use and habitat impacts

The magnitude of environmental externalities associated with aquaculture production hinges largely on the land-use and land-cover transitions its expansion entails. Land-use and land-cover change can adversely impact biodiversity via the conversion of natural to unfavourable habitats. If aquaculture expansion in the Amazon requires newly deforested land or conversion of wetlands, it is unlikely to prove environmentally sustainable. If it instead uses previously deforested or degraded land that has been abandoned, it may provide a unique opportunity to produce substantial quantities of profitable food with a limited land footprint (Box 1 and Fig. 4).

In addition to the potential impacts on biodiversity, the land footprint of aquaculture can increase GHG estimates per kilogram of fish produced depending on land-use history. For example, converting forests to ponds would have a different GHG footprint than converting degraded pastures into ponds. In addition, although the land required to produce a ton of fish is less than for a ton of beef (Fig. 1b), fish feed production may demand land and freshwater resources elsewhere[28]. For example, the area required for feed production is three times that of fish rearing produced in semi-intensive systems[37]. Despite these potential direct and indirect land-use impacts, Amazonian aquaculture's land footprint per biomass of live weight produced can be more than 100 times lower than that of cattle ranching (Fig. 3b), which is magnified by the low land-use efficiency of cattle ranching. A thorough accounting of the land use associated with Amazonian aquaculture expansion is needed to understand its environmental footprint.

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BOX 1

Land-use and restoration potential

The shift towards aquaculture in the Amazon could be a game-changer in the region's struggle against deforestation, traditionally driven by extensive livestock production[83]. As a more efficient way of using land, aquaculture expansion could help align economic growth with conservation efforts. Although deforestation dynamics are complex, aquaculture expansion opens possibilities for vast tracts of the Amazon to be relieved from agricultural and cattle ranching pressure. Regions such as Roraima and Tocantins in Brazil and countries such as Colombia and Peru are transitioning towards increasing aquaculture while reducing or stabilizing cattle production[1,15] (Fig. 5). However, the full spectrum of advantages and drawbacks of this shift has yet to be thoroughly assessed.

The freed-up land from shifts to aquaculture could not only help reduce deforestation rates but also provide valuable opportunities for ecological restoration. Land restoration could have multifaceted benefits, such as biodiversity conservation and the enhancement of ecosystem services[84]. In addition, these restored regions might become potential sites for carbon credit projects, providing financial motivation to preserve and increase forest coverage[85]. This strategy could have a crucial role in global carbon offsetting and bolster local economies, thereby reinforcing the integration of aquaculture into the Amazon's sustainable development plan. Moreover, if successful, this approach could lay the groundwork for similar strategies in other regions in the world where aquaculture is rapidly expanding, setting a precedent for balancing development and conservation.

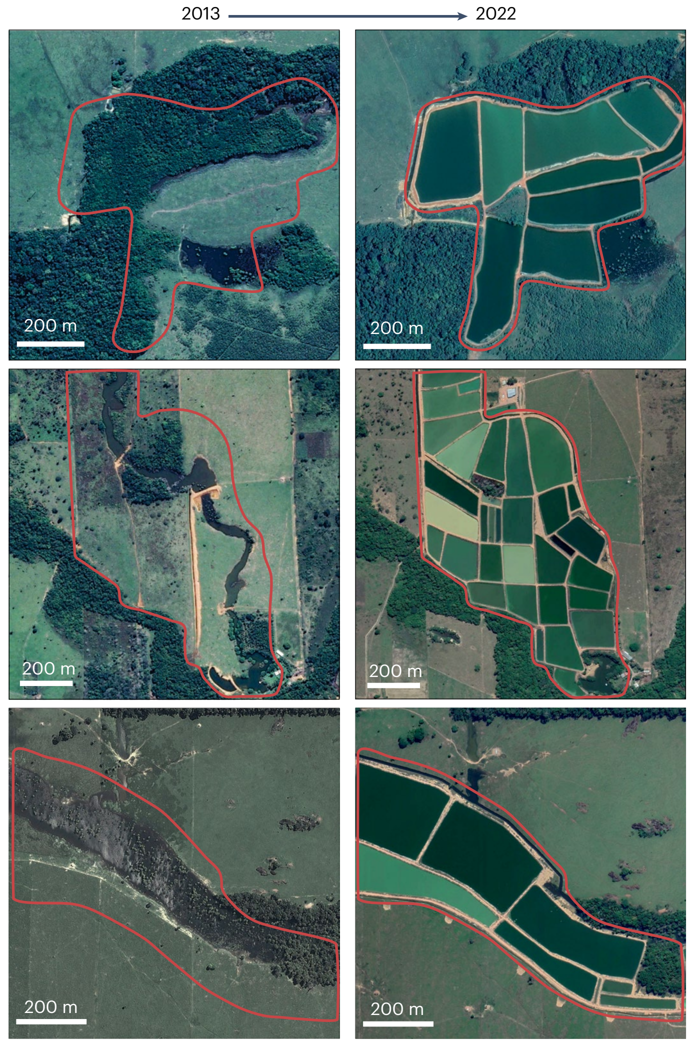

Fig. 4 | Satellite images from 2013 and 2022 from three sites with constructed fish ponds in Rondônia reveal myriad land-use transitions associated with expanding aquaculture, which need to be integrated into land-use and GHG accounting. Left: 2013; right: 2022. The red lines circle the same area in both years for reference to the previous land cover. Credit: satellite photographs, Google, ©2024 Maxar Technologies, CNES/Airbus.

Beyond traditional land-use impacts, many farms in the Amazon rely on building dams and ponds on river channels, which can disrupt river network connectivity (Fig. 4). River fragmentation is among the most significant threats to freshwater ecosystems globally and in the Amazon[38,39]. A large number of small dams for aquaculture farms have already been built over the Amazon basin, notably in the metropolitan region of Manaus and the states of Acre and Rondônia[40]. The construction of dams for aquaculture disrupts fish migratory patterns, alters flow regimes and leads to habitat loss, including in river confluences, which are migratory hotspots[41,42]. This disruption tends to reduce biodiversity and adversely affect certain species, including those that are economically valuable[42].

Farmed fishes and biodiversity risk

Cultivating non-native fishes in the Amazon presents a growing threat to freshwater biodiversity. Using spatio-temporal records covering over 80% of the Amazon region, ref. 29 revealed an alarming trend in increased non-native fish occurrence. While the first non-native fish introduction in the Amazon can be traced back to 1939, 75% of occurrences are dated between 2000 and 2020. Many of these non-native fishes are linked directly to aquaculture, including pirarucu, tilapia and rainbow trout. Pirarucu, which is native to the Amazon River, was restricted to the lowlands but was introduced through aquaculture and now has become invasive in Bolivia and Rondônia[43]. While impacts on native species and ecosystems are uncertain, as the largest freshwater fish in South America and a top predator, pirarucu could lead to food-web changes and cascading ecosystem effects. Tilapia are well known to alter aquatic ecosystem processes globally[44,45] (Box 2). For example, in various ecosystems worldwide, tilapias have outcompeted native species[46], altered habitats[44] and even hybridized with native fish, leading to a loss of genetic integrity[47]. The use of *Pangasianodon hypophthalmus* (striped catfish) in aquaculture was reported in many places in South America but not in the Amazon[48]. Should this species become established in Amazonian rivers, it may directly compete for resources and spawning grounds with native species belonging to analogous trophic guilds[49].

Aquaculture is frequently seen as a solution to overfishing by offering a different fish source (Box 3). Yet it may affect wild fish biodiversity as farmers typically depend on wild populations for broodstock or young fish, notably in the central and western Amazon floodplains for pirarucu cultivation[50]. The extent of this practice is unknown, but hatcheries are being established to reduce dependency on wild stocks[51].

Water demand and nutrient loading

The water-use efficiency of aquaculture is often compared with cattle ranching (Fig. 3c). This comparison underscores the notion that aquaculture, while not inherently more water conservative than terrestrial livestock farming, exhibits a nuanced impact on water resources

BOX 2

The Amazon's non-native fish dilemma

The burgeoning presence of non-native fishes in the Amazon signals potential harm to its endemic species[29]. Many of these non-native fishes possess traits that are desirable to producers but also enable them to thrive and invade new habitats. Numerous regulations in Amazon countries have given precedence to non-native fishes over native species due to their perceived economic benefits. Such decisions, such as Colombia's to naturalize Nile tilapia, highlight this concerning trajectory[86]. Similarly, encouraged by business interests, Brazil has been flirting with the idea of naturalizing by decree the Nile tilapia, which has been introduced in much of the country outside the Amazon region[87,88]. Amidst these policy incentives, the vital importance of native fish species for sustainable aquaculture often remains overlooked.

Tilapia farming epitomizes the discussion on potential challenges and opportunities for sustainable Amazonian aquaculture. While the production of non-native fishes poses risks to biodiversity, a well-managed and strategically planned aquaculture system can reap benefits from non-native fish production, such as tilapia. The high efficiency of tilapia production underlies its economic attractiveness as it is inexpensive to produce and has a healthy domestic and global market[2]. Further, tilapia's robustness and disease resistance potentially reduce the need for excessive chemical treatments of antibiotics, fostering a more environmentally friendly aquaculture model[89]. From a social perspective, tilapia cultivation has been instrumental in generating employment and invigorating local economies from raw material sourcing to distribution[90]. However, tilapia's potential ecological impacts are pervasive, but comprehensive studies in the Amazon are still limited. The expansion of tilapia farming, with its economic benefits yet potentially large environmental costs, underscores the need for thorough risk assessments and coordinated management efforts when introducing non-native fishes into the Amazon.

BOX 3

Relieving fisheries overharvest with aquaculture

Inland capture fisheries are vital for food security and livelihoods in the Amazon[91], but are also driving changes in aquatic biodiversity and ecosystems[5]. Large-bodied species, some of which are also farmed (for example, *A. gigas*, *C. macropomum*), are showing signs of overexploitation[92]. Thus, government agencies and nonprofit organizations have promoted aquaculture as a solution for relieving pressure on wild fishes, while still providing a source of nutrition. Yet aquaculture's potential to provide an alternative food source while shifting demand from wild to farmed fish and relieving overexploitation is poorly understood.

The degree to which aquaculture can be integrated into conservation approaches and address the immediate threats of overexploitation on freshwater biodiversity depends on myriad factors, such as whether the same species are being cultivated in farms and caught in the wild, and the degree of market integration. For example, when farmed and wild fish of the same species are substitutable in the market, an increase in farmed fish supply can drive down prices, making it less profitable for wild fishers[93]. Over time, this could lead to reduced overexploitation of wild stocks. However, aquaculture and fisheries production often operate in parallel, serving different markets and beneficiaries. Instead of replacing wild-caught fish, the growth of aquaculture has been additive to wild fish availability, as aquaculture has responded to an overall increase in fish demand, benefiting farmers rather than those who rely on wild fisheries[94–96]. While such studies do not exist for the Amazon, little evidence elsewhere supports the notion that aquaculture suppresses wild fisheries overexploitation[94]. In addition, aquaculture producers often capture fingerlings from the wild, so the activity could further contribute to population declines[97]. Moreover, marine fish are a major ingredient in fish feed, and even if farming fish relieves overexploitation in the Amazon, the impact on wild fisheries could shift to other ecosystems[98,99]. However, there is limited evidence that aquaculture has caused declines in wild fish stocks, since many of the fishery species in fishmeal are not overexploited[100]. Ultimately, disentangling the effects of aquaculture on wild fisheries is challenging and requires information that is often not available in the Amazon.

that is highly species specific. Water-use efficiency in aquaculture is particularly important in the context of climate resilience, as water scarcity and extreme drought events are increasingly common in the Amazon[52]. Further, the high water demand for aquaculture can lead to conflicts between various water uses and users, such as domestic water supply and energy production, even in regions with abundant water, such as the Amazon[53].

Nutrient-loading risks, expressed as eutrophication potential in life-cycle assessments, suggest that aquaculture has a lower probability of causing excessive nutrient enrichment and subsequent water body over-fertilization compared with cattle ranching over the entire production cycle (Fig. 3d). Despite a smaller total nutrient footprint, as aquaculture facilities are usually located adjacent to or within rivers and streams, even small pulses of nutrient release might have important consequences for nearby aquatic ecosystems over short or long periods. Consideration of nutrient loading is especially important within the arc of deforestation, where the highest rates of agricultural expansion and ecological degradation are already occurring. Nutrient loading from aquaculture, in addition to cattle or crop production, and the reduced capacity of forests to sequester nutrients before entering aquatic systems could further exacerbate local ecological strain. Such scenarios are already unfolding. For example, the Brazilian state of Rondônia—situated in the arc of deforestation—is the Amazon's largest producer of farmed fish[54]. Together with the rapid expansion of soybean cultivation, which already compromises water resources in the region, increased aquaculture will require more water and drive further eutrophication[55].

Social dimensions of Amazonian aquaculture

Sustainable development of Amazonian aquaculture will depend on the sector's ability to contribute to human well-being through equitable benefits sharing and by facilitating positive food security and health outcomes[4]. The Amazon is socioeconomically diverse, with people living across rural and urban communities, some of which are remote and others highly connected. Hence, aquaculture's social and economic impacts will be contextually dependent on the full food system portfolio, including wild fisheries and cattle. Here, we outline some potential impacts of aquaculture on human well-being in the region. We focus on livelihood access, nutrition and disease incidence,

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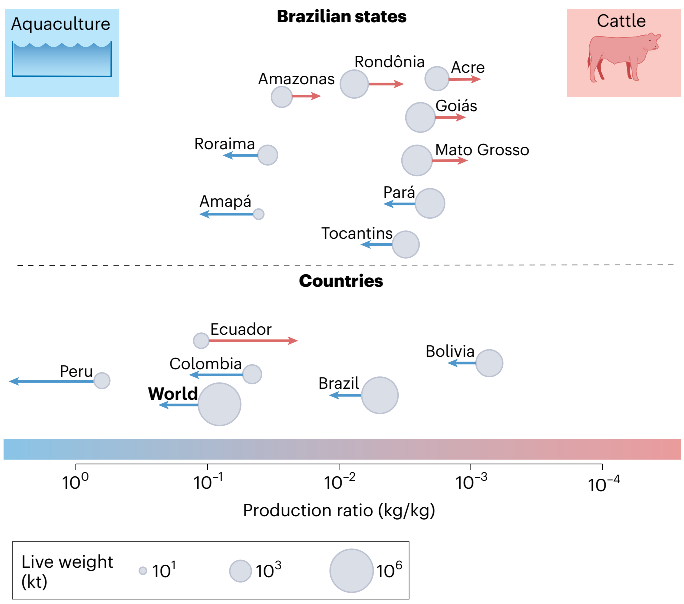

Fig. 5 | Ratio of freshwater aquaculture production to cattle production by weight in various Amazon Brazilian states and countries, highlighting the scale and trend of aquaculture compared with traditional cattle farming. The blue and pink arrows indicate whether the production ratio (the ratio of freshwater aquaculture to cattle products in terms of kilograms of freshwater aquaculture per kilogram of cattle) is increasing or decreasing, respectively. The arrow size is proportional to the change in the ratio between 2013 and 2021. The size of the dots indicates the sum of aquaculture and cattle production in kilotons of live weight in 2021. Data from FAO (https://www.fao.org/faostat/en/) and IBGE (https://www.ibge.gov.br/en/). Figure created with BioRender.com.

as these social dimensions are often emphasized when assessing the sector's contribution to food systems sustainability[4,10].

Livelihood access

Sustainably managed aquaculture food systems can improve flows of economic revenues and improve livelihoods[56], although few studies exist for the Amazon. Equitable access to aquaculture benefits will depend on the structure of supply chains and the economic policies that drive their development[57]. Small and large aquaculture operations in the Amazon face contrasting challenges in the aquaculture supply chain[58]. Small aquaculture farms in the Amazon are often family run and smaller than 1.5 hectares. These farms are often based on a 'farmer-controlled' supply chain, which integrates various economic roles, from production to direct sales to consumers, enabling them to capture a larger revenue share despite their lower production levels. Small aquaculture farms rely on temporary labour and rudimentary technologies, impacting costs and operational efficiency[58]. In addition, while beneficial for revenue capture, their direct-to-consumer sales model restricts production scale and market reach[59,60]. Thus, livelihood access through small-scale farms that struggle with profitability may be variable and unstable. By contrast, larger farms are often based on an 'intermediary-controlled' supply chain, which utilizes distribution intermediaries and typically targets value-added and higher-volume production strategies to benefit from market access and economies of scale. While capable of generating higher total revenues due to larger-scale production, these farms can contribute to a narrower distribution of wealth and potentially benefit fewer people[16,61].

Aquaculture policies can influence supply chain development through investments into infrastructure, formalization of extension support services and economic incentives that promote business development, among a suite of other levers. Collaborative development of aquaculture policies incorporating producers and regulators thus presents an important opportunity to promote equitable livelihood access and benefit sharing for Amazonian aquaculture food systems[4,8]. The farmer-controlled supply chain ensures wealth distribution, significantly benefiting small farms and supporting sustainable development goals such as poverty alleviation, food security and reduced inequalities[61]. In addition, small producers can benefit from collective practices, such as cooperatives or producer associations, which can pool resources for better market access, shared processing facilities and collective bargaining power[59,60,62]. However, intermediary-controlled supply chains are more favourable for larger operations that have the capital to invest in technologies such as cold storage and fast transportation. While there is potential for spillover effects from larger commercialized operations to support economic opportunity for adjacent small-scale farmers by developing markets and distribution infrastructure, the degree to which this occurs is not well understood[63,64].

Implications for human health

Aquaculture expansion could have positive and negative consequences for people's health. For example, in the Peruvian Amazon, aquaculture could enhance food security by providing a stable supply of essential macro- and micronutrients as wild fisheries stagnate or decline[2,65]. However, shifting diets from wild to farmed fishes could also undermine nutrition since aquaculture species tend to be of lower nutritional quality than wild fishes[9,65]. Further, although maintaining access to a diverse portfolio of food species is paramount for providing adequate nutrition, aquaculture is often characterized by few species prioritized for economic rather than nutritional reasons[65]. Some aquaculture species produced in the Amazon tend to be more expensive than small-bodied nutrient-rich wild fishes, making them less financially accessible[65]. This price difference could hinder access for poorer population segments, especially when compared with wild fish[10].

In addition to nutrition, aquaculture can affect human health via increased disease incidence. For example, mosquitoes that carry malaria (*Anopheles* spp.) are often more abundant in stagnant water bodies, including aquaculture ponds[66]. Indeed, the proliferation of aquaculture has been linked to increased malaria incidence in the Amazon, but the broader factors (for example, landscape features, management practices) that affect transmission have not been well accounted for[67]. In addition, although rare, cases of Haff disease have been associated with consumption of certain farmed fish (for example, *C. macropomum* and *P. brachypomus*)[68] (Supplementary Fig. 1). Other potential health impacts of aquaculture can come from farm effluent discharge, which contaminates nearby water sources with antibiotics and other chemicals and poses a risk to human health if contaminated fish are consumed[69] (Supplementary Fig. 2).

Towards aquaculture sustainability

Conventional food systems, including livestock and wild fisheries, have taken a major ecological toll on the Amazon. Amazonian aquaculture is still in the early stages of growth (Fig. 5), and this sector could follow a path of conventional expansion that contributes to ongoing ecosystem degradation or, if sustainably developed, could serve as a lever for positive social and ecological outcomes with the potential to offset impacts from other food systems. Following a sustainable path of expansion would require adhering to five key principles.

Sustainable aquaculture development embraces a broader land-use context. The environmental impact of aquaculture in the Amazon, and specifically its carbon and habitat conversion footprint, is intertwined with the historical land-use context in which it occurs. Aquaculture expansion in the Amazon is occurring across a mosaic of land-use history, including vast tracts of intact old-growth rainforest and regions dominated by highly degraded pastures such as in the arc of deforestation. Policies that incentivize siting of aquaculture operations on already degraded land can help reduce further land conversion and facilitate the development of climate-smart aquaculture in the Amazon. For example, developing aquaculture operations on cattle ranches could contribute to food production and livelihoods while potentially offsetting the need for further deforestation of inefficient livestock-based food systems. Siting aquaculture operations on previously degraded lands away from stream networks could also reduce impacts on rivers. Indeed, damming rivers for pond construction should be discouraged as these practices impact river connectivity and can increase nutrient and pollution outflow to water bodies (Fig. 2).

Biodiversity-centred strategies promote opportunities for food production efficiency and lower the ecological risks of aquaculture. The Amazon basin is Earth's most diverse freshwater system, with over 2,500 fish species. Yet Amazonian aquaculture is concentrated on few species, which are often produced in monocultures. Integrating biodiversity within farms and tapping the broader biodiversity available in the region can advance aquaculture sustainability. For example, polycultures typically increase resource use efficiency in aquaculture ponds[56]. In addition, leveraging the existing genetic diversity within wild populations of farmed species can yield varieties that are more disease resistant, reducing the need for antibiotics and other management practices that may have high economic and ecological costs. That said, a cautious approach to leveraging fish biodiversity for food production is warranted since new varieties can also contaminate wild populations. Indeed, non-native species, particularly tilapia, threaten Amazonian fish biodiversity, and similar detrimental impacts, including inbreeding and disease transfer, could also arise from the introduction of new genetic varieties of native species. These risks underscore the need for monitoring farm-level practices and for policies and regulations that incentivize the use of diverse native species over non-native species.

Sustainable aquaculture enhances equitable benefits sharing. The Amazon is culturally, politically and socially diverse, encompassing large urbanized population centres and a matrix of remote rural communities. In this context, economic and political barriers present obstacles to aquaculture supply chains that promote equitable benefits sharing. For example, remoteness, high input costs, poor distribution infrastructure and lack of access to capital impede the profitability of small aquaculture farms throughout the Amazon. If left unaddressed, these logistical headwinds may favour conventionally intensified large aquaculture operators based on intermediary-controlled value chains that leverage economies of scale and ultimately concentrate wealth in a small subset of sector participants. Thus, aquaculture development policies that balance a diversity of both farmer-controlled and intermediary-controlled value chains are critical. Further, ensuring access to alternative livelihoods for actors who are displaced by expanding aquaculture is essential for just food system transitions, especially if aquaculture is to contribute to offsetting ecosystem impacts of other food systems. For example, cattle ranchers are already leveraging aquaculture to diversify their livelihoods, whereas wild-capture fisheries participants are not yet integrated into aquaculture, impeding the potential for farmed fish production to alleviate pressure on wild fisheries in the Amazon. Growing evidence from case studies across other developing aquaculture regions emphasizes a need to avoid policies that target small-scale or larger-scale aquaculture operators in isolation and rather highlight the need for integrative policy development that considers a diversity of producers and aquaculture-adjacent food sectors[64].

Information flows are essential for operationalizing sustainable aquaculture. Widespread data deficiencies on the location of aquaculture operations and farm-level practices currently impede effective management and hamper opportunities to develop sustainable aquaculture policies in the Amazon. These deficiencies range from a lack of information on production statistics (for example, species cultivated, feed sources, disease incidence) and market dynamics to poorly accounted environmental footprint of aquaculture production (for example, GHG emissions, land-use conversion). This data deficiency represents a barrier to effectively scaling up our understanding from individual farms to the broader regional context of the sector's impact. Leveraging contemporary data generation and data processing technologies such as remote sensing, smart aquaculture equipment and artificial intelligence will enable more accurate assessments of environmental impacts and facilitate better management practices and tailored effective policy development. Although initiatives such as the Brazilian Agricultural Research Corporation's geoweb platform (SITE aquacultura, https://www.embrapa.br/en/site-aquicultura) represent efforts towards overcoming these limitations.

Access to technology and financial resources is requisite for boosting production at reduced environmental costs. Aquaculture farms in most regions of the Amazon lack access to modern aquaculture technologies and practices, instead relying on traditional 'extensive' practices with low productivity and poor environmental performance[66] (Fig. 2). Modern aquaculture technologies such as bubblers that prevent deoxygenation of waters, feed control systems that minimize waste, and optimized rearing densities can reduce aquaculture's GHG footprint and simultaneously improve livelihoods by increasing farm-level production efficiency[70]. However, there is a risk that greater access to technology could drive intensification, potentially leading to increased land clearance in the pursuit of higher profitability. To mitigate this, strong regulatory frameworks and land-use planning will be essential to ensure sustainable intensification. Broadening access to technologies and knowledge requires both regional public investment in infrastructure as well as local support for farmers through extension and education programmes. Similarly, access to financing aimed to support farmer implementation of sustainable practices will be critical[71]. While long-term increases to public budgets for sustainable aquaculture management are unlikely, the 'conservation financing' space that harnesses private or public–private partnership investment strategies seeking dual ecological and investment returns holds great promise for mobilizing financial resources to promote sustainable aquaculture practices. Activity in the conservation finance space is already increasing in the mariculture sector[72], and sector surveys indicate demand from potential investors for conservation investments in aquatic systems. However, a lack of investable projects currently hampers flows of capital towards projects that improve sustainable aquaculture development[73]. Greater cooperation across finance, aquaculture and environmental disciplines could help catalyse the development of investable sustainable aquaculture projects in the Amazon[74].

Outlook

The expansion of aquaculture in the Amazon presents opportunities as well as challenges. Embracing the core principles offered in the preceding will be key for building an enduring and resilient foundation towards sustainable aquaculture in the world's most biodiverse biome. Failure to adhere to these principles risks adding further strain to already vulnerable ecosystems. Inevitably, the course of aquaculture development will contrast sharply among regions, with some parts of the Amazon marked by large swaths of old-growth rainforest and others by the arc of deforestation. In the context of this regional variation, we have highlighted some of the major environmental and social impacts of Amazonian aquaculture, as well as some of its promises. However, it is crucial to recognize that aquaculture has historically contributed to intensification rather than alleviating pressures on other food systems, such as fisheries and livestock production. We conclude that for Amazonian aquaculture to be sustainable, it will require harmonizing environmental stewardship with the burgeoning need for food production in a manner that respects the unique biodiversity and cultural heritage of the region. Strong regulatory frameworks, land-use planning and careful management of intensification will be essential to prevent aquaculture from becoming an additive pressure in this fragile region.

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Competing interests

The authors declare no competing interests.

Additional information

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