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Complex, diverse and changing agribusiness and livelihood systems in the Amazon

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ABSTRACT

Finding pathways to more sustainable agriculture and resource use remains the most pressing challenge for Amazonian countries. Characterizing recent changes in the structure and types of agrarian production systems, this review identifies responses to deal with the challenges and opportunities to promote more sustainable production and extraction economies in the Amazon. While regional agriculture and resource economies rest on a rich diversity of producers, knowledge, and production systems, the expansion of agribusiness enterprises has come to dominate the distribution of subsidies, institutional support, and logistical infrastructure. These trends are associated with forest loss and degradation, pollution of waterways, pressures on and/or displacement of indigenous and rural communities, and increased greenhouse gas emissions, all of which undermine ecosystem services. We analyzed the diverse and complex impacts of socio-economic and hydro-climatic changes on livelihoods, environments and biodiversity in Amazonian countries, with a more in-depth focus on changes in key agrarian production systems in the Brazilian Amazon using agrarian census data from 1995, 2006, and 2017. The quantitative analysis is complemented by a qualitative and empirically grounded discussion that provides insights into the changes and impacts of different activities, how they are interlinked, and how they differ across Amazonian countries. Finally, we provide recommendations towards promoting adaptive, profitable, and more sustainable smallholder production and management systems that reduce deforestation and support local communities and economies in the context of increasing urbanization and climate change.

KEYWORDS: production trajectories, agriculture, livestock, agroforestry, fisheries, land speculation

Complexidade, diversidade e mudanças no cenário agricultural na Amazônia

RESUMO

Encontrar caminhos para a agricultura e uso dos recursos mais sustantáveis ainda apresenta o desafio mais urgente para os países amazônicos. Esta revisão caracteriza o status quo e as mudanças recentes na estrutura e nos tipos de sistemas de produção rural, e identifica respostas para lidar com os desafios e oportunidades na promoção de economias extrativistas e agrícolas mais sustentáveis na Amazônia. Enquanto a agricultura regional e economia de recursos se baseiam em uma rica diversidade de produtores, conhecimentos, e sistemas de produção, a expansão do agronegócio chegou a dominar a distribuição de subsidios, o apoio institucional e a infraestrutura logística. Estas tendências estão associadas com a perda e a degradação das florestas, a poluição das águas, pressão e/ou deslocamento de comunidades indígenas e rurais, bem como o incremento nas emissões de gases com efeito de estufa, minando os serviços ecossistêmicos. Analisamos os impactos diversos e complexos das mudanças sócio-econômicas e hidroclimáticas sobre sistemas de

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produão, nos meio-ambientes e na biodiversidade nos países amazônicos, com um enfoque mais aprofundado sobre os sistema-chave de produção agrária na Amazônia brasileira usando dados dos censos agropecuários de 1995, 2006 e 2017. A análise quantitativa é complementada por uma discussão qualitativa e empiricamente fundadas sobre as mudanças e impactos de diferentes atividades, como estão interligadas, e como diferem entre os vários países amazônicos. Finalmente oferecemos recomendações para a promoção de sistemas de produção e gestão de pequenos agricultores adaptáveis, rentáveis e mais sustentáveis, que reduzam o desmatamento e apoiem as comunidades e economias locais no contexto da crescente urbanização e mudanças climáticas.

PALAVRAS-CHAVE: trajetórias de produção, agricultura, gado, agrofloresta, pescaria, especulação de terras

INTRODUCTION

This review is derived from a chapter of the report produced by the Science Panel for the Amazon (https://www.theamazonwewant.org/). The aim of the report was to perform a scientific assessment of the current state of the Amazon and explore opportunities for policy relevant actions. Broad accessibility to this information is at the core of understanding the complexity of the Amazon basin and the urgency for conservation actions.

Finding paths to transition agriculture and resource use from unsustainable to more sustainable practices is among the most pressing challenges faced by Amazonian countries. This review focuses on recent rapid changes in the structure and systems of production by which specific types of actors in the Amazon region produce economic value (by combining labor, natural resources, and technology in different systems). It also explores the implications of these changes for the environment and society of the region and highlights local responses to deal with the challenges and opportunities to engage in more environmentally sustainable production and use of natural resources in the Amazon.

The discussion focuses on Brazil, due to the rich data available, which reveals the rapid expansion of agribusiness over the past few decades in the Brazilian Amazon. Favored by pro-short-run growth and export policies, the gross value of agricultural, livestock and extractive production (GVP) of the municipalities that make up the Brazilian Amazon biome grew from USD 5.1 billion in 1995 to USD 20.2 billion in 2017, expanding nearly fourfold over the two decades.[1] This growth was due largely to the rapid expansion of agribusiness production structures and systems, which grew from 48% of the total GVP in 1995 to 80% in 2017. In contrast, the small farm sector collapsed from 52% to only 20% in the same time period.

In the territories of the different countries that share the Amazon, agro-industrial economies have been expanding rapidly in recent decades, reflected in the increased area of the soy-corn system, livestock, and palm oil plantations. This dynamic growth, with important impacts on public lands, has been favored by pro-short-run growth policies (Hecht *et al.* 2021). Historically, both traditional, long-term and recently-arrived large-scale farmers and smallholders have interacted with one another and with the highly diverse, complex natural environment of the Amazon, mediated by different institutions and alternative technical resources, thus shaping a plural, multifaceted reality (Hecht *et al.* 2021). The impacts of socio-economic and hydro-climatic changes on livelihoods, environments and biodiversity are very diverse and complex in each Amazonian country, involving distinct actors within different modes and structures of production.

The in-depth quantitative case study on the Brazilian Amazon focuses on changes among key agrarian production systems (dominated by agriculture, cattle raising, agroforestry or tree plantations), through analysis of comparable agrarian census data from 1995, 2006, and 2017. It demonstrates the growth of agribusiness, which entailed the large-scale appropriation of about 13 million ha of public land between 1995 and 2017 (Supplementary Material, Table S1). Appropriated lands were increasingly transformed into pastures and agricultural areas, from 37 million ha (43.0% of total owned land) in 1995 to 57.8 million ha (58.5%) in 2017. This structural land-use shift resulted in deforestation of 20.8 million ha between 1995 and 2017, and a concomitant critical reduction in labor demand from 2.3 million workers in 1995 to 1.7 million in 2017, leading to a massive out-migration of people from agrarian employment to jobs in infrastructure, extractive industries, and Amazon towns and cities (Supplementary Material, Tables S2 and S3).

The quantitative analysis of these changes in the Brazilian Amazon is complemented by a qualitative empirical discussion that provides more in-depth insights into the changes and impacts of the different activities, production systems and structures, and how they differ from other Amazonian countries. In the final section, we provide proposals to document, test and promote adaptive, profitable and more sustainable production and management systems in the context of urbanization and climate change.[2] We end with a series of recommendations and suggestions to transition to more sustainable production and resource use that can facilitate Amazonian countries achieving the Sustainable Development Goals (SDGs) (Griggs *et al.* 2013).

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[1] All values in Brazilian Real (BRL) were adjusted to 2019 prices by the IGP-FGV index (Brazil), and converted from BRL into USD by the exchange rate of 31 Dec 2019: USD 1:BRL 4.0307.

[2] Although the review discusses the importance and relevance of local knowledge systems, it does not provide an analysis of the agriculture, husbandry, extractive, or other types of production by Indigenous groups. The knowledge systems of more than 300 ethnicities cannot be covered in a document of this length.

MATERIAL AND METHODS

The Brazilian Institute of Geography and Statistics (IBGE) published versions of the Agricultural and Livestock Censuses of 1995, 2006 and 2017 that included separate sets of information about "family farming" and "non-family farming landholdings". *Family farming* or *family agriculture* in Brazil has been defined (Law 11,326/2006), by four criteria followed by IBGE: 1) size of holding: a maximum land area defined regionally; 2) reliance on mostly family labor; 3) income predominantly originating from farming activity; and 4) operated by the family. These criteria describe the particular logic of family enterprises that include diverse livelihood activities (agriculture, forestry, fishing, aquaculture, and both rural and urban off-farm employment) to meet their social, economic, and environmental needs. Increasingly, such households also rely on urban incomes, state transfers of various kinds, and remittances, in the creation of multi-sited, complex systems of household income formation (see also Hecht *et al.* 2021). By definition "non-family farming landholdings" are establishments that do not fit these criteria: they are agribusiness establishments with a predominance of wage labor and with larger land plots; hence, they are medium and large-farms and rural companies.

We refer to these two types of establishments as "smallholder" or "family-based", in contrast to "agribusiness" or "wage-based". As just explained, the use of the term "family-based" regards the predominance of the *labor* involved, not necessarily *ownership,* as many large-scale agribusiness companies and ranching enterprises in the Amazon might be *family-owned,* but operated as large-scale agribusiness enterprises relying predominantly on wage labor. In this review we used the terms "large-scale", "wage-based", "agribusiness", or "commercial" interchangeably to refer to these larger establishments, while referring to smaller-scale family systems as "smallholders," "small-scale," and "family-based".

Within these two broad categories, the census data permit the comparison over time of six key types of actors and productive structures based on the social relations of production, three of them mainly "family-based" and three mainly "wage-based". The productive structures are further identified within each of these two broad categories as "agroforestry", "crops", "plantations", and "livestock" according to the activity that has a greater share in the value of total production and a greater importance in net income and investments than other types of crops and activities (following Costa 2009a; 2021).

The use of census data from Brazil and the above mentioned typologies has some limitations, but nevertheless facilitates the analysis of data trends over time. These types of actors are not necessarily "specialized," since they may combine multiple activities, certainly with significantly greater diversity among the family-based types (Supplementary Material, Figure S1). The great majority of smallholders make a living by a combination of agriculture, some type of livestock, agroforestry, temporary wage-labor, periodic urban migration, government welfare programs, fishing, hunting and extraction of forest resources. Part of the extraction of forest resources (primarily logging by actors not listed in the agricultural censuses), hunting and fisheries activities were not included in the quantitative analysis of key production actors because comparable census data were not available. Consequently, it was possible to discern a group of establishments in which temporary agriculture predominated, here called "family-based crops", another in which agroforestry systems predominated, named "family-based agroforestry", and still a third in which cattle raising predominated and so was denominated "family-based-livestock".

Within the wage-based agribusiness establishments, those in which livestock dominated (in the same sense mentioned earlier) were grouped as "wage-based-livestock" – basically cattle ranching or livestock enterprises. Commercial agricultural enterprises were classified as "wage-based-crops," usually forms of agro-industrial production, especially soy and corn, and those based on homogenous plantations of permanent crops or trees, as "wage-based-plantations" -- for example, the extensive commercial plantations of palm oil or *açaí* in the states of Pará and Amazonas.

In the analysis that follows, we focus on these six actor-structure types (family -based crops, agroforestry and livestock, and agribusiness livestock, plantations, and crops) and their evolution over time, which we refer to as "productive trajectories," or "PTs" (Costa 2008; 2009a; 2009b; 2016; 2021). These concurrent trajectories (Arthur 1994; Costa 2013) in land use, labor absorption, income generated, institutional support, and other factors showed distinctive trends in the Brazilian Agricultural Censuses data from 1995, 2006 and 2017, and provide empirical evidence of the dramatic and significant agrarian shifts underway in the Amazon region, whose implications are explored to suggest concrete recommendations for future policies. Unless otherwise cited, the figures shown in this review for Brazilian agrarian production are based on this source.

Based on the census statistics from Brazil, average net CO_2 emissions were estimated per year between 1995 and 2006 and between 2006 and 2017 from forest clearing alone (without considering emissions from equipment and tractors, fertilizer application, and subsequent soil management). The model applied (Costa 2016) linked the balance sheets of deforestation-linked emissions to the different production trajectories.

The considered territory was that comprising the 556 municipalities located in the Amazon Biome, respecting the limits with the *cerrado* and savannas established by IBGE (2020). It thus comprises all municipalities in the states of Acre, Amapá, Amazonas, Pará, Rondônia and Roraima and those from Maranhão, Mato Grosso and Tocantins with Amazonian ecological characteristics. Figure 1 shows the territorial domain of PTs in 2006 and 2017.

KEY SECTORS IN AMAZON RURAL DYNAMICS

Family-based agroforestry and fisheries

Family-based and community agroforestry systems, including fisheries systems, are managed by some of the oldest and most diverse populations in the Amazon region and were also adopted by other groups of immigrant smallholders who arrived in the Amazon region both before and after the rubber economy boom. They deserve extensive discussion here due to their deep historical roots, strong connection to Amazonian biodiverse resources and habitats, complex knowledge systems, and their unrealized potential as a basis for more sustainable development strategies in the region (see Supplementary Material, Appendix S1).

People in the Amazon have long relied on agroforestry, hunting and fishing as sources of food and livelihoods (Posey and Balée 1989; Balée 1998; Athayde *et al.* 2021; Neves *et al.* 2021). However, large scale exploitation of these sources started to emerge during the second half of the 18th century (Larrea-Acázar *et al.* 2021), and expanded during the rubber boom, when rubber tappers were joined by other groups of migrants coming from other regions of Amazonian countries in the second half of the 19th century and the first half of the following century. Some migrated into rubber estates while others supplied foodstuffs to urban centers (Weinstein 1983; de Castro 2013). With the rubber crisis triggered by plantations in Malaysia in the early 20th century, many rubber tappers released from bankrupt *seringais* (rubber estates) throughout the Amazon joined the ranks of small producers, settling along the region's rivers (Schmink and Wood 1992; Nugent 1993; 2002; Harris and Nugent 2004; Costa 2019) and dedicating themselves to complex livelihood systems based on management of the biome's natural resources.

These "historical peasants" (Nugent 1993; Costa 2019) preserved a very special condition: they were heirs to Indigenous and local knowledge (ILK), and their systems of extraction, agriculture, production, management, and conservation were interconnected, complex and fundamental to both their well-being and the sustainable provision of biological resources, as well as more general environmental services (Caballero-Serrano *et al.* 2018; Sears *et al.* 2018). The multiple

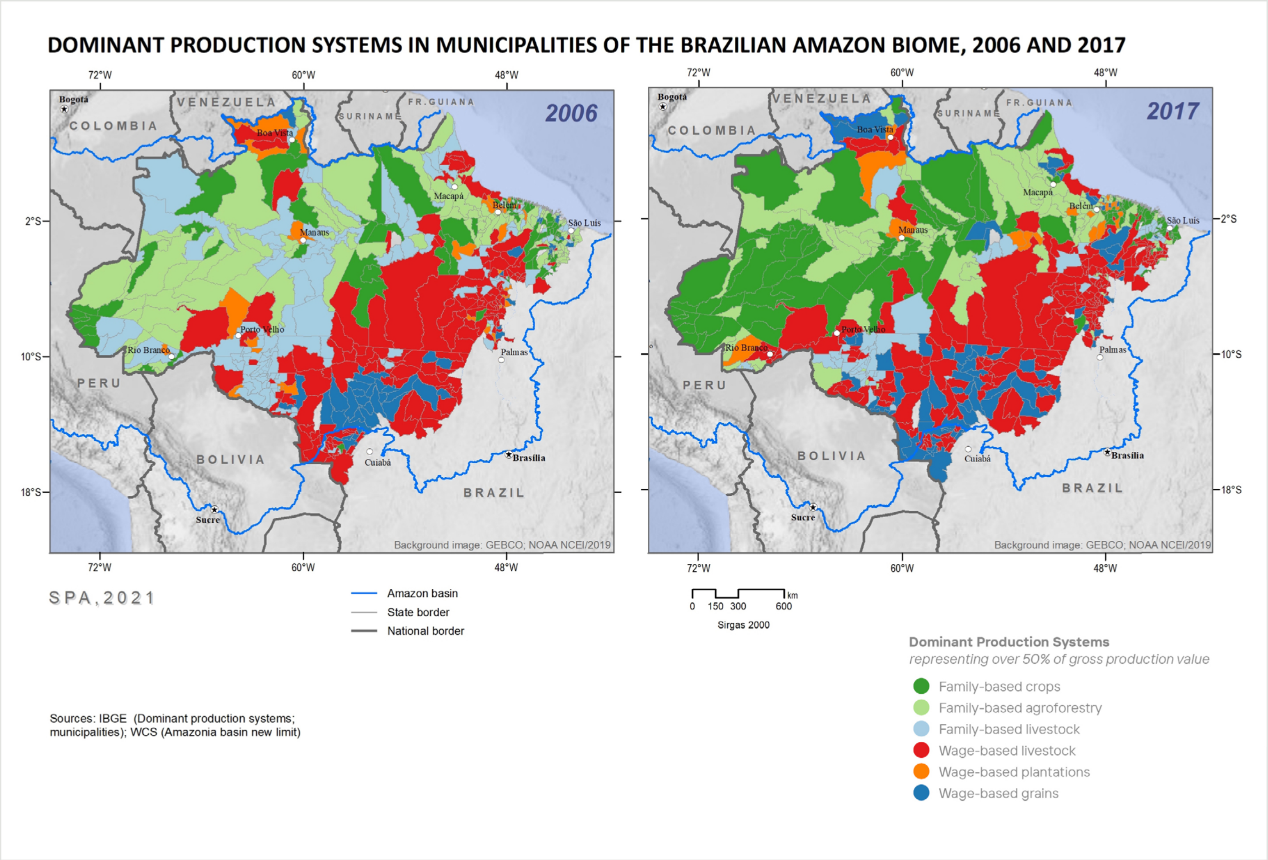

Figure 1. Dominant productive trajectories (PT) with over 50% of gross value of production (GVP) of municipalities of the Brazilian Amazon in 2006 and 2017. Sources: IBGE (2006 and 2017) and LiSS- Laboratory for investigation of Socio-Environmental Systems at INPE - Project Trajectories (SinBIOse/CNPq).

dimensions and functions of their forest product knowledge have been widely documented (Reyes-Garcia *et al.* 2007; Vogt *et al.* 2016; Alencar *et al.* 2021; Athayde *et al.* 2021). Both Indigenous and non-Indigenous Amazonians have generated a great diversity of knowledge and practices by constantly innovating and adapting their extraction, conservation and production systems and portfolios of diversified livelihoods in response to specific socio-economic and environmental changes (Reyes-Garcia *et al.* 2007; Brondizio 2009; Vogt *et al.* 2016). Their systems integrate both local communities and modern knowledge to manage, produce and conserve plants, animals (including fish) and other biological resources (Sears *et al.* 2007; Thomas *et al.* 2017). Their flexibility, resilience, and linkages among extraction, conservation and production, have greatly facilitated the process of production and stewardship of valuable terrestrial and aquatic resources. These also involved domestication of landscapes, and the use and management of a range of semi-domesticated species (Balée and Erickson 2006; Erickson 2006; Vogt *et al.* 2016; Levis 2018; Levis *et al.* 2018; Maezumi *et al.* 2018; Coomes *et al.* 2020; Franco *et al.* 2021; see also Athayde *et al.* 2021; Neves *et al.* 2021; Rosero-Peña *et al.* 2021). The flexibility and complexity of linked systems highlight the diversity found among family-based agroforestry and fisheries production systems explored here.

In Amazonian local communities, forest extractivism – the collection of non-timber and timber – is an important activity that has been carried out by Indigenous peoples and local communities for generations (Almeida *et al.* 2016; Thomas *et al.* 2017).[3] Inhabitants of extractive communities in the Brazilian Amazon occupy over 8 million ha of public forests established as sustainable use reserves, depending for their livelihoods on extraction of marketed non-timber forest products, including those for global export such as Brazil nuts (*Bertholletia excelsa* Humb &Bonpl), *açai* (*Euterpe oleracea* Mart.), and rubber (*Hevea brasiliensis* Muell.Arg*)*, as well as products for more regional markets such as oil from *copaiba* (*Copaifera reticulata* Ducke*)* and *andiroba* (*Carapa guianensis* Aubl.*)* (Barham and Coomes 1996; Cleary 2001; Hemming 2008; Josse *et al.* 2021). Smallholders' understanding of the impacts of extraction allows them to manage yields and avoid the risks of over-harvesting Brazil nuts (Guariguata *et al.* 2017), over-tapping of rubber trees (Almeida *et al.* 2016) and excessive hunting of game species (Ponta *et al.* 2019). Women play a prominent role in forest extractivism, especially in the Brazil nut economy (Lazarin 2002; Stoian 2005; Shanley *et al.* 2008), which accounted for nearly half of Bolivia's documented forest-related exports in 2005 and provided an estimated 22,000 jobs – including women working in urban processing of nuts – in the northern Pando region in 2001 (Cronkleton and Pacheco 2010). Other important forest products include fruits of *Mauritia flexuosa* L Mart. (Peru), babassu nuts (*Attalea speciosa* Mart.ex Spreng) and many other tree fruits that find a niche in regional markets, and well as leaves of several palm species for thatching, artisanal and household use (*Geonoma macrostachys* Mart..) in Bolivia and timber (Sears *et al.* 2007; Brondizio 2008; Pinedo-Vasquez and Sears 2011; Cronkleton and Larson 2014; Porro 2019).

Within Amazonian communities, men and women have adopted multiple strategies to manage forests, generate productive house gardens and farmlands, and produce crops for their own food consumption and for market, drawing on deep cultural traditions as they adapt to changing conditions. Women's important productive work within Amazonian family enterprises is often invisibilized due to their focus on family subsistence, yet women often manage home gardens with fruits, medicinal plants, and small animals, as well as taking care of water provision and quality (Grist 1999; Murrieta and WinklerPrins 2003; Hecht 2007; WinklerPrins and Oliveira 2010; Mello 2014; García 2015; Schmink and Gómez-Garcia 2015; Mello and Schmink 2017). They also labor in family crop fields, manage livestock and agroforestry systems, and collect and process non-timber forest products and fish; in effect, unpaid family labor constitutes a key household subsidy to family production systems in the Amazon (Hecht 2007). Diverse and complex livelihood strategies (drawing upon fisheries and a variety of forestry and agroforestry production and extraction) provide family-based enterprises with greater resilience to economic volatility and climate change than smallholders whose livelihoods are limited to agricultural production alone (Nugent 1993; Nugent 2002; Nugent and Harris 2004; Brondizio and Moran 2008; de Castro 2009; Porro *et al.* 2012).

A highlight among agroforestry products is *açaí*, managed in the floodplain and planted on dry land (Costa and Costa 2007; Brondizio 2008; see also Abramovay *et al.* 2021). In 2017, 478,000 tons, or 74% of the total *açaí* produced in the Brazilian Amazon came from agroforestry. The values associated with such production increased substantially between censuses, from USD 160 million in 2006 to USD 390 million in 2017. In 2017, *açaí* represented no less than 35% of the value of the total production by family-based-agroforestry enterprises. This growth in production figures probably reflects the better monitoring and commercial nature of *açaí* compared with the myriad of other products that flow through Amazonian circuits, varying throughout the basin (Padoch *et al.* 2008; Bolfe and Batistella 2011; Blinn *et al.* 2013; Vogt *et al.* 2015; Buck *et al.* 2020).

Associated with the production of *açaí* and other products of the biome economy (Costa 2020) is an urban, industrial and service economy that has grown rapidly, producing and

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[3] In the development literature, the term "extraction" largely has been used to describe destructive economic systems that use up or destroy natural resources, and that have exclusionary institutional structures benefiting a small coterie (Svampa 2019; Acemoglu and Robinson 2012).We focus on small scale management and exploitation, terminology that refers to non-timber and largely sustainable forest resources use and commercialization which was largely how the term was used in Amazonia until recently.

distributing pulp, processed foods, nuts, heart of palm, oils and herbals: recent estimates suggest that in the state of Pará (Brazil), total added value of thirty of such products grew by 8.2% per year since 2006, reaching USD 1.34 billion in 2019. Employment reached 234,640 jobs, including 184,128 rural and 50,512 urban, industrial, and commercial jobs (Costa *et al.* 2021). This indicates that more diversified livelihoods drawing upon complex engagements with agroforestry production, fisheries and extraction of forest products also lead to greater synergies with activities up and down the production chain, including formal and informal connections to urban markets, increasing the dynamism of local markets employment in the region, and their broader national and international global connectivity (see also Abramovay *et al.* 2021).

These complex agroforestry systems are prevalent through Amazonian lowlands as well as the "Andean Amazon," and the "Caribbean Amazon" reflecting the long history of extensive regional settlement history in pre-Columbian times, and the adaptation and modification of these within the contexts of relatively recent colonization in the 1970s and 1980s. These systems also reflect the different logics of small and large farmers in a context of rapid land-use change (Balée and Erickson 2006; Erickson 2006; Jacobi *et al.* 2015; Carson *et al.* 2016). Peruvian small farm agroforestry systems have been the focus of extensive research, in part because of the smallholder-focused history of much of Peruvian Amazon's development politics, the importance of the region as an "escape valve" for economic constraints in the highlands, and periodic stimulation of colonization programs where smallholders have remained an important constituency in peri-urban, rural and urban labor systems (Padoch *et al.* 2008; Putzel *et al.* 2013; Sears 2016; Sears *et al.* 2018; Hecht *et al.* 2021). As in Bolivia and Colombia, peasants farming at mid-high elevations was also subject to coca interdiction, which stimulated research on alternative cropping systems, and larger attempts at subsidizing the development of alternative production systems, largely for political but also ecological reasons (Angrist and Kugler 2008; Gootenberg 2017; Dávalos 2018; Huezo 2019; Grisaffi 2022). The historical dynamics of coca were rooted in agroforestry systems for millennia, and in the face of precarious prices, transportation difficulties, and other kinds of vulnerabilities, coca has remained a durable smallholder commodity working through traditional, modern, as well as criminal circuits, especially in the absence of other economic opportunities (Hecht *et al.* 2021).

Agroforestry systems of the upper Amazon remain integrated into multiple urban and rural networks, and typically include global niche products such as *coca (Erythroxyum coca* Lam.), cocoa *(Theobroma cacao* L.*)* and coffee (*Coffea arabica* L.), regional and national products, and increasingly, other kinds of medicinal plants, such as *ayahuasca* (*Banisteriopsis caapi* Spr.). However, recent transportation networks and the expansion of the hydrocarbon economies are destabilizing these systems through problems related to oil spills, expansion of access roads, other forms of pollutions such as those associated with gas flaring, siphoning away of labor and also, in some cases, herbicide drift from coca eradication efforts (Sherret 2005; Finer *et al.* 2008; Brain and Solomon 2009; Suarez *et al.* 2009; Bass *et al.* 2010; Valdivia 2015; Lyall 2018; Huezo 2019; Vargas *et al.* 2020).

Fisheries are a core component of these diverse agroforestry systems, providing a major source of livelihoods as well as nutrition for many people inhabiting riverine communities – including urbanized ones - throughout the Amazon (Barthem and Goulding 2007; Begossi *et al.* 2019; Duponchelle *et al.* 2021). Fisheries in the Amazon are multispecies, with more than 90 recorded species included in the catch in individual regions, while only 6-12 species or species groups account for 80% of the local commercial catch (Abramovay *et al.* 2021). The composition of the catch and the importance of fisheries to local populations varies throughout the basin, associated with variations in water quality of the different sub-basins (Goulding *et al.* 2018) and river types (see Moraes *et al.* 2021; Val *et al.* 2021; Zapata-Rios *et al.* 2021). Amazon fisheries are closely associated with the highly productive white-water rivers with their extensive floodplains, oxbow lakes and back lakes, while clear and black water rivers are far less productive (Junk 1984).

Amazon fisheries are highly seasonal, and fishing activity is related to the seasonal rise and fall of the Amazon River (Junk *et al.* 1989). Along the main channel of the Amazon, high water occurs between May and June and low water in October-November. Three main groups of fish can be distinguished. Long distance migratory catfish, several of which travel across the basin, spawn in Andean headwaters and pass their juvenile phase in the Amazon estuary (Barthem and Goulding 1997; Duponchelle *et al.* 2021). A second group of middle-distance migratory species, of which the *Characidae* family are the most important, move in and out of the floodplain over their life cycle, feeding in flooded forests during the highwater season. The third group consists of sedentary species, such as the highly prized *pirarucu* or *paiche* (*Arapaima gigas* Cuvier) that spend much of their lifecycle in floodplain lakes (Barthem and Goulding 2007; see Abramovay *et al.* 2021).

Several types of fisheries sub-sectors, often overlapping, exist in the Amazon, from those practiced by family groups in small riverside communities and urban areas to those that are primarily large commercial enterprises centered around urban areas (Coomes *et al.* 2010; Gregory and Coomes 2019). Fishers located in rural communities might both subsist on fish and also supply boats (or *lanchas*) with fish that are then transported to the city, processed and sold either wholesale or directly to consumers in regional markets. Long-term information on the total amount of fish caught, sold and consumed in the Amazon is largely unavailable, reflecting the invisibility of some fisheries and ornamental fish commerce and lack of large-scale governmental support (Lopes *et al.* 2021). Community-led grassroots movements sought recognition by the government for their rights to local lake fisheries developed in the 1980s. In the state of Amazonas, Brazil, these initiatives were initially fostered by the pastoral action of the Catholic Church and came to constitute the so-called "Lakes Preservation Movement," headed by the CPT (Pastoral Land Commission) (Benatti *et al.* 2003; Pereira 2004). These served as the basis for participatory lake conservation with the innovative development of the Mamirauá fisheries reserve (Padoch 1999; Castello *et al.* 2011).This social movement served as a sociopolitical basis for the development of public policies recognizing decentralized and collaborative community-based management systems based on local fisheries agreements and management of key fish species such as *Arapaima* spp. (see below; Oviedo and Bursztyn 2017; Campos-Silva *et al.* 2019; Abramovay *et al.* 2021; Duponchelle *et al.* 2021).

In addition to historical peasantries and their long-term forged technical capacities, other groups of immigrant smallholders arrived in the Amazon region both before and after the rubber economy boom, from other regions of the Amazonian countries and from outside the region. These groups typically developed productive systems with a greater focus on agriculture, but their practices also evolved over time to agroforestry systems in response to their experience in the Amazon environment (Costa 2020).

Japanese migrant colonies are found in Brazil and Bolivia. In Brazil, beginning in the 1920s Japanese farmers settled in Tomé-Açu, Pará, where they introduced new crops such as jute and black pepper (Homma 2007). Over time, their systems shifted to agroforestry: increasingly diversified fruit crop systems that mimicked natural succession, generating 300 polyculture combinations that used 70 different species (Subler and Uhl 1990; Serrão and Homma 1993; Subler 1993; Yamada 1999; see also Box 30.1 in Abramovay *et al.* 2021).

Migrant farmers in northeastern Pará state, and agricultural colonists settled along the Trans Amazon Highway and in Rondônia state in the 1970s, also adapted their cropping systems over time, first focusing on annual crops---which were often labor intensive and soil depleting (especially rice) using shifting cultivation methods. Farmers responded to falling productivity by diversifying their production systems through intercropping of cacao or coffee with other perennial crops, including fruits (*açai,* mango, pineapple, tangerines and other fruits) and timber trees [mahogany (*Swietenia macrophylla* King), cedar (*Cedrela odorata* L), pines (*Pinus caribbea, Schizolobium amazonicum* Huber ex Ducke), and other local species (Smith 1978; Smith *et al.* 1996; Browder *et al.* 2008; Costa 2020).

The diversity and resilience of family-based agroforestry systems discussed here make them a key economic sector for the region's past, present and future, far beyond their importance in the statistics of production systems for the region (Franco *et al.* 2021). These statistics, however, are *per se* eloquent: rural agroforestry establishments in the Brazilian Amazon numbered 125,160 in 1995, and increased to 186,341 in 2017, spread over a wide area of the region (Figure 1). Their contribution to the agrarian economy has grown significantly, on average 4.2% annually from 1995 to 2017, increasing from USD 400 million to USD 1.1 billion (Figure 2). The number of people employed in 2017, in turn, remained at around 403,978 people, 92% of them family workers (Supplementary Material, Table S1).

A number of federal agricultural policies and programs were created in Brazil in the 1990s specifically to support smallholder farmers, forest extractivists, and fishers, under the purview of the Ministry of Agrarian Development (MDA), which was established to oversee land reform in Brazil and promote sustainable practices (Niederle *et al.* 2019). The National Program for Strengthening Family Agriculture (PRONAF) provided subsidized rural credit, linked to state rural technical assistance and rural extension agencies. The Insurance for Family Farmers (SEAF) program provided insurance to farmers who adopted certain technologies that conserved natural resources on the farm and reduced their vulnerability to climatic fluctuations. In 2010, the National Policy of Technical Advisory and Extension Services for Family Agriculture and Agrarian Reform (PNATER) was established, along with the National Program of Technical Advisory and Extension Services (PRONATER) (Valentin and Garrett 2015). However, in 2019, the MDA was demoted to the status of a Secretariat of Family Agriculture and Cooperativism, under the agribusiness-oriented Ministry of Agriculture, and in the following years many policies and programs were weakened or eliminated as resources and staff to support them were drastically reduced (Niederle *et al.* 2019).

Family-based annual crop systems

A technical focus on commercial crop specialization by credit, extension and research agencies in the Brazilian Amazon (and in Brazil more generally) induced many family farmers to concentrate on production of an ever-smaller number of products, especially commercial products. The number of the censuses are clear about this. In fact, by 1995, nine products made up 90% of the production value of these Brazilian small farmers; cassava was the main product and the only regionally exported commodity. By 2017, 93% of family-based production focused on five products (cassava, soybeans, corn, sugar cane and pineapple). Cassava remained the dominant commercial product in many small farms; other products,

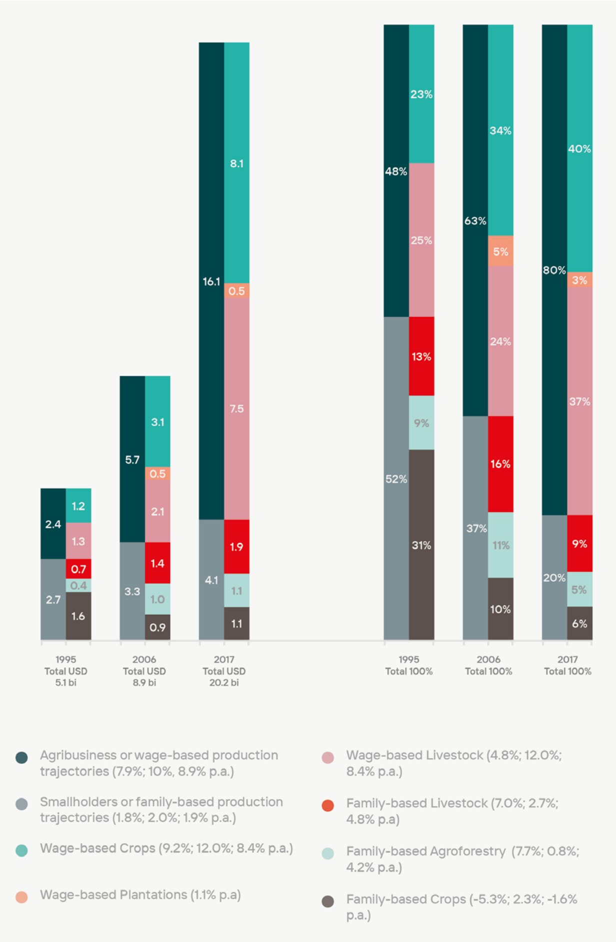

Figure 2. Gross value of production (GVP) of the rural sector in the Brazilian Amazon biome by agribusiness (wage-based) and smallholder (family-based) productive trajectories (PT) in 1995, 2006 and 2017 in USD billion at 2019 prices (left graph); and contribution of each PT in % of the total (right graph). The percentages in the graph legend refer to the annual growth, respectively, in the periods 1995-2006, 2006-2017 and 1995-2017. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Supplementary Material Table S1. Values in BRL from each year were adjusted to 2019 value by the IGP-FGV index (Brazil) and converted to USD by the exchange rate of 31 Dec 2019.

including the ones of home gardens, represented 7% of GVP (see Supplementary Material, Figure S3).

The family-based-crops productive trajectory in the Brazilian Amazon contracted substantially from 1995 to 2017, in terms of number of establishments (dropping from 337,000 to 179,000), amount of owned land (from 9.33 to 5.44 million ha) and land area in use (from 3.99 to 2.96 million ha), along with a drastic decline in workers (from 1.179 million to 393,000) (Supplementary Material, Table S2 and S3).

Most family-based establishments in this trajectory shifted their land resources into livestock (3.1 million ha) and agroforestry systems (0.2 million ha) throughout the 1995-2017 period (Figure 3). While some released workers went to the other family-based trajectories, about 585,000 went to urban sectors or wage-based trajectories (542,000 between 1995 and 2006 and 44,000 in the following inter censuses interval): 70% of all workforce released from family-based trajectories shifted to urban or rural salaried market in the period (Figure 4). At the end of this period in 2017, the GVP of family-based-crops had declined from 31% of total GVP in 1995 to one fifth of its earlier value.

Family-based livestock farming

Livestock ranching, introduced in the colonial period, was often dominated by ecclesiastic settlements in the 17th and 18th centuries, and has been a widespread activity in the Amazon ever since, although until the post-war period, the production was based largely on natural grasslands (Costa 2019). Practiced in large estates since the 18th century in Marajó (Ximenes 1997), it was also present, by the 19th century, as part of productive systems of small producers in the lower and middle Amazon in Brazil (Harris 1998; Folhes 2018), where it persists today using floodplains and natural grasslands (Costa and Inhetvin 2013). Alongside the large cattle ranches that developed since the 1960s with the subsidies, land transfers, new pasture technologies, and credit policies implemented by the military governments and all subsequent governments, ranching also expanded throughout the Amazon with road construction from the 1960s onward (Hecht 1993; Costa 2000). Since the 1990s, when the *Fundo Constitucional do Norte* credit program was implemented in Brazil to support small livestock, beef and milk production, this land use has continued to expand with preferential credit lines at all scales of production, and is the dominant land use throughout the basin on natural and planted pastures; in Brazil, family-based agriculture has shifted over time to cattle systems due to their low labor demand and other advantages discussed below (Veiga and Tourrand 2000; Salisbury and Schmink 2007).

As a result, Brazil stands out among Amazonian countries due to the strong dominance of livestock systems in the region. Surveys conducted by the Brazilian National Institute of Space Research (INPE) and the Brazilian Agricultural Research Corporation (EMBRAPA) in Brazil (INPE 2016) pointed to 37.7 million ha of productive pastures (albeit at low stocking rates for the most part), out of a total of 48.4 million ha of pastures. This is compatible with the agricultural census of 2017, which identified 45.4 million ha of pasture in the Amazonian biome. The cattle herd in the region almost doubled from 28.3 million head in 2006 to 52 million in 2017 . Of this herd, 5% were held by family-based-crops systems, 5% in family-based-agroforestry systems, 2% in wage-based-plantations, and 15% in wage-based-crops agribusiness enterprises, while extensive commercial livestock ranching accounted for the largest proportion: 49%. Smallholder livestock raising, the subject of this section, was responsible for 24% of the cattle herd (Figure 5).

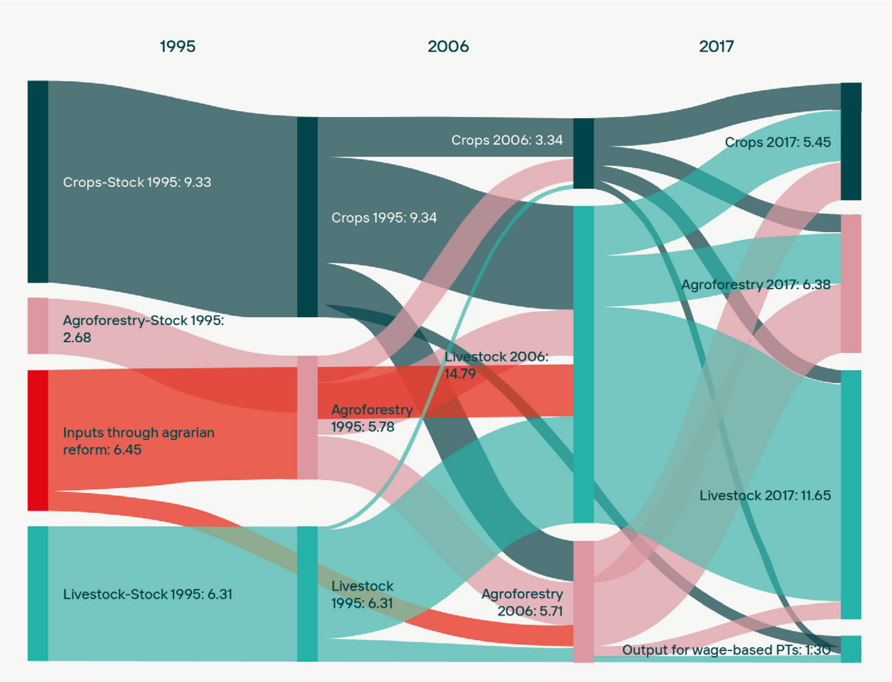

Figure 3. Shifts in land ownership in family-based productive trajectories from 1995 to 2017 (in millions ha) in the Brazilian Amazon. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Supplementary material, Tables S2 and S3. The original entries are represented in the left hand first column of the diagram by two sources: beginning "stocks" registered in the agrarian census of 1995 and the "inputs" that occurred between the censuses. The following vertical lines in the diagram represent specific "nodes" that show how the stocks increased or decreased for each production trajectory in the analyzed periods. It starts with node "1995," which results from the sum of "stock-1995" values with the "inputs" until the next census, and continues with node "2006" which adds the stocks registered in the 2006 census with the entries until 2017; and so on. In this way, the diagram shows how the relative share of each production type shifted as a result of these changes. Definitive outputs from the agrarian sector, if they occurred in only one period, are shown as a specific node at the end of that period. If they occurred in several periods, they are presented as a specific node in the end of the last period.

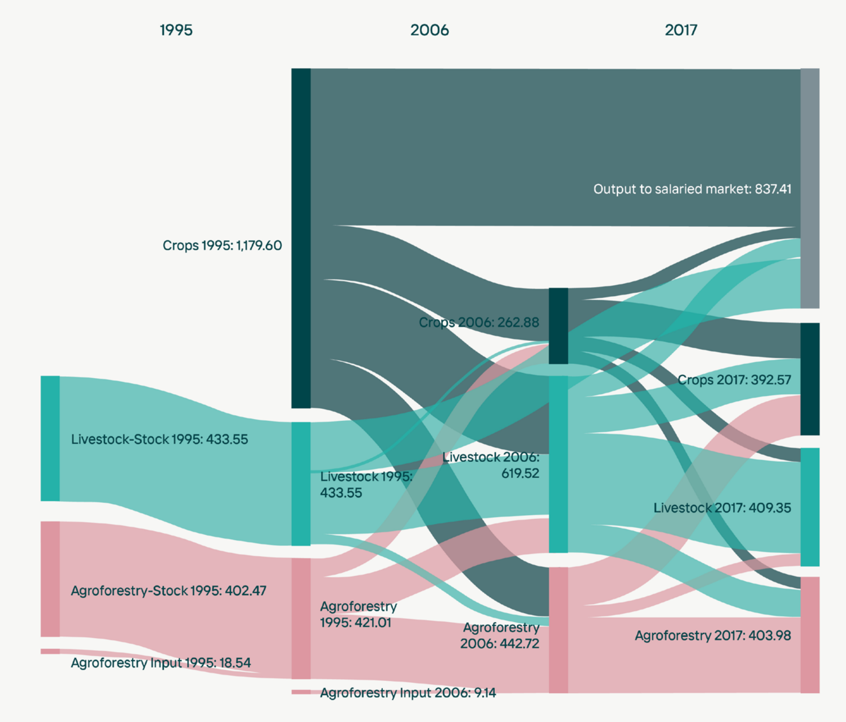

Figure 4. Shifts in employment among family-based production trajectories from 1995 to 2017 (in thousand employees) in the Brazilian Amazon. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Supplementary Material, Tables S2 and S3.

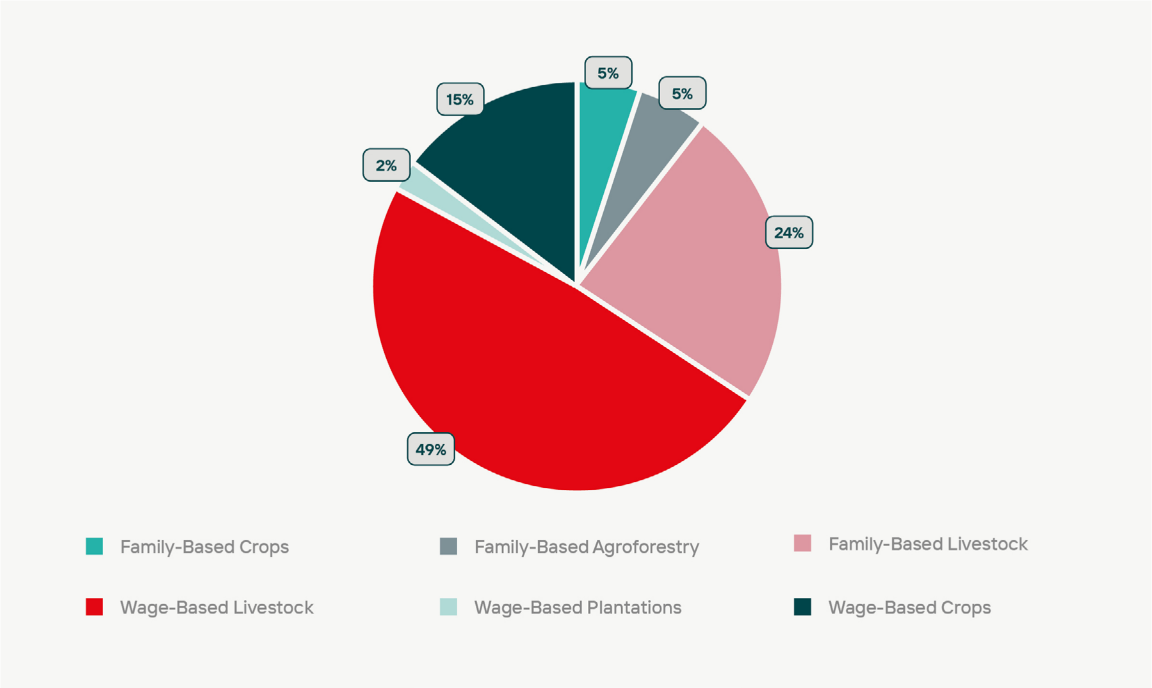

Figure 5. Distribution of cattle in the Brazilian Amazon biome in 2017 by production trajectory (% of the total). Source: IBGE, Agricultural Census 2017.

Family-based-livestock farms, despite decreasing in number in the last intercensal period (128,806 in 1995, 257,122 in 2006 and 198,804 in 2017), stand out as an economically expanding group among family farmers, whose total GPV increased on average at 4.8% p.a. from 1995 to 2017. Their small farm production systems depend increasingly on livestock, mainly beef, whose share of total production value went from 32% in 2006 to 55% in 2017. Dairy cattle, in turn, increased from 16% to 20% in the same period (Supplementary Material, Figure S1). Altogether, the products of cattle raising (beef and dairy) grew from 48% to 77% of the value of this small farm production trajectory during the same period, making it fundamentally a livestock sector, reflecting labor characteristics and credit availability.

With the significant shift that family-based-farms underwent from agriculture into livestock, total land in family-based-livestock farms nearly doubled from 6.3 million in 1995 to 11.6 million ha in 2017 (Figure 3; Supplementary Material Table S2 and S3). Among smallholders, it was the PT that grew fastest, 4.8% annually from 1995 to 2017. The production value basically tripled over these decades, from USD 0.67 billion to USD 1.86 billion, even though the stocking rate, about one animal unit/ha, has remained static for decades. The labor deployment involved reduced slightly, from 433,550 in 1995 to 409,348 in 2017, 92% of which were family laborers as opposed to salaried workers.

Family-based-livestock enterprises are much more diversified production systems compared to wage-based livestock farms, and more oriented towards self-consumption and local and national economies. The systems differ significantly in terms of the average size of properties, pastures and herds, respectively, 58.6 ha, 40.3 ha and 61.7 heads, in family-based and 655.5 ha, 318.9 ha and 338.3 heads in wage-based-livestock farms, resulting in a density of 1.53 and 1.06 heads per ha, respectively. In wage-based-livestock farms, close to 3,000 of the 75,000 establishments have herds over 1,000 heads.

Cattle ranching remains an appealing land use in more remote regions of the Brazilian Amazon, where land is abundant and cheap relative to labor and capital, and where overland transport and marketing of crops is economically unviable. Even at low stocking rates and within more established agricultural regions, ranching is also extremely persistent. It is perceived as having lifestyle and social advantages over cropping, and much lower expenditures, which is beneficial to debt- and risk averse peasants who can use livestock as a highly mobile "savings account" to be sold for reliable prices when needed (Hecht 1993; Valentin and Garrett 2015; Garrett *et al.* 2017). It also has low labor demand and stable prices, making it useful in the portfolio strategy of households, and a part of the more general allure of this sector for large holders as well. It also continues to have a significant role in land grabbing and land speculation (Roebeling and Hendrix 2010; Campbell 2015; Miranda *et al.* 2019; Ferrante *et al.* 2021, Carrero *et al.* 2022). Demand for beef is strong in Brazil, unlike Peru, where beef is not as widely consumed, and where poultry consumption is growing exponentially (Heilpern *et al.* 2021; Kovalskys *et al.* 2019).

Wage-based livestock enterprises

The wage-based-livestock trajectory has grown rapidly: the number of establishments more than doubled in the Brazilian Amazon from 1995 to 2017, while their GVP increased more than five-fold (Figure 2; Supplementary Material, Table S1). Indeed, there is evidence in the censuses that the intensity of land use (monetary productivity of used land equivalent to total GVP, divided by total used land area) in wage-based livestock has grown almost four-fold: from USD 67.2/ha in 1995, to USD 244.4/ha in 2017 (Supplementary Material, Figure S2). However, cattle ranches remain among the lowest of all production systems in land use intensity, since their profitability depends on extensive land use and grows with the scale of that use (Costa 2016). Land use intensity grows with the potential to capture various institutional rents, and to realize land speculation and money laundering (Fearnside, 2002; Davalos *et al.* 2014).

The history of large-scale cattle ranching presents opportunities for speculation during intense periods of land grabbing, discussed in more detail in the Supplementary Material, and in Hecht *et al.* (2021). In 1995, wage-based-livestock controlled a land stock of 45.5 million ha, a legacy of particularly intense land grabbing during the authoritarian period (1964-1985) (Fernandes 1993) and later during the Bolsonaro presidency, 2019-2023. A full 16 million ha of this stock shifted productive trajectories: 4.8 million to wage-based plantations, 2.4 million to wage-based crops, and 8.8 million to family-based enterprises through agrarian reform programs (Figure 6; Supplementary Material, Table S1; Costa and Fernandes 2016). Cattle enterprises bought or appropriated forested land at a relatively low market price, and, after "producing" land without forest, transferred it at the much higher price of land covered by pasture (Costa 2012b). Considering average land prices of the 2001-2006 period (Supplementary Material, Figure S3), these operations may have yielded USD 400 million per year in profit, equivalent to about 20% of the wage-based livestock trajectory's GVP, or 110% of its net income in 2006 (Figure 2; Supplementary Material, Table S1).

Between 1995 and 2006, wage-based livestock establishments gained about 16 million ha of land that shifted away from wage-based crops, and between 2006 and 2017 land use shifted back, 12.5 million ha to wage-based crops and 1.4 million ha to wage-based plantations (Figure 6; Supplementary Material, Tables S2 and S3). This operation may have yielded, just by the inter-period price differences of pasture (Supplementary Material, Figure S3), a total of USD 5.1 billion, or USD 463 million per year during this period, equivalent to 6.2% of GVP or 87% of net income for the wage-based livestock productive trajectory in 2017 (Figure 2; Supplementary Material, Table S1). In any case, land equity real value grew in the 1995-2017 period on average 7.6% per year if forested, and even faster, 7.8% per year, if covered with pasture.

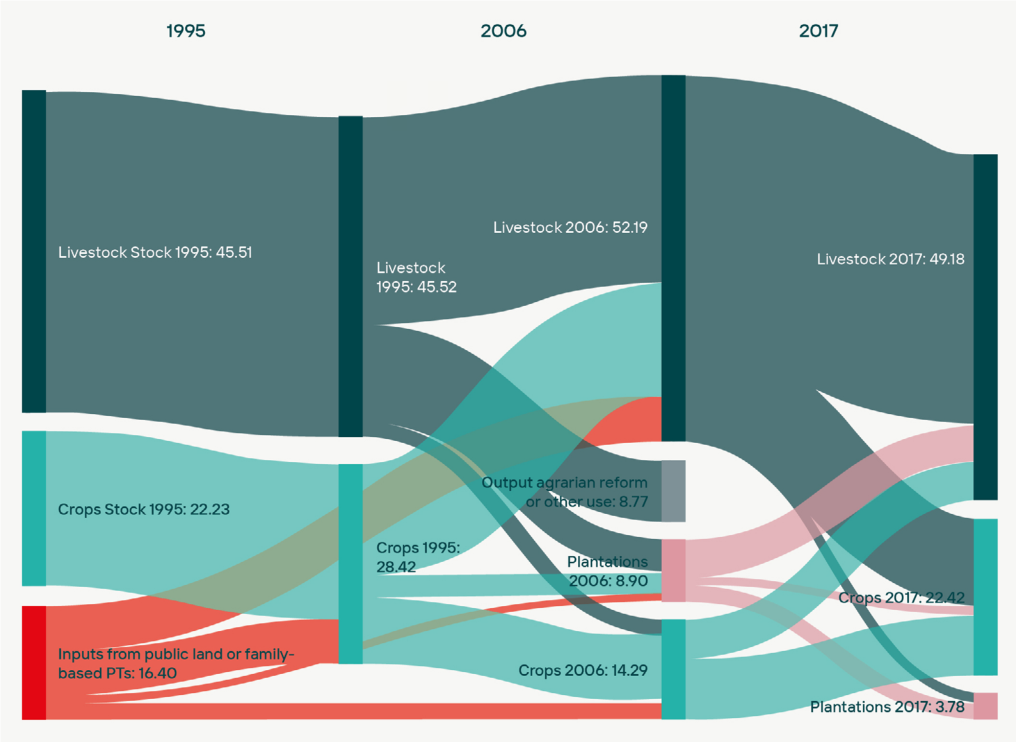

Figure 6. Shifts in land ownership in wage-based productive trajectories from 1995 to 2017 (millions ha) in the Brazilian Amazon biome. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Supplementary Material, Tables S2 and S3.

This indicates the centrality of wage-based livestock to the processes of expanding agricultural frontiers, forest clearing, land speculation, privatization of public lands, and displacement of alternative and more socio-ecologically sustainable livelihoods (Hecht 2011). Explaining part of the expansion dynamics, soil nutrient decline and pasture invasion by brush (the widespread "*juquira*") contribute to the pressure to clear and burn more native or secondary forest in order to use the ash from burning as a kind of fertilizer for crops, while the need for timber extraction as a form of financing also stimulates further clearing (Hecht, 1993; Costa, 2016). Consequently, ranching establishments are heavily involved in timber extraction to finance pasture production (see Supplementary Material, Appendix S2). Also, the use of fire in pasture clearing risks burning understories of adjacent forested areas that may have been degraded through timber extraction, or just through increasing dryness from larger processes of climate change and hotter pasture microclimates (Balch, Massad *et al.* 2013; Berenguer *et al.* 2014; Brando *et al.* 2014; Alencar *et al.* 2015; Lovejoy and Nobre 2018).

Wage-based crop production

The wage-based productive trajectory – dominated in the Brazilian Amazon by the soy-corn agro-industrial annual cropping system – responds to both comestible and industrial product demand in national economies, but remains largely export-oriented (Oliveira 2016; Oliveira and Hecht 2016; Nepstad *et al.*, 2019). In Brazil, its expansion would not have been possible without decades of state-sponsored research led by plant geneticists and agronomists from EMBRAPA, which led to the development of so-called "miracle" soy cultivars able to tolerate the acidic soils, uniform day length and aluminum levels in the soils (Hecht and Mann 2008; Oliveira 2013). EMBRAPA's research on biological nitrogen fixation by plants allowed the reduction and, in other cases, elimination of nitrogenized fertilizers in soy cultivation, reducing the costs of production, to permit Brazilian soy to compete on the international market (Dobereiner 1990).

Besides the already mentioned supportive research, the government promoted the expansion and modernization of Brazilian agriculture through monetary and agricultural policies, providing credit to farmers at below market interest rates, and financing the building of roads and waterways, logistical centers, ports, storage infrastructure, and equipment (Garrett and Rausch 2015). In the Amazon, the private sector, especially seed companies, plays a critical role in providing credit, especially in the context of informal or contested land tenure claims (Garrett *et al.* 2013a), but more recently in the context of the shift from public credits to private financing (Hecht *et al.* 2021).

In the Brazilian Amazon, in 1995, soybeans already represented 43% of wage-based crop production value. Along with soy, its rotational crop, corn grew in value, from 4.4% in 1995, to 13.6% in 2017 (Supplementary Material, Figure S4). Strongly determined by this composition, the growth of wage-based crops reached 9.2% annually over the entire period, raising its GVP from USD 1.2 billion in 1995 to USD 8.1 billion in 2017 (Figure 2).

With the rapid growth of wage-based crops, the demand for deforested land reached 13.1 million ha in 2017. To cover this need, 7.2 million ha of deforested land from wage-based livestock, and 0.7 million from wage-based plantations shifted to wage-based crops in addition to 5.2 million ha already in operation (Figure 7).

At the end of the period, the total land stock of wage-based crops was practically the same as at the beginning: 22.4 million ha (Figure 6). However, there was a fundamental change: despite the Soy Moratorium (Supplementary Material, Appendix S3; see also Berenguer *et al.* 2021; Larrea *et al.* 2021a), the proportion of the area deforested in relation to the total area of wage-based crops grew from 43% in 1995 to 58% in 2017 - practically the same proportion as for wage-based livestock (Supplementary Material, Figure S5).

Large-scale cropping systems, particularly soy and oilseed production that compete globally, require high levels of capital inputs, mechanization, and infrastructure to achieve economies of scale, as well as the best available seed technologies and chemical inputs, and are disciplined by international markets and the high level of consolidation in the global oil seed markets (Oliveira and Hecht 2016). Soy remains the most lucrative of the commercial annuals due to large and increasing demand globally, and substantial government subsidies, particularly in Brazil (Oliveira 2016; Oliveira and Hecht 2018). Double-cropping corn with soy production is increasing, due to demand for animal feed in Asia, Europe and the Middle East. Meat demand is growing in Andean regions, which import from the Amazon through the new Transoceanic highway in the western Amazon. In the Brazilian Amazon, new state aquaculture initiatives are also bolstering clusters of cropping production – largely soy for fish feed (Klein and Luna 2021; da Silva and de Majo 2022).

The evolution of soy in the Brazilian Amazon has led to a complex land possession process. At first, the entry of soy and its high level of mechanization reduced, in absolute terms, the need for land from soy cultivation. Thus, deforested lands between 1995-2006 registered large shifts of 8.8 million ha from wage-based crops to wage-based livestock, and 1.6 million to large plantations, leaving a stock of 5.2 million ha. At the same time, however, the technical and logistical requirements of soy led to a demand for land with special characteristics – areas that are flat (slope less than 12%), with well-drained soils – in specific locations, near major highways and relevant supply chain infrastructure and supporting services (Garrett *et al.* 2013b).

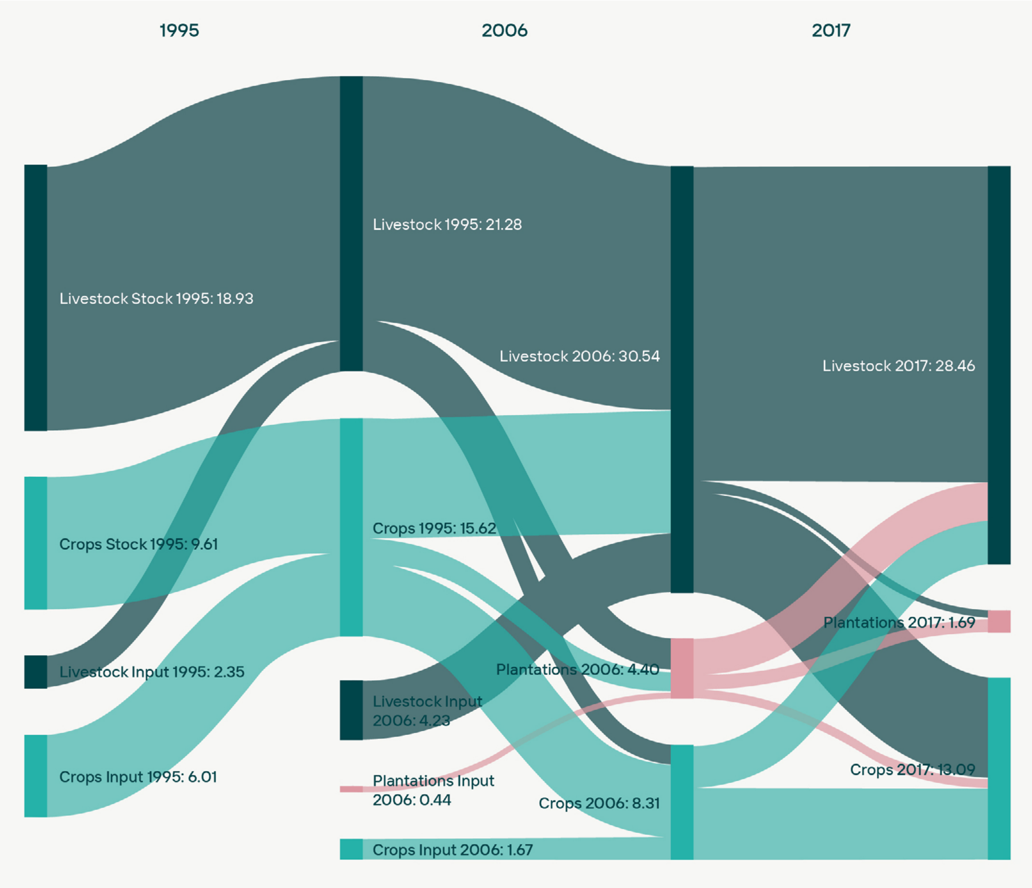

Figure 7. Shifts in land use in wage-based productive trajectories from 1995 to 2017 (millions of hectares). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Supplementary Material, Tables S2 and S3.

Hence, wage-based crop enterprises also registered subsequently significant acquisitions of 7.8 million ha of cleared land between 2006-2017. These either came from smallholders, associated with land conflicts and local resistance, typified by the highly publicized soy producing regions of Santarém (Steward 2007) and settler frontiers more generally (Sauer 2018; Domingues and Sauer 2022), or from previously formed stock of deforested areas by wage-based livestock, or deforestation of new areas (Figure 7; Supplementary Material, Tables S2 and S3). Although soy has complex interactions with land clearing and cattle via speculation, it occupies a smaller proportion of the agricultural area in the Brazilian Amazon compared to cattle and has been very important for regional development trajectories. Nevertheless, soy and other annuals generate substantially more total taxable revenue than any other activity except for ranching, and participate in an expanding global market in animal feed. Moreover, "agrocities" emerge in these nascent soy regions as new businesses are established to sell non-agricultural goods and services to farm and agribusiness employees, leading to new employment opportunities both related to and outside of the agricultural sector.

Because of these dynamics, soy production tends to be associated with higher incomes, educational attainment, and health access, versus other wage-based land uses and even versus non-agricultural municipalities (VanWey *et al.* 2013; Garrett and Rausch 2015). However, soy production is also a highly exclusionary process and tends to exacerbate inequality (Guedes *et al.* 2012; Garrett *et al.* 2013b; VanWey *et al.* 2013; Weinhold *et al.* 2013; McKay and Colque 2016; Oliveira 2016; Oliveira and Hecht 2016)4-10-09Te©^4. This means that much of the concentration of benefits within "agrocities" accrues to landowning elites and skilled workers in the agribusiness sector at the expense of migrant labor from other regions, as well as relative dis-investment in alternative economies (including far more sustainable and lucrative agro-ecological production of fruits, vegetables, and other higher-value added products), and aggravation of socio-ecological conflicts due to rising inequality and the dynamics of land appropriation. The best-paid jobs and better quality of life often flow to migrants to the Amazon from other regions, while locals are often excluded from these benefits but bear the brunt of the negative impacts, for example, of environmental contamination due to increased agrochemical use (Oliveira 2012). In Bolivia in particular, due to historical land development programs and a lack of legal protections for small landholders, much land was given away to foreign investors, mainly Brazilian companies (Hecht 2005; McKay and Colque 2016). There also is a highly active Mennonite presence in agro-industrial production in Bolivia (Hecht 2005) and now in Peru, and they are currently very active in land transformation in Peru and Bolivia (le Polain de Waroux *et al.* 2021). Most soy production in Brazil and Bolivia is exported without processing, limiting the potential value-added gains and benefits to local communities (McKay 2017).

Historically cattle ranching and commodity crop production have been driven by different sets of actors, industries, and even development paradigms. However, as more farmers are looking for ways to add value to their land in light of declining expansion opportunities (Cortner *et al.* 2019), the degree of integration and fluidity between different land use types is constricted ultimately by land use lock-ins (path dependencies), entry costs, forms of capital scarcity, availability of institutional rents and cultural dimensions. Past practices provide a great deal of rigidity to future transformations, by requiring "big push" policies and large upfront investments to solve collective action problems (Cammelli *et al.* 2020; Hecht *et al.* 2021).

Another major rigidity stems from the cultural norms that have co-evolved with agricultural systems in the Amazon. Ranchers and croppers tend to have different backgrounds, and ranchers may look down upon cropping as an activity (Cortner *et al.* 2019). Ranching is linked to historical Iberian colonization processes and cattle cultures (Baretta and Markoff 1978; Hoelle 2015), while soy and other row crop farmers, who migrated more recently to the region via private colonization programs, and some state colonizations, come from German and Italian communities in the south of Brazil, and are linked to modernization and new technologies (Jepson 2006, Oliveira and Hecht 2016). These historical trajectories influence land users' abilities to engage in different systems, with the soy farmers generally benefiting from higher capital access from their family networks, government subsidies, private sector (including seed sector and crusher) financing, and both financial and technological training and assistance from the United States and Japan (Garrett *et al.* 2013b; Nehring 2016; Oliveira 2016).

Wage-based plantations

What distinguishes wage-based plantations (rubber, oil palm and other global commodities) is the importance of permanent tree crops in large areas of homogeneous planting. The first such business experience in the Amazon was Henry Ford's ill-fated project for a rubber plantation in Fordlândia and Belterra (Pará, Brazil), from the 1920s to the 1940s (Costa 1993; Grandin 2009). Other experiences followed with the promotion of rubber plantations by companies such as Pirelli, and public policies, such as the Brazilian federal government's National Program for the Development of Rubber (PROBOR) in the 1970s, with equally disappointing results (Costa 2000). In all cases, the homogeneous rubber tree plantations in the Amazon had little resilience in the face of attacks by pathogens abundant in the hot and humid ecosystems of the region (Dean 1987). In Brazil, the number of monocrop rubber tree plantations and their economic contributions have declined in recent years.

Oil palm has had explosive growth in Peru, Ecuador and Colombia; Amazonian plantations are for oil palm and coconut (Supplementary Material, Figure S6). In 2017, according to the agricultural census, monocrop plantations produced 94% of the 659,800 tons of palm oil and 92% of the 124 million bay-coconut fruits. The Brazilian government actively promoted the expansion of oil palm in the eastern Amazon (Pará state). Commonly called *dendê* in Brazil, oil palm was first introduced to the eastern Amazonian lowlands in 1940, and experimental plantations were established with government finance in 1968 and 1975 even though *dendê*, a key product in African and Afro-Brazilian cuisines, had been introduced as a food crop by slaves at a much earlier period (Watkins 2021). But until 1980, oil palms only covered about 4,000 ha in the whole state of Pará, and most production was undertaken by small-scale farmers, either organized in cooperatives or independently, supplying regional food markets (de Almeida *et al.* 2020).

Gradually, however, those plantations were acquired by Agropalma, currently the largest palm oil producer in Brazil, and possibly in Latin America as a whole. Agropalma (or companies that were eventually incorporated into it) continued acquiring thousands of hectares of land, mostly degraded pastures, on which to expand plantations through the 1980s and 1990s. These decades were a period of intense deforestation and violent conflicts in the region, and while Agropalma was starting to consolidate its palm oil agribusiness, the sector was also coming under pressure from international non-governmental organizations (NGOs) who condemned the deforestation, agrochemical contamination, and the displacement of smallholders and food production associated with the sector. This was particularly the case in southeast Asia, where oil palm production had expanded the most, but concerns were also reaching the burgeoning sector in Brazil (Monteiro 2013; Alonso-Fradejas *et al.* 2016). Thus, in 2002, Agropalma reformulated a smallholder contract system mimicking those of Malaysia, through which it could promote the social and environmental benefits of oil palm production in eastern Pará, arguing it would not only diversify the local small-scale commercial farming economy, but also curtail deforestation by creating a "sustainable" economic activity on "marginal" land, primarily degraded pastures (Monteiro 2013). These arguments were adopted by the incoming Workers' Party administration in Brazil, which included palm oil production by small-scale farmers as a pillar of its National Biodiesel Production and Use Program (PNPB) in 2004. Agropalma built the first biodiesel refinery to operate with palm oil in Brazil in 2005, and a wave of investments was unleashed by Brazilian private and state-owned companies, as well as foreign agribusinesses (Monteiro 2013; Potter 2015).

Since the early years of the national biodiesel program, however, it was becoming clear that palm oil agribusinesses were unable to profitably scale-up production to operate their refineries with supplies contracted from small-scale family farmers. The new corporate investors (from the United States, Canada, Portugal, Japan, China, and Brazil itself) began establishing their own large-scale monocultures and/or acquiring oil palm plantations from smallholders who established them, but were unable to sustain operations when labor-intensive harvests began (usually two to three years after palms are planted) (Oliveira 2017). Thus, government support and encouragement for small-scale farmers to switch to oil palm was basically serving as a mechanism of indirect dispossession and land concentration among the new agribusinesses that were establishing themselves in the region (Bernardes and Aracri 2011; Monteiro 2013; Potter 2015). From the logic of agribusiness investors, self-managed large-scale plantations seemed the best instrument for palm oil production and processing in the region, despite the original intentions of the Brazilian government's biodiesel plan and the "socially inclusive and environmentally sustainable" discourse still promoted by the agribusiness corporations that were quickly gaining ground in the region. Yet there continues to be partial adoption or maintenance of some contract farming with small-scale farmers, particularly by Agropalma, ADM, and the companies in which the Brazilian state itself participated, such as Petrobras and Biovale, in order to secure subsidies from the PNPB program's support for small-scale farmers (Backhouse 2015, Brandão *et al.* 2019).

Similar dynamics were also present in the Ecuadoran and Peruvian Amazon, where neoliberal policies enabled company-community partnerships that captured social benefits for oil palm processors, while small-scale farmers were adversely integrated and driven to deforest additional land to remain in business. Furumo and Aide (2017) calculated land-use change for oil palm across Latin America from 2000 to 2014. They found that the Amazon region had the highest rate of forest conversion for oil palm plantations in the Americas (alongside Guatemala).

On a national scale, Peru experienced the highest rate of woody vegetation loss from oil palm expansion (76%), amounting to 15,685 ha. This was particularly striking in the vast Loreto region of the Peruvian Amazon, where 86% (11,884 ha) of local oil palm expansion occurred at the expense of forest. In the Sucumbíos and Orellana departments of the Ecuadorian Amazon, there were 15,475 ha of oil palm plantations in 2014; 3,665 ha were associated with land conversion, including 1,582 ha of woody vegetation loss in these departments (43%). The Brazilian Amazon state of Pará featured the largest area of country-scale forest loss associated with oil palm expansion in the study: 70,923 ha of oil palm expansion were detected, of which 40% (28,405 ha) replaced woody vegetation (Furumo and Aide 2017, p. 6). The environmental effects have been problematic (Córdoba *et al.* 2019; de Almeida *et al.* 2020).

Wage-based plantations' production, however, covers a wider range of permanent crops. In the order of importance of the GVP among the permanent crops, in addition to oil palm and *coco-da-baia*, with 37.4% and 11%, respectively, there are cocoa, with 20.7%, *açaí*, with 12.6%, and oranges with 4%, to name the most important (Supplementary Material, Figure S6). Homogenous *açaí* plantations started to expand in the Amazon (and elsewhere in Brazil) during the past decade, motivated by EMBRAPA's development of varieties adapted to upland soils (Costa, 2022). IBGE started accounting for homogenously planted *açaí* in 2015. According to its agricultural annual estimates (PAM), from 2015 to 2019, the area planted with *açaí* in the Northern region (mostly Pará) expanded from 136,312 ha to 194,405 ha (IBGE 2019, table 1613). The agricultural census of 2017 confirmed 129,210 ha of *açaí* plantations, of which only 12% were wage-based plantations. The most important *açaí* plantations were in family-based agroforestry, with 64% of the total. Large-scale homogeneous *açaí* plantations are predominantly irrigated, but homogeneous *açaí* plantations are not necessarily more intensive than well-managed small-scale *açaí* agroforestry systems, particularly in riverine areas. The best managed *açaí* agroforestry areas can have equivalent productivity, and comparable density of clumps/stems/ha to more recent *açaí* plantations and its value on a per hectare basis is often greater than soy (Brondizio 2008).

Between 2006 and 2017, the number of establishments in wage-based plantations decreased from 20,000 to 16,000 in the Brazilian Amazon, while growing modestly, at 1.1% annually, from a GVP of USD 0.46 to USD 0.52 billion. With such a performance, the PT reduced its participation in the region's rural economy from 5% to only 3%. The number of workers remained constant at around 70,000, and there was a decline in land area from 7.8 to 3.8 million ha and in lands used, from 4 to 1.7 million ha (Figure 2; Supplementary Material, Tables S2 and S3).

Evidently, the expansion of commercial plantations has not taken place as fast or as widely as soy in Brazil, but they are quickly becoming a major form of land occupation in the Amazon. This is playing a role in driving direct deforestation, particularly in the lower Amazon (Pará state in Brazil) and more recently in the western Amazon (especially Peru, Ecuador and Colombia). Deforestation for oil palm expansion is one of the potential threats to forests in the "Trans-Purus" region in the western part of Brazil's state of Amazonas, as evidenced by the attempt of Malaysian oil palm firms to purchase land in this area in 2008 (Fearnside *et al.* 2020), and the purchase by Malaysian groups in the Loreto region of Peru.

SECTORAL DYNAMICS AND THEIR IMPLICATIONS

The analysis above does not include all economic sectors and livelihood strategies in the Amazon. Industry and service sector economies, concentrated in a few major cities like Manaus and Belém in Brazil, for example, contribute to a significant share of the region's gross domestic product (GDP), employment, and economic dynamism (Vergolino and Gomes 2004; Cooney *et al.* 2008; SUDAM 2021). Agribusiness pressures have led to the expansion of access infrastructure (e.g., dams, fluvial ports and waterways, paved roads, and plans for additional railroads; see Berenguer *et al.* 2021; Fearnside *et al.* 2021; Hecht *et al.* 2021). The consolidation of petroleum and large-scale mineral extraction, particularly in the western Amazon (Ecuador, Peru, and northwestern Brazil) are important phenomena that attract a significant amount of labor (albeit temporarily regarding the construction of the Belo Monte dam and the double dams of Santo Antônio and Jirau in the Madeira River, among others), and link labor and livelihood strategies in the Amazon to global circuits of capital and commodities (Klinger 2018; Hecht *et al.* 2021).

In some locations, as in Madre de Dios, Peru, and the Tapajós region in Brazil, small scale (artisanal) mining (particularly for gold) plays a determinant role in local labor markets and livelihood strategies. However, it is often associated with boom-and-bust cycles of mineral exploration, and socio-ecological ills associated with the footloose economy of mining booms and busts (e.g., trafficking, violent crimes) (Bebbington *et al.* 2018a; Kolen *et al.* 2018) and can lead to invasion of national parks and indigenous lands (RAISG 2020). A central problem is also related to the mercury toxicity and more general river turbidity that impacts aquatic ecosystems and the people who depend on them (Balzino *et al.* 2015; Asner and Tupayachi 2017; Cortes-McPherson 2019; Guiza, Penuela *et al.* 2020). Moreover, the socio-economic and environmental impact of infrastructure and unsustainable extractivist activities, usually associated with gold mining and timber harvesting, goes beyond the number of people employed and the area occupied; these activities literally lay the foundation for further rounds of speculative land clearing, expansion of cattle ranching and illicit crops such as coca as a means of money laundering, and stimulate agricultural production in their wake, to supply workers in these activities. They also make distant markets more accessible through the roads built to access these new infrastructure construction sites and extractivist activities in the first place (Fearnside 2015; Bebbington *et al.* 2018; Bebbington *et al.* 2020; Ferrante *et al.* 2021; Hecht *et al.* 2021).

Large-scale appropriation of public resources

The dynamics described above involved large scale private appropriation of public lands in the Brazilian Amazon, generally those covered with primary forest. Data from agricultural censuses allow us to estimate that wage-based productive trajectories incorporated 15.1 million ha of public land between 1995 and 2017, the difference between a 16.4 million total increase (node "Inputs from public land or family-based PTs" in Figure 6) minus 1.3 million corresponding to the portion of these inputs that came from family-based PTs that shifted to wage-based production systems (node "Output for wage-based PT" in Figure 3). The composition of the flows suggests that wage-based crops accounted for 38% of the public lands incorporated in the 1995-2006 period. In the 2006-2017 period, wage-based livestock accounted for 40%, wage-based crops for 15% and wage-based plantations for 6% of the public lands incorporated into production.

A full 8.8 million ha of these lands were transferred out of wage-based livestock structures (node "Output agrarian reform or other use" in Figure 6), a portion of them to family-based enterprises through agrarian reform programs (6.45 million ha, node "Inputs through agrarian reform" in Figure 3) and another portion destined for urban, or infrastructure uses, definitively leaving the agrarian sector (the remaining 2.3 million ha). It follows that, in 2017, around 12.4 million ha of public land appropriated remained in the agrarian sector, a final result that summarizes the process of shifts in the land holdings of the different production structures (Figure 8): wage-based crops grew the most, by 8.7 million ha; followed by family-based agroforestry, by 4.1 million; family-based livestock, by 1.8 million; and wage-based plantations, by 1.1 million. In turn, lands of family-based crops were reduced by about 900,000 ha, and wage-based livestock, the great intermediary in the exchange processes, by 2.2 million ha (see Supplementary Material, Table S3, last segment).

Intensification and deforestation

Ultimately, the degree of integration and fluidity between different land use types is constricted by land use lock-ins, capital scarcity, and cultural dimensions. Consequently, the intensification of large commercial agriculture and ranching itself becomes a driver in the further expansion of these large-scale commercial production systems, dashing the common hope that intensification can "spare land" for conservation. This belief that intensification may reduce pressure for land clearing if strict conservation regulations are established and enforced (Nepstad *et al.* 2019), overlooks how Amazonian landholders are participants in a market economy and respond to opportunities for greater profits by expanding those activities rather than limiting them (Fearnside 2002; Thaler 2017; Muller-Hansen *et al.* 2019).

The soy-livestock integrated systems (wage-based crops) may have substantially higher profits and shorter payback periods, as compared to extensive pasture systems (wage-based livestock) (Gil *et al.* 2018), but most analytics do not include

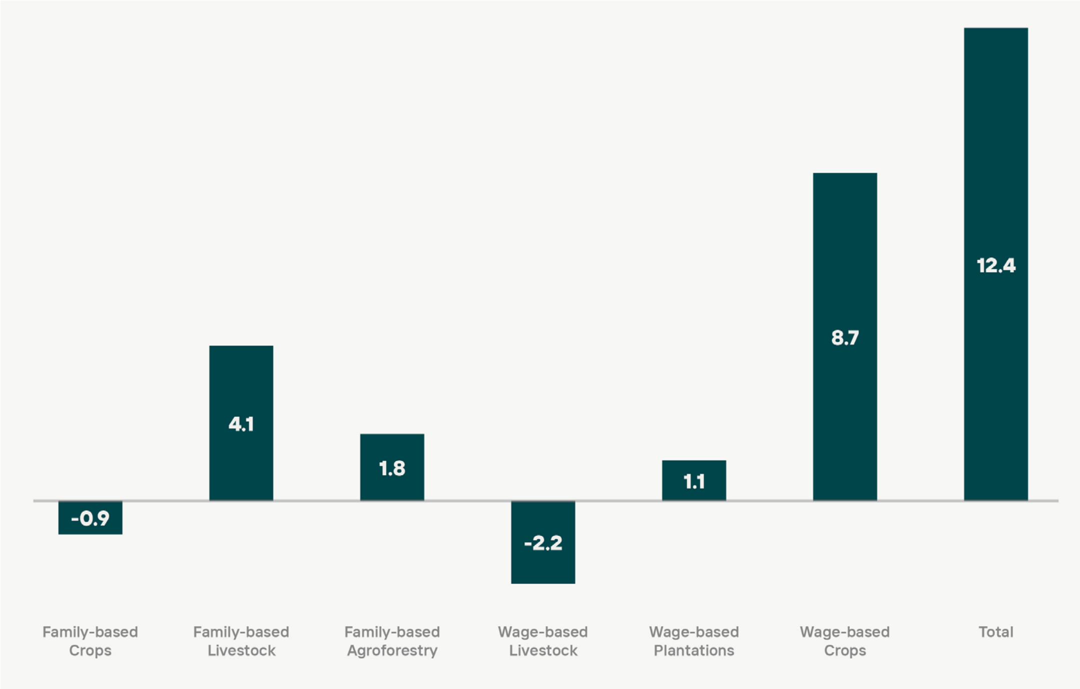

Figure 8. Shifts in private land tenure (million ha) in the agrarian sector of the Brazilian Amazon by production trajectory from 1995 to 2017. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Supplementary Material, Table S3, last segment.

the returns to land speculation. However, intensification also increases political and economic incentives for further expansion of agricultural production and ranching if it enhances productivity and profits. This is known as the "Jevons paradox" - that agro-industrial innovation can exacerbate, rather than curtail, deforestation and other forms of socio-ecological degradation (McKay and Colque 2016; Oliveira and Hecht 2016; Thaler 2017). Moreover, deforestation alone is an extremely narrow metric to gauge environmental impacts and socio-ecological sustainability, and when the intensification of agricultural production occurs through increased mechanization and application of agrochemicals (pesticides, herbicides, and synthetic fertilizers), it also significantly exacerbates ecosystem degradation through pollution of soils and waters, loss of biodiversity, soil erosion, and other impacts (Oliveira 2012).

Privatized lands were subjected to different uses in Brazil, which mainly entailed removal or impoverishment of forest and water resources. The deforested area grew from 37.2 million ha in 1995 to 57.8 million ha in 2017. Between 1995 and 2006, 12.6 million ha were added to production, 2.3 million in wage-based livestocking (deforested in processes that predominantly produced pasture), and 6.0 million in wage-based cropping (in processes that, in the end, produced temporary croplands). Together they represented two-thirds of the total (Figure 9).

Between 2006 and 2017, an additional 8.2 million ha were converted to non-forest production, 72% of which by wage-based livestock and agriculture systems.[4] Throughout the period, a systemic cooperation was established between these two productive systems (as discussed above): the former functioned as a supplier of deforested land, the latter as its client. Among smallholder systems, only family-based livestocking deforested 2.2 million ha. It is important to note that these figures measure only deforestation associated with land clearing, but not other forms of disturbance such as degradation, or pollution from agrochemical use (Matricardi *et al.* 2020).

Carbon emissions and sinks, and land degradation

Based on the census statistics from Brazil, average net CO_2 emissions (without considering emissions from equipment and tractors, fertilizer application, and subsequent soil management) were estimated to be 0.144 Gt per year between 1995 and 2006 and 0.109 Gt per year between 2006 and 2017 from forest clearing alone, which can cause an equally substantial or even larger amount of climate-change inducing emissions over time. The model applied (Costa 2016) linked the balance sheets of deforestation-linked emissions to the different production trajectories: between one period and the next, the contributions of emissions from wage-based livestock grew, respectively, from 60% to 65% while those from large commercial agriculture fell from 11% to 1%. The systemic cooperation between these two production systems explains these results, which should be read in aggregate

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[4] To corroborate the census data, an equivalent area of 8.6 million ha, was recorded by Brazil's Program to Calculate Deforestation in the Amazon (PRODES) in the same period (MapBiomas 2020).

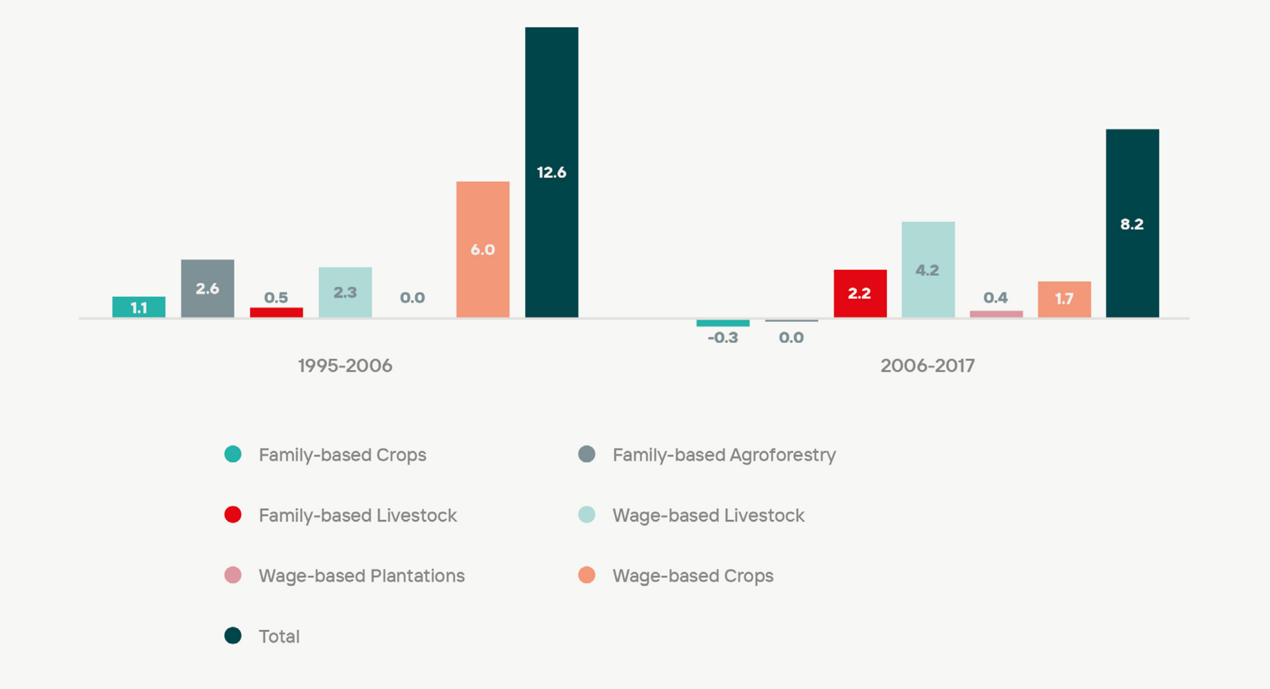

Figure 9. Changes in used/deforested lands in inter-census periods (in million ha). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Supplementary Material, Table S3, last segment.

(i.e., for a total of 66% in 2017), as land cleared proximately for cattle ranching typically is then turned over for soy production a few years later after pastures become degraded. The contribution to CO_2 emissions by family-based livestocking also grew from 22% to 33% in the same period.

In turn, family-based agriculture turned into a CO_2 sink, wage-based plantations reduced their contribution from 5% to 2% of CO_2 total net emissions, and family-based agroforestry continued to contribute virtually no CO_2 emissions through the whole period (Figure 10). This is because these family-based production systems do not rely upon or drive further deforestation, and even increase the organic content in the soil, capturing CO_2 from the atmosphere and transforming it into plant nutrients, although over time cleared areas can release more carbon than native forests.

The same model, as an assumption for the calculation of CO_2 balance, estimated the area of three different forms of secondary vegetation, reaching a total in 2017 of 8.6 million ha in the Brazilian Amazon.[5] The three types of land with secondary vegetation included "fallow lands" associated with shifting cultivation (total 580,000 ha, distributed among the peasant production systems); "degraded land" (mainly degraded pastures – total 2.9 million ha, half of which associated with cattle ranches); and finally, the largest portion was "land in unspecified reserves" (total 5.1 million ha). Half of this belonged to commercial cattle ranches; the other half was distributed among the other land uses, without notable distinction (Supplementary Material, Figure S7). One can only conjecture about the nature of these reserves: one hypothesis is that they are part of the stocks of "land producers" – they are explained by the logic of speculation with land.

According to Walker *et al.* (2020), forest degradation accounts for a large majority of carbon loss in the Brazilian Amazon (68.8% in 2016), a proportion that was even higher in the other Amazonian countries: for the Pan Amazon as a whole, forest degradation accounted for 87.3%, of carbon losses. This forest degradation is from all sources, including logging, fire, edge effects and tree death during droughts (see Berenguer *et al.* 2021), but logging, together with the fires that occur due to the disturbance from previous logging and pasture management, are undoubtedly a large part of this enormous impact.

Predatory commercial production and asymmetric policies

Wage-based livestock and crops are the largest land use categories in the Brazilian Amazon and their development has required deforestation, with greater environmental impact expressed in the largest shares of net carbon emissions that occur in the rural sector of the Brazilian Amazon. Both sectors have been rewarded with increasing profitability, with

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[5] This estimate converges with the estimate of 8.9 million ha of secondary forests reported in the Fourth National Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases for the United Nations Framework Convention (see BRAZIL - Ministério de Ciência, Tecnologia e Inovações 2021, Matrizes de dados de atividade e resultados de emissões e remoções de CO2, Figure 21, Matriz de conversão de uso e cobertura da terra do bioma Amazônia de 2010 a 2016, column FSEC, lines FSEC)..

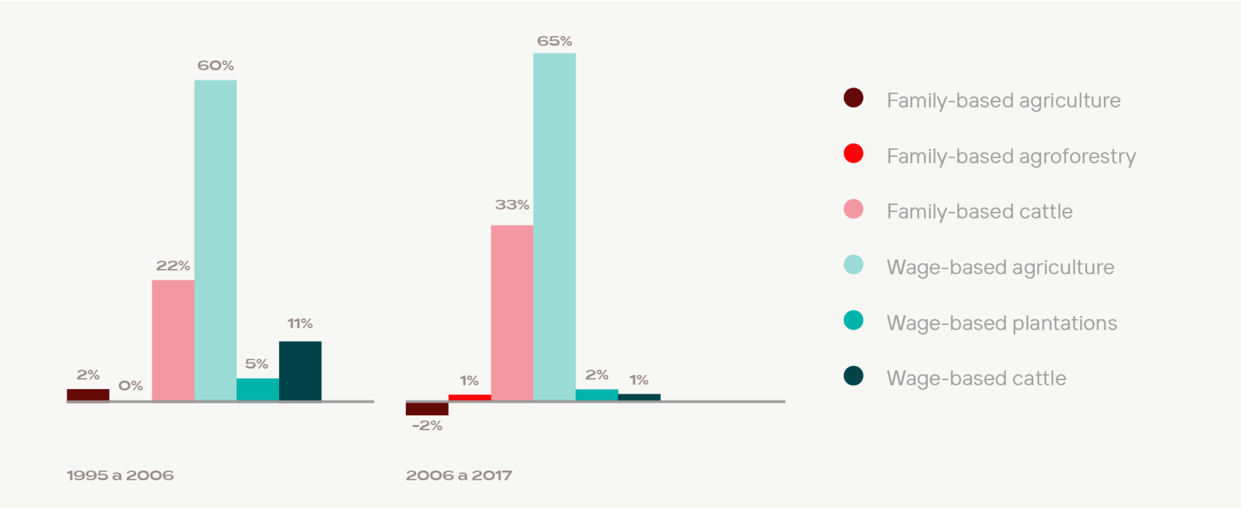

Figure 10. Contribution of productive trajectories to total net emission of CO_2 of the agrarian economy within the Brazilian Amazon biome in the periods 1995-2006 and 2006-2017 (% of total). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Costa 2016.

additional returns derived from the processes of speculation with land (described above), given the dominant illicit appropriation, and through illegal timber production (Fernandes 1999; Araújo 2001; Treccani 2001; Brazil 2002; Benatti 2003; Fearnside 2015; Ferrante *et al.* 2021; Carrero *et al.* 2022). Both cattle ranching and commercial agricultural enterprises have also been the preferred recipients of favorable public policies, institutional and political support, securing critical technological knowledge for homogenous agriculture and livestock establishments (Hecht and Mann 2008; Gasques *et al.* 2010; Oliveira 2013). Indeed, in 2006 and 2017, the largest volume of development credit was granted to agricultural enterprises (25% and 28% of GVP in those years, respectively), while cattle ranchers obtained financing that corresponded to 10% and 29% of GVP in the same years, respectively, essentially tripling the support received (Figure 11). Access to official technical assistance aligned precisely with what was observed with credit (Figure 12).

Given these advantages, the competitive power of these large-scale production systems has proved overwhelming: in 2017 they represented 77% of GVP of the rural economy in the Brazilian Amazon (Figure 2). Their considerable competitive power to shape institutions and national politics often relies upon unequal access to resources and local politicians, encourages deforestation, and unleashes other environmental impacts on land and rivers that undermine environmental services and possibilities for more resilient, equitable and sustainable development pathways.

There are issues specific to the context created by the dynamics of large-scale cattle and agricultural enterprises in the Brazilian Amazon. One problem is the antagonism generated in relation to recommended "forest management" practices. Well-intentioned management companies face competition from illegal logging and unsustainable legal forest management. Right from the start, there are economic impediments that stem from the widespread availability of wood from illegal, predatory and unsustainable sources (see Barlow *et al.* 2021; Hecht *et al.* 2021). Besides, the system can be unsustainable due to various loopholes that have been created to legalize unsustainable management, as well as frequent violation of regulations both by government licensers and by those who receive the licenses. For example, various ways have been devised to allow harvesting to deviate from established cutting cycles, in which one logging compartment is harvested each year until the cycle is completed, after which logging is repeated in the logging compartment harvested in the first year (Miranda *et al.* 2019). If the entire management area is harvested in the first few years (or even in the first year) and the management company or property owner is expected to remain without income for the remainder of a 30-year cycle, the theoretical sustainability of the system becomes meaningless (Fearnside 2020).

The wage-based-plantations, production systems based on permanent crops and reforestation, have recurring problems related to the vulnerability of homogeneous botanical systems that show low resilience in the region (see wage-based plantation systems section). Also, the high opportunity cost of managed wood, resulting from the relatively low growth rate of trees in the original forest compared to the yield rates of investment alternatives from the results of the immediate liquidation of forest assets, is a problem for forest management worldwide (Clark 1973; Fearnside 1989; 1995a). However, there is a strong component in shifting cultivation systems that produce wood for local systems and construction, using fast-growing species such as *Bolaina* (*Guazuma crinite* Mart.) (Sears 2016).

Volatility of family-based production net income and vulnerability

Regarding family-based production systems in Brazil, two aspects stand out. First, family-based livestock followed the trend of the wage-based production systems, as it doubled net income per family worker. Also, like the latter, family-based livestocking was

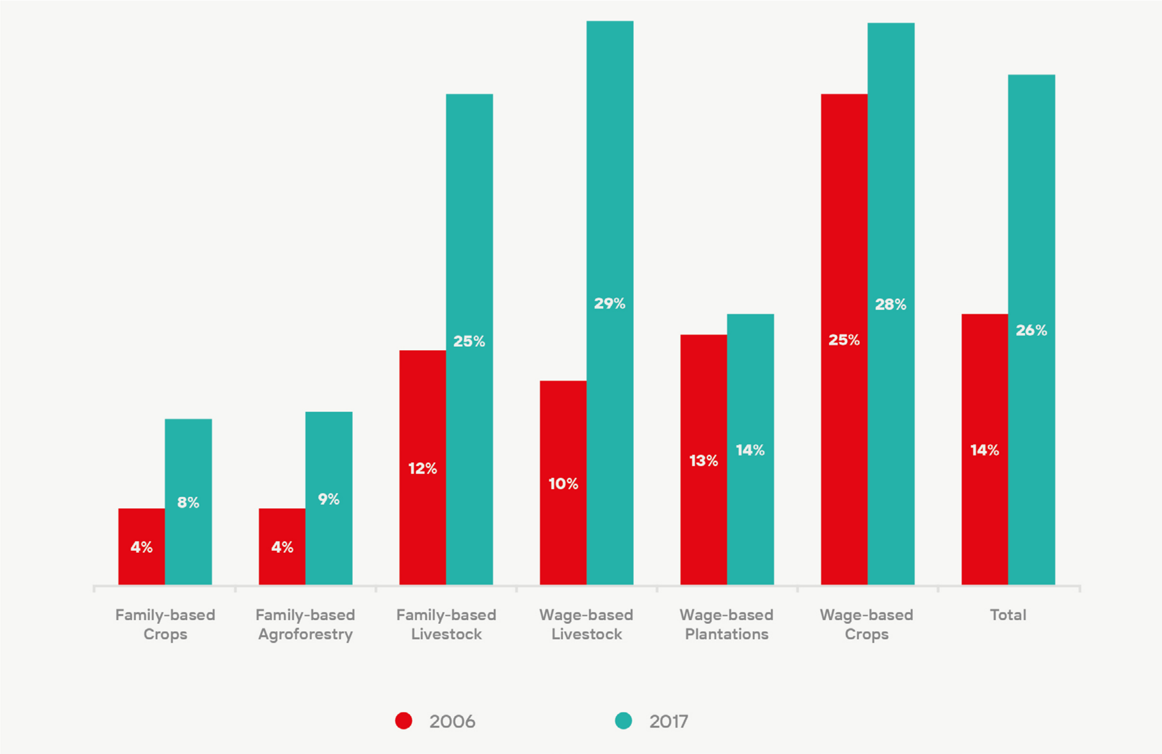

Figure 11. Ratio of credit to GVP by productive trajectory in the agrarian economy within the Brazilian Amazon biome in 2006 and 2017 (in %). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Brazilian Central Bank; Supplementary Material, Table S1.

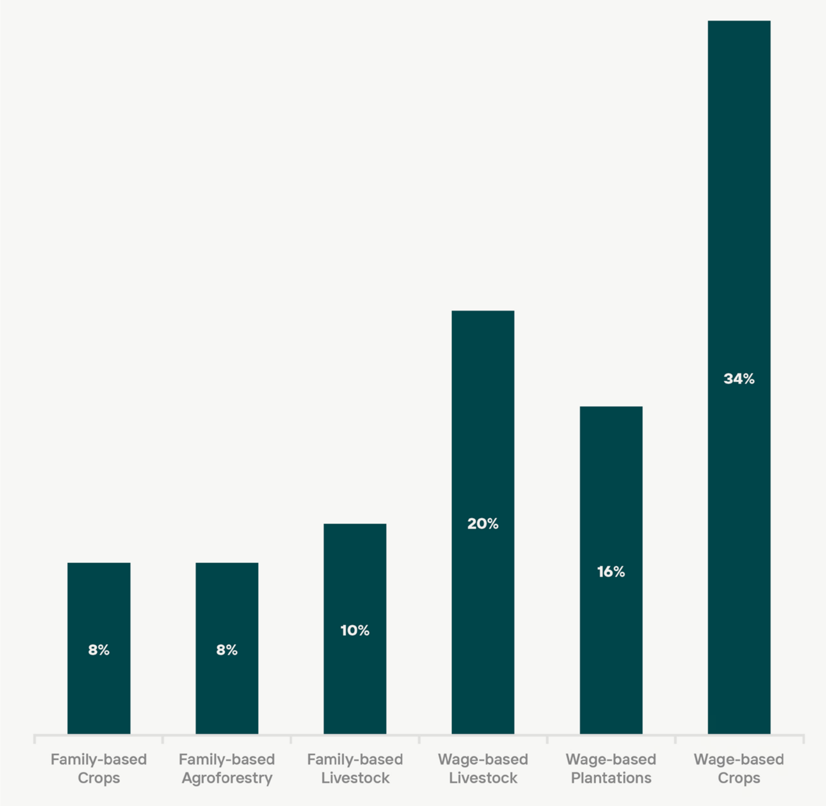

Figure 12. Ratio of the number of establishments with technical assistance to the total number of establishments of productive trajectories in the agrarian economy within the Brazilian Amazon biome in 2017 (in %). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Supplementary Material, Tables S1 and S3.

strongly supported with credit capital, which represented 25% of its total GVP in 2017, an increase from only 12% in 2006. In 2006, the participation of family-based cattle enterprises in credit was the most important among all family-based systems. In turn, family-based agriculture and agroforestry had the lowest access to credit compared with other producer groups (about 4% in 2006, about 9% in 2017, Figure 11), and the lowest access to technical assistance (10% for family-based livestocking, and 8% for agriculture and agroforestry, Figure 12).

Secondly, the net income per family worker of family-based agriculture and agroforestry, after experiencing strong growth, decreased severely for the former and stagnated for the latter: respectively from USD 1,141.20 in 1995 to USD 3,051.60 in 2006, dropping to USD 2,034.40 in 2017 (for agriculture), but increased for agroforestry, from USD 918 in 1995 to USD 2,059.20 in 2006 and remained basically at this value in 2017 (Figure 13). The volatility of family-based agriculture's income produced a crisis, certainly heightened by the tensions surrounding land, materialized in the transformation into urban or rural wage workers of over half a million workers (see family-based annual crop systems section), and in the reduction of their role in local supply. The income stagnation of family-based agroforestry, notable for its sustainability attributes, indicated limits in its capacity to expand and to improve the living conditions of those involved. Considering the fact that the prices of its key products were increasing, this situation implied reduction of physical productivity or marketing distortions. Indeed, climate change and increasing urbanization are posing new and considerable challenges to family-based agriculture and agroforestry systems.

KEY QUESTIONS AND PROPOSALS TO IMPROVE FAMILY-BASED PRODUCTION SYSTEMS

Adaptation to climate change and urbanization

The methods by which Amazonian local communities manage landscapes and exploit natural resources are changing in response to the region's growing urbanization (Padoch *et al.* 2008; Brondizio *et al.* 2011; Padoch, *et al.* 2011; Eloy and Lasmar 2012; Hecht *et al.* 2015; Franco *et al.* 2021). In much of the Amazon region, the economy and ways of life of the rural populations have been based on different combinations of subsistence and commercial activities of annual and perennial agriculture, gathering of forest products, fishing, and hunting (Moran 1991; 1994). This polyvalent strategy, which combines a multiplicity of primary subsistence activities, allows these populations to adapt and utilize the diverse Amazonian ecosystems, from dense forests and savannahs of drylands to the aquatic environments of the small tributaries and great river's floodplains (Witkoski 2010). These activities are now supplemented with wage labor, remittances, state transfers and urban migration (Padoch *et al.* 2011; Hecht *et al.* 2014). This adaptability underlies the ability of diverse local production systems to persist and adapt, even under unfavorable conditions, as well as their importance for future strategies to support more sustainable production systems (Eloy and Lasmar 2012; Brondizio *et al.* 2021; Franco *et al.* 2021).

Climate variability is changing the timing as well as the frequency and intensity of heat waves, severe storms, floods, drought spells and other hydro-climatic extreme events (see Supplementary Material, Appendix S4; Marengo *et al.* 2021), which have produced catastrophic impacts on livelihoods and environments (Marengo *et al.* 2013; Espinoza *et al.* 2020). Localized short-lasting and intense hydro-climatic events have become the main constraints for farming annual and perennial crops in the Amazon, while urban expansion and the integration of the Amazon to regional, national and international markets are mentioned by policy makers, producers and experts as factors that have changed patterns of production and supply of food crops to Amazonian cities (Coomes *et al.* 2016; Abizaid *et al.* 2018).

The annual and perennial crop fields of Amazonians are highly vulnerable to short-duration and highly damaging floods, droughts and rainstorms (Kawa 2011; Sherman *et al.* 2016; Espinoza *et al.* 2019; List *et al.* 2019). Based on interviews and published information, producers in the Amazon delta are dealing with two types of extreme tidal flooding (locally known as *lava praias* and *lançantes*) and producers from the upper to lower Amazon are dealing with damaging out-of-season floods. These floods, locally known as *repiquetes,* are produced by local extreme rainfall events, causing sudden increases in river level during the dry season (Ronchail *et al.* 2018; Espinoza *et al.* 2019; List *et al.* 2019).

Climate change is interfering negatively in the production of *açaí* in hot years (Tregidgo *et al.* 2020). More generally, its productivity has been affected by the erosion of diversity of *açai* varieties resulting from the greater intensification of the management of açai stands or *açaizais* (Freitas *et al.* 2015; Campbell *et al.* 2017). Amazonians are adapting in diverse ways to these challenges. They are increasingly planting cassava, corn, beans and other annual crops in upland and (*terra firme*) on the highest sections of levees, locally known as *restingas altas* to protect from floods (Gutierrez *et al.* 2014; Coomes *et al.* 2020). Similarly, the data show that farmers are increasingly engaging in collective action to control fire during land preparation to avoid accidental or escaped fires (Gutierrez *et al.* 2014). In the delta, farmers are planting vegetables, spices and other annual crops in suspended platforms, locally known as *canteiros* or *girais*; in the floodplains, farmers are planting flood-tolerant varieties of rice, beans and other annual crops to attract and harvest fish in low areas of the floodplain that are vulnerable to *repiquetes* (Kawa 2011; Steward *et al.* 2013).

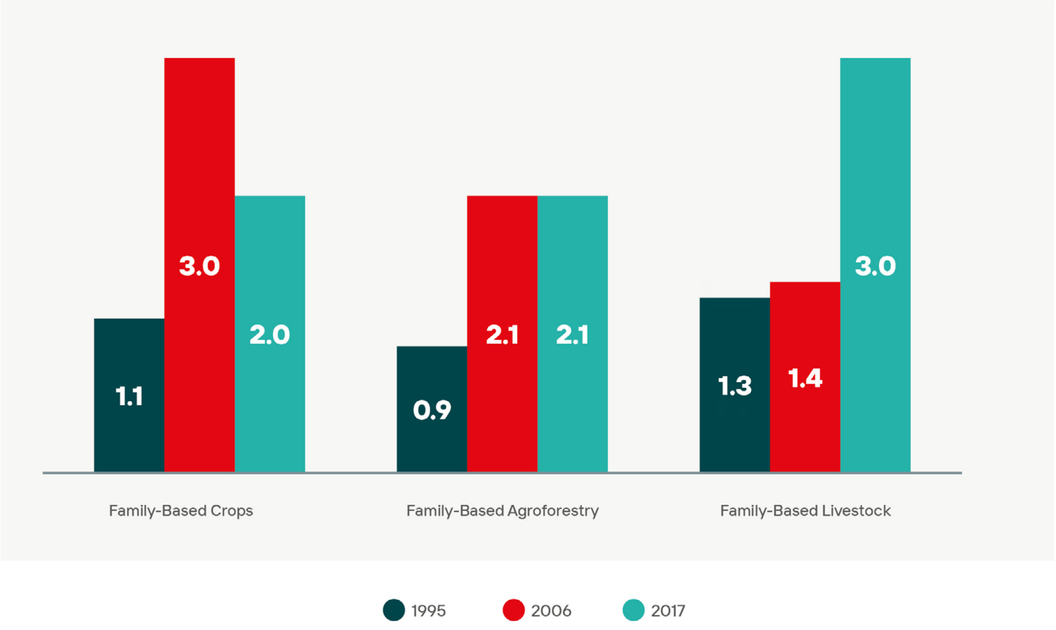

Figure 13. Net income per family worker [(GVP-costs)/family worker-equivalent] in family-based productive trajectories in 1995, 2006 and 2017 (in USD 1.000/year). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Supplementary Material, Table S1.

In the Amazon delta, the adaptive processes of farming annual crops are leading to the expansion of house gardens and enriched and managed fallows and forests for the production of *açaí*, fruits and other perennial crops (List *et al.* 2019). The conversion of banana fields to enriched and managed fallows and forests, has greatly increased the production of *açai*, fruits and other perennial crops (Vogt *et al.* 2015). In the levees along the floodplains of the upper Amazon, agriculture fields have been converted into enriched fallows with fast-growing timber species, fruits and other perennial crops (Sears *et al.* 2018). The capacity of Amazonians to adapt to climate change explains why annual and perennial crops continue to be important sources in sustaining the livelihood of millions (Winkler Prins and Oliveira 2010; Sherman *et al.* 2016) and underscores the importance of their systems for the future.

While hydro-climatic disturbances are considerably impacting the yield and diversity of annual and perennial crops, Amazonian producers continue relying on a great diversity of annual and perennial crops to manage vulnerability and risks associated to changes in the market produced by the process of urbanization (Coomes *et al.* 2020; Langill and Abizaid 2020). In all Amazonian countries, producers are responding to the constraints and opportunities produced by urban expansion by: (i) changing their focus or decision making, in some cases from market oriented to subsistence oriented cultivation of rice, corn, beans and other annual crops and, in other cases, from subsistence oriented to market oriented production of perennial corps (Coomes *et al.* 2020); (ii) changing food processing systems, from manual to mechanical processing (Brondizio 2008); (iii) changing their sources of seeds and other planting materials, by integrating seeds that are sold in the markets to the local seeds systems (Abizaid *et al.* 2018; Coomes *et al.* 2020; Oliveira *et al.* 2020;); and (iv) changing trade systems, from randomly selling in all markets to directly selling to distributors or contributors (locally known as *pedidos*) or contracts (locally known as *habilitación*) mediated by social networks and cell phones (Abizaid *et al.* 2018).

Fisheries development

The expansion of modern commercial fisheries greatly increased pressure on floodplain lake fisheries, mobilizing floodplain communities throughout the Amazon floodplain network to implement collective agreements called "*acordos de pesca*" to regulate local fishing activity (Smith 1985; McGrath *et al.* 1993). Community management of floodplain fisheries was based on local community land tenure systems, which considered lakes to be collective property, and on the logic of the diversified household economy. Households employed economic strategies including various combinations of commercial and subsistence fishing, annual and perennial crops, forest management, hunting and collecting (e.g., turtles, crabs), and small and large animal husbandry (ducks, chickens and cattle). Fishing was central to these strategies, providing the main source of animal protein, cash to purchase household necessities, and working capital for investment in the other productive activities. Community management sought to maintain the productivity of local fisheries so that fishers could optimize time spent fishing, with the allocation of household labor to other productive activities (McGrath *et al.* 1999).

Among the most important innovations in fisheries management has been the development of a management system for the *pirarucu* or *paiche* (*Arapaima* spp.), one of the largest and highest-priced fish species in the Amazon. A highly successful management system that combines scientific and local fisher knowledge and skill was developed for *pirarucu* at the Mamirauá Sustainable Development Reserve (Castello 2004; Duponchelle *et al.* 2021). This system made it possible to simultaneously increase annual catch rates, numbers of fishers and populations of *pirarucu* in managed lakes (Castello *et al.* 2009). The management system has been widely disseminated in the state of Amazonas (Brazil) and in the Peruvian Amazon. In Amazonas, total catch of managed *pirarucu* increased from 20 tons in 2003 to more than 2,600 tons in 2019 (Campos-Silva and Peres 2016; McGrath *et al.* 2020). The ability to count individual fish reduced uncertainty, and motivated fisher groups to invest in sustainably managing *pirarucu*, and in the process created governance conditions that benefitted other important fish species and, more generally, aquatic biodiversity (Castello *et al.* 2009).

While some researchers have questioned the viability of community-managed fisheries, studies have shown that lake fisheries with effective management agreements can be 60% more productive than unmanaged lakes (Almeida 2006). Other studies have shown that migratory species, such as the *tambaqui (Colossoma macropomum* Cuvier) and *surubim (Pseudoplatystoma fasciatum* Linnaeus), which spend their juvenile phase in managed lakes, tend to be significantly larger than those in unmanaged lakes (Castello *et al.* 2011). With adequate government support and technical assistance, the community-based management system could be extended to the entire Amazon floodplain and ensure the sustainable management of floodplain fisheries (Duponchelle *et al.* 2021). Progress has been made in managing floodplain fisheries, but there has been minimal progress in sustainably managing stocks of the long-distance migratory catfish (Fabré and Barthem 2005; Goulding *et al.* 2018). While these species continue to play a major role in Amazon's commercial fisheries, largely uncontrolled fishing and dam construction threaten their viability (Castello *et al.* 2013; see also Fearnside *et al.* 2021).

This is a critical time for Amazon fisheries (see Supplementary Material, Appendix S5). After centuries of largely uncontrolled exploitation, important commercial fish species are overexploited. Yet, as a whole, Amazon fisheries are still productive, and continue to sustain hundreds of thousands of rural and urban families. In some states, effective management systems are contributing to the recovery of regional fisheries, and if such policies were implemented throughout the floodplain system, the decline of Amazon fisheries could be reversed, improving the livelihoods of Indigenous peoples and local communities, urban fishers and other supply chain actor groups (Duponchelle *et al.* 2021).

Beyond capture fisheries, federal and state government policy makers are enthusiastically promoting aquaculture as the modern way to produce fish and fill the gap created by the depletion of the Amazon's wild fisheries (McGrath *et al.* 2015). Aquaculture's rapid expansion in the Amazon holds the potential to provide an alternative to cattle production, helping diversify local incomes and rural and urban food supplies while reducing the land footprint of animal-based foods (McGrath *et al.* 2020). However, the degree to which aquaculture will become an environmentally sustainable, nutritious, and equitable component of Amazonian food systems depends on a myriad of factors, including improving production efficiency, culturing a diverse set of native species, reducing initial investment costs, and ensuring that farmed fish are accessible to people who rely heavily on fish, including rural, poor and Indigenous people (Heilpern *et al.* 2021). Fisheries also are challenged by the serious problems of contamination from mercury from gold mining (Lacerda *et al.* 2012), petroleum by-products from oil extraction and flaring (Webb *et al.* 2015), and from the chemical toxicities from agro-industrial inputs, in addition to the problems of water flow with climate change associated with regional deforestation and dams (Coe *et al.* 2017). While much uncertainty remains around the tradeoffs between aquaculture, capture fisheries, cattle and other animal-sourced foods, it is clear that well-managed fisheries, both wild and farmed, could continue to be a culturally relevant and sustainable component of the Amazon's future bioeconomy (see Abramovay *et al.* 2021).

Integrating local and scientific knowledge

Local or Indigenous systems integrate both local and modern knowledge to manage, produce and conserve plant, animal, fish and other biological resources (Posey and Balée 1989; Sears *et al.* 2007; Thomas *et al.* 2017; Franco *et al.* 2021). Amazonians have demonstrated over millennia that these systems can be adapted successfully to changing conditions, persisting and even expanding over time despite relatively weak supportive policies compared to agribusiness. They have proven their ability to support food security and promote agrodiversity through such strategies as shifting crop fields, adopting new varieties and preserving germplasm, and managing enriched fallows and home gardens. They have also successfully developed networks to collectively manage fire use, lake fisheries, processing plants and marketing, to the benefit of linked rural and urban communities in the Amazon, strengthening regional economies. The many encouraging examples of ways to reduce environmental impacts while improving the well-being of Amazonian populations provide a strong foundation for future efforts to support more sustainable production alternatives.

Rural and urban populations are increasingly linked through multi-sited households and networks across the Amazon, posing both challenges and opportunities for more sustainable development efforts (Hecht *et al.* 2021; see also Brondizio *et al.* 2011; Padoch *et al.* 2011; Hecht *et al.* 2015). Increased urbanization can translate into stronger demand for locally produced goods of multiple types, if it is accompanied by effective support for peri-urban, urban and regional small farm agricultural systems. While large scale supermarkets now dominate urban food supply, more extensive systems of small-scale markets could enhance the viability of such systems, and preferential purchase by schools, hospitals and cafeterias can help create a more predictable demand. In addition, "niche market" chains for organic goods, cooperatives, and fair-trade items are mechanisms that can also support small scale producers, as the *acai* system has convincingly shown. International environmental markets for *açai*, Brazil nut and *cacao* can provide significant income and employment if supported by improved supply chain practices, branding of producer organizations, and supportive infrastructure (e.g., refrigeration, better drying and sanitation systems (Abramovay *et al.* 2021).

Recently the relations of Amazonian small producers with research institutions have intensified. In Brazil, EMBRAPA has generated new drought-resistant cultivars and new technologies for family producers, as well as supporting community forest management; for example, the highly organized agroforestry systems managed by the RECA (Consortium and Densified Economic Reforestation Project) community in Rondônia state produce Brazil nut, *pupunha* (*Bactris gasipaes* Kunth.) and *cupuaçu* (*Theobroma grandiflorum* Schum.*)* and process them into fruit pulp and palm heart to supply regional and national markets (Valentin and Garrett 2015). Furthermore, there is a growing relationship between local systems and industrial arrangements that have been rapidly building up around the processing of *açaí*, *cacao*, oils and cosmetics (Costa *et al.*, 2021). De-centralized education and inter-cultural dialogue are needed for applied ecology, bio-economies and new technologies rooted in local knowledges, and oriented to equitable returns to ILK (see Posey and Dutfield 1996; Frieri *et al.* 2021), for both local and broader markets.

For this relationship to become a positive long-term process, which protects the capacities of the Amazon biome and offers a dignified life to those who interact with it in their productive and reproductive processes, a strategy of science, technology and innovation (ST&I) is needed, aiming at new competencies for economies based on, and compatible with, the Amazon biome. In a land that has been home to continuous biopiracy for centuries, protection of intellectual property rights remains key, although such institutions and legal safeguards are largely non-existent. Rural smallholders and urban producers should participate integrally in the construction of new policies to support their evolving systems, to promote food security and regional economic health. Coordinated mechanisms should integrate rural producers with already existing centers and others yet to be formed, for the production and dissemination of appropriate knowledge for local and regional actors with alternative development approaches. In rural areas, a shift is required from a focus on specific crops, to a portfolio of diverse products and activities including forest and fisheries management, and climate change adaptation; in industrial and marketing, a shift is needed from a focus on scale to explore scope and branding economies, and to support production and consumption systems that bridge and support rural, peri-urban, and urban areas.

CONCLUSIONS

The Amazon is home to diverse populations who depend on the region's natural resources for their agricultural, extractivism, agroforestry, hunting, fisheries, and other productive activities to make a living and to generate important economic returns. The different actors involved in both larger wage-based and family-based systems of production interact in complex ways that vary across Amazonian countries, with important impacts on ecosystem services. Supportive pro-short-term growth policies regarding land tenure, agricultural credit and technical assistance, as well as the expansion of roads, waterways and other infrastructure have favored the rapid expansion of agribusiness and increasing appropriation of public lands, especially by cattle ranching and soy enterprises, with increasingly negative social and environmental consequences. These transformations have empowered agribusiness as well as speculative interests and undermined the ability of local communities to defend their own interests and practices, which are more attuned to the sustainability of the Amazon's resource base and the well-being of Amazonian peoples. The findings in this review point to the need to re-orient development to support small-scale, diverse production systems that provide employment and economic dynamism for local communities. Building on the rich biodiversity and local knowledge that supports many promising initiatives to adapt those systems to climate change and growing urbanization in the region, policies should focus on improving forestry, agroforestry and fishing systems managed by local communities.

RECOMMENDATIONS

Amazonian communities and populations have long relied upon a combination of subsistence and commercial activities for their livelihoods. They are adopting diverse strategies and practices in response to a changing climate and economies including reliance on a greater diversity of annual and perennial crops for managing vulnerability and risks associated with changes in the market linked to processes of urbanization. These promising examples of more sustainable and equitable systems of production should constitute a core focus of future policies.

Land policies and governance are required to contain the increasing appropriation of public lands for predatory uses, and to avoid the correlated negative social and environmental consequences.

Community-managed local fisheries provide rural families with a reliable source of animal protein, cash to purchase household items and working capital that can be used to invest in other productive activities. With adequate government support and technical assistance, the community-based management system could be extended to the entire Amazon floodplain and lake fisheries to benefit rural families, and to ensure more sustainable management of floodplain fisheries for both rural and urban families.

Across the Amazon, Indigenous and place-based ecological knowledge integrate both local communities and modern knowledges to produce, manage and conserve plant, animals (including fish), and other biological resources. Collaborations between local producers, cooperatives, research institutes and industrial and manufacturing processing facilities around *açaí*, *cacao* and cosmetic oils based on native Amazon palms have shown promising results. A strategy of ST&I with participation by smallholder producers could further enhance these initiatives and support the development of diverse, local production systems that provide both rural and urban employment and economic opportunities for Amazonian populations while reducing deforestation, greenhouse gas emissions and other environmental threats.

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SUPPLEMENTARY MATERIAL

Costa *et al.* Complex, diverse and changing agribusiness and livelihood systems in the Amazon

Appendix S1. Historic Amazon fisheries

For more than 350 years, until the second half of the 20th century, the immense fisheries resources were the major source of animal-derived nutrients, such as protein, fatty-acids, iron and zinc for Amazon populations (Crampton *et al.* 2004). Beyond providing a major source of subsistence for riverine communities, fish were a main staple of the *aviamento* credit and supply system through which virtually all Amazon production and trade was organized.(Nugent 1993). Fish were processed in salting stations on the shores of floodplain lakes and river margins where they were cleaned, salted and dried, and stored for sale to river traders and/or transported to urban merchants who shipped dried fish upstream to rubber and Brazil nut producing areas (Veríssimo 1895; Weinstein 1983; McGrath 2003).

This commercial system began to change with technological innovations including smaller diesel engines, synthetic fibers for nets, ice making technology, and styrofoam for ice boxes. These innovations enabled fishers to travel further and catch and store larger amounts of fish, as well as to ship fish across larger distances (McGrath *et al.* 1993). Commercial fisheries shifted from a seasonal activity producing and selling dried, salted fish, to a year-round activity involving fresh iced and frozen fish for growing urban markets, and the developing fish processing industry (Smith 1985). Through this process, commercial fisheries developed two distinct, though overlapping supply chains, one focused on migratory catfish to supply fish processing industries that exported fish to other parts of Brazil, and the other focused on fish with scales, especially *characins*, to supply regional Amazon urban markets (Crampton *et al.* 2004; Isaac *et al.* 2008). In Peru, Ecuador and Colombia, Amazonian fisheries supply local markets, since stiff competition with well-developed marine fisheries challenges expansion of river fish into coastal and Andean markets (Coomes *et al.* 2010).

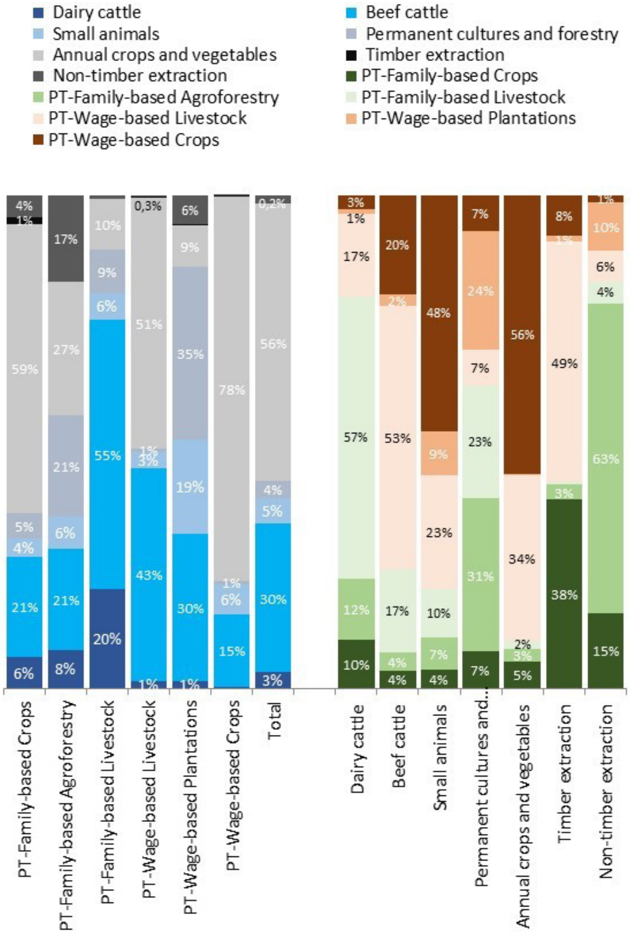

Figure S1. Production composition by productive trajectory of the agrarian economy in the Brazilian Amazon biome in 2017 as % of gross value of production, GVP. Source: IBGE, Agricultural Census 2017; Supplementary Material Table S1.

Appendix S2. Land grabbing in the Amazon: clearing for claiming

In many places of the world land grabbing involves nation states selling off or allocating national areas to other nations or corporations for food or biofuel, plantation production or, as mining or timber concessions on lands already occupied by other occupants or claimants. These can be historical territories, as is the case with Indigenous peoples and local communities whose tenurial regimes may not be recognized by the state, or settler/peasant farmer lands that may be simply expropriated by fiat or violence (Schmink 1982; Schmink and Wood 1992; Oliveira 2013; Grajales 2015; Ferrante *et al.* 2021; Carrero *et al.* 2022). In many situations land rights can be divided, but usually subsurface resources remain the purview of the state.

Amazonian lands can involve such large-scale international transnational transfers for corporations for land development. The classic case here is Fordlandia, but other international land grants during Brazil's authoritarian regimes included Daniel Ludwig's *Jari*, the Volkswagen ranch, the Caterpillar ranch (among many others who received fiscal incentives), as well as transfers to many large-scale national corporations. Rights over large-scale subsurface resources for hydrocarbons, minerals and concessional timber rights are common, and typically worked out through state concessions and complex sharing agreements. Because nation states typically assert subsurface rights, allocation and auction of such rights to international consortia (and sometimes with national partners) occurs widely, even if the lands and resources associated with such concessions are occupied by people whose livelihoods, lives, resources, cultures and histories can be dramatically undone by these actions (Finer *et al.* 2008; Perreault and Valdivia 2010; Valdivia 2015; Bebbington *et al.* 2018a; Bebbington *et al.* 2018b). The impacts on local populations can involve displacement, destruction of critical resources or subsistence resources like fish and tree crops, resource theft, contamination, introduction of disease, as well as cultural assaults including violence, local enslavement and attacks on women, leaders and forest guardians. Well documented cases include the Yanomami and informal gold mining, formal mining on *quilombos* on the upper Trombetas River, and pipelines on *quilombo* land near the Barcarena port in Pará state, Brazil. Indigenous land was opened for oil extraction in Ecuador, Bolivia, Peru and Colombia (Sawyer 2004; Finer *et al.* 2009; Widener 2009; Hindery 2013; Bebbington *et al.* 2018a; Bebbington *et al.* 2018b).

Large-scale infrastructure such as dams also involves expulsion and appropriation of land and resources of current occupants, and the overflooding of catchment ponds can lead to "river murder". Displacement, flooding, alteration of access rights, loss of resources and destruction of cultural heritage and overriding of legal occupation rights are a repeating and common story (Hernández-Ruz *et al.* 2018; de Lima *et al.* 2020).

Land grabbing can also reflect overlapping tenurial regimes that are a function of land laws and property rights enacted at different historical times but that still are more or less legal, like land tenure granted in the Brazilian state of Acre and by Bolivia over the same territories before the adjudication of national territories occurred. Sometimes simple occupation rights have been validated for a period, and then new regimes change the legality of the holding, as when collection concessions were transformed into legal property (Emmi 1988). Sometimes different land agencies with different jurisdictional remits (federal and state for example) have validated claims to the same holding with competing owners. Sometimes historical rights have been validated – as in indigenous territories and *quilombo* lands or local communities – or new categories of land categories have come into play, such as various kinds of protected areas. Because land is important as an asset, a means of production, a way to launder money from illicit or clandestine activities (Dávalos *et al.* 2014), a mechanism for capturing institutional rents such as credit and other production subsidies, and a vehicle for speculation with relatively low entry costs (Merry and Soares 2017), shifting forest to cleared land has been among the best ways of "conjuring property" (Campbell 2015). Land rights have also been secured through title fraud, violence, and more recently in the current Brazilian federal regime (2021), through amnesty. In this complexity of tenurial regimes, or the case of undesignated federal lands (*terras devolutas* as they are known in Brazil) competing surface land rights are resolved through clearing for claiming, the ancient dictum in Roman law*, uti possedetis*: he who has, keeps (Grajales 2015; Azevedo-Ramos and Moutinho 2018; Carrero, Walker *et al.* 2022). Into this maelstrom of tenurial regimes, cattle ranching and the infrastructure that attends it has had a special role. Cattle have multiple logics in Amazonian contexts: they do not need much labor, they are both an asset and a means of production of other assets (more cattle), they can be flexibly harvested, can be subsistence or market, local or regional goods, as well as a global commodity.(Hecht 1993). The development of pasture itself is relatively simple and cheap: it involves cutting forest, letting it dry, and setting it on fire. Subsequent seeding with exotic pasture grasses follows, and what had been a highly diverse forest of hundreds of species is reduced to a few in order to create a habitat for one species: bovines that roam at low densities over increasingly depauperate landscapes (Barona *et al.* 2010; Bowman *et al.* 2012; Bustamante *et al.* 2012). The creation of pasture from forest largely nullifies any alternative, forest-based or most agricultural land uses that do no t employ herbicides, which is why gatherers of forest products and forest people more generally, and small scale farmers, have resisted the expansion of livestock, and why ranching has become such a central feature of land encroachment on protected and indigenous areas, areas of road expansion and new colonization, and why this land use is so often contested (Simmons *et al.* 2007; Grajales 2011; Ballve 2013; Botia 2017; Schmink *et al.* 2019).

The usefulness of cattle as a product, however, mediates a far more valuable asset which is via "clearing for claiming" – the showing of effective land use - which is an element required for the defense of land claims, and the transformation of seemingly "amorphous" lands into private property. In this context, title, however dubious, helps in real estate transfer and has given rise to a gamut of fraudulent practices, including most recently, the ability to buy georeferenced but illegally claimed and cleared Amazonian land on Facebook (Fellet and Pamment 2021).

The increase in land prices "heats up" the land market and everything it mobilizes, including the mark-up of "producing" land and expanding the land grab effort. The great growth in the volume of appropriated lands in recent years in other countries than Brazil, corresponding to a rate of 1.2 million ha per year, may indicate a harbinger of a new cycle of land grabbing which precedes a corresponding cycle of "producing land", i.e., turning it into a commodity (Araújo *et al.* 2009; Campbell 2015; Rajão *et al.* 2020). The expanding infrastructure programs for all of the Amazon with its vast new regional road networks and the strong association of roads and land clearing (Pfaff *et al.* 2007; Perz *et al.* 2013; Pfaff *et al.* 2018, Hecht et al 2021) and with speculation, suggest accelerated clearing, especially under current lax regulatory conditions, which mimic those of earlier times (Hecht 1985, 1993; Barona *et al.* 2010; Bowman *et al.* 2012; Dávalos *et al.* 2014). The speculative aspect is especially relevant in the context of land tenure uncertainty, expanded infrastructure development, advancing crop frontiers and financialization of land (Bowman *et al.* 2012; Richards *et al.* 2014; Campbell 2015; Garcia-Arias *et al.* 2021; Carrero *et al.* 2022). Ranching can be financially appealing in the context of land speculation, as a way to cheaply secure large areas of land until land prices rise, and as a means of capturing an array of institutional rents (Hecht 1993; Mann *et al.* 2014; Miranda *et al.* 2019; Escolhas 2020; Meyfroidt *et al.* 2020). By institutional rents we refer to value that comes from government infrastructure and services, including various fiscal incentives (credit lines, trade policy and subsidies), research, and favorable policies. Deforestation for livestock expanded 1.2 million ha per year between 1985 and 1995, and 1.9 million ha per year between 1995 and 2006 (IBGE 2020; INPE-MapBiomas 2020). It represents so far, the largest land use after deforestation,

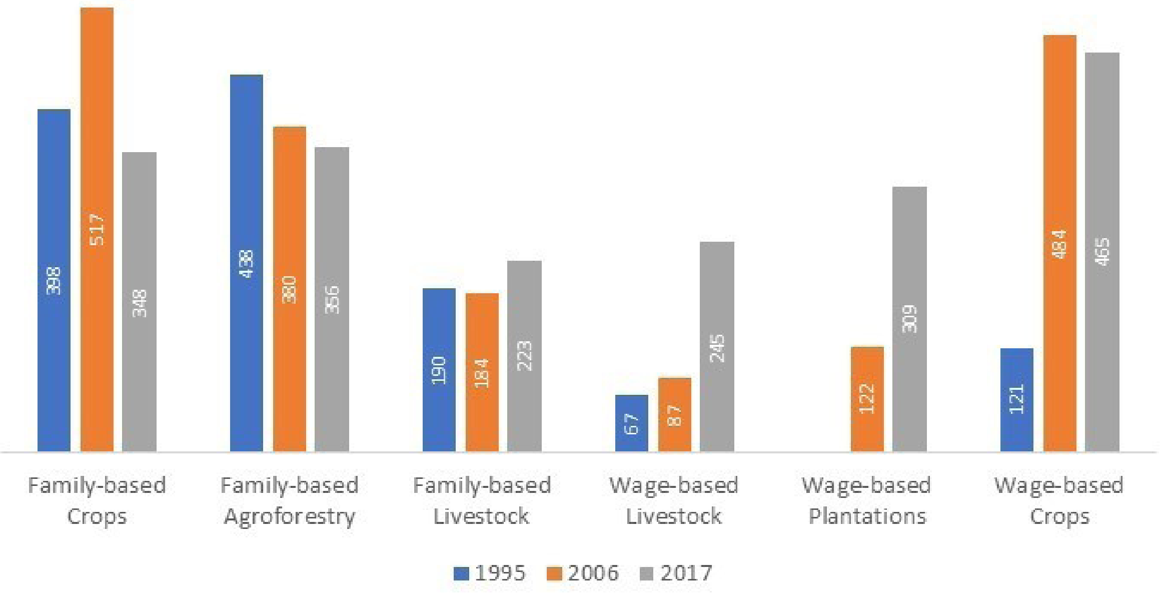

Figure S2. Gross value of production (in USD) per unit of applied area by productive trajectory (PT) in the agrarian economy of the municipalities within the Brazilian Amazon biome in 1995, 2006 and 2017. Source: IBGE, Agricultural Censuses 1995, 2006 and 2017. Values in BRL from each year were adjusted to 2019 value by the IGP-FGV index (Brazil) and converted to USD by the exchange rate of 31 Dec 2019.

Appendix S3. Soy Moratorium

The small number of traders who handle South American soy have made commitments to limit deforestation in the Amazon, which was called the Soy Moratorium. This agreement, which is basically non-binding, was triggered by threats by the European Union (EU) to boycott Brazilian soy, and, like other global commodities such as organic, or fair-trade goods and certifications, involved the use of the supply chains as levers on the sources of commodities. Brazil's Soy Moratorium was the first voluntary zero-deforestation agreement implemented in the tropics, and set the stage for supply-chain governance of other commodities, such as beef and palm oil. In response to pressure from international retailers and mostly conservation NGOs, major soybean traders signed the agreement to not purchase soy grown on Amazon lands deforested after July 2006. The soy industry extended the Soy Moratorium to May 2016, by which time they expected that Brazil's environmental governance and land use monitoring would obviate the need for such an agreement (Gibbs *et al.* 2015; Meijer 2015). Deforestation in the Arc of Deforestation, and in the Brazilian Amazon more generally, declined by close to 80% between 2005-2012, and reflected intensification to some degree, but this decline in deforestation did not slow forest loss, but rather deflected clearing (Hecht 2005; de Waroux *et al.* 2016; Nolte *et al.* 2017; de Waroux *et al.* 2019). This process is called leakage (Miranda *et al.* 2019). In this case, deforestation exploded in the Argentine *Chaco*, Bolivia's *Chiquitania*, the Brazilian central *Cerrado* and the eastern *Cerrado* and *Caatinga* areas that form part of the new soy frontier known as Matopiba, an acronym composed of the first syllables of the states of Maranhão, Tocantins, Piaui, and Bahia. The dynamics of this leakage are complex, reflecting the impacts of more lax regulation in the fugitive areas (these other areas have far less monitoring), cheaper land prices, credit dynamics, promotional land settlement policies, among others, as well as displacement of livestock systems into new forest areas, speculation along roads, and pressure for paving and expanding existing road networks with their associated clearing (Meijer 2015; de Waroux *et al.* 2016; de Waroux *et al.* 2019; Nepstad *et al.* 2019; Meyfroidt *et al.* 2020).

The stickiness and concentration of market power in the hands of a few companies is subject to intense debate. Some believe this opens up the opportunity to leverage private sector interventions for improved sustainability governance in the Amazon (Reis *et al.* 2020), while others maintain this consolidates unsustainable practices, enhances institutional capture, and forecloses more agroecological and socially just alternatives for rural development (Oliveira and Hecht 2016). As a partner to the Soy Moratorium, the idea of an Amazon beef moratorium also emerged. Brazil is now the world largest beef exporter, so the beef moratorium, crafted along the lines of the Soy Moratorium and relying on some super markets and the major slaughterhouses, dominated by meat packers JBS, Marfrig and Minerva, hoped to restrain ranching expansion and enhance intensification of beef production. The division of labor between cow-calf breeding operations and fattening operations, however, meant that animals reared on deforested frontier land (cow-calf) could be "finished" on deforestation free ranches, thus using the production division as a loophole to evade full compliance. JBS has been mired in multiple corruption scandals (Nishijima *et al.* 2019). The low market share of slaughterhouses that have made stringent sustainability commitments (de Waroux *et al.* 2019 is minimal compared with mostly beef cattle slaughter likely going to domestic markets, which is more difficult to track (Hoelle 2017; SEI 2020). Recent research revealed that at least 17% of beef shipments to the European Union from the Amazon region and *Cerrado*, Brazil's savanna, may be linked to illegal forest destruction (Rajão *et al.* 2020). According to an investigation by Global Witness, JBS, Marfrig and Minerva bought cattle from a combined total of 379 ranches between 2017 and 2019 where illegal deforestation had taken place. The firms also failed to monitor 4,000 ranches in their supply chains that were connected to large areas of deforestation in Mato Grosso state. This illegal deforestation contravenes these beef giants' public no-deforestation pledges and agreements with federal prosecutors in Brazil (Global Witness 2020). Other reviews that focused on livestock vaccination records also revealed a great deal of non-compliance (Klingler *et al.* 2018).

The period of the Soy Moratorium did show a decline in deforestation, but the over-emphasis on the moratorium as a kind of silver bullet is problematic. Ascribing the decline in clearing to only the Soy Moratorium ignores the multiplicity of other processes, including demarcation of more than 50 million ha of protected areas, declaration of extractive and indigenous reserves along major deforestation corridors to slow active clearing frontiers, community organizations that tried to block forms of land grabbing and speculation (Campbell 2015), global commodity price slowdowns, changes in exchange rates (Fearnside 2007; Richards *et al.* 2012), acceleration of monitoring and enforcement, leakage, evasion of detection by clearing smaller lots, credit black-outs in high deforestation areas, among a broad array of other institutional and civil society initiatives (Oliveira and Hecht 2016). The explosion in deforestation during the Bolsonaro period also revealed how larger scale institutional attacks coupled with political amnesty for clearing can undermine successful suites of activities that helped control deforestation (Correa 2019, Hecht 2020, Phillips 2020, Rapozo 2021).

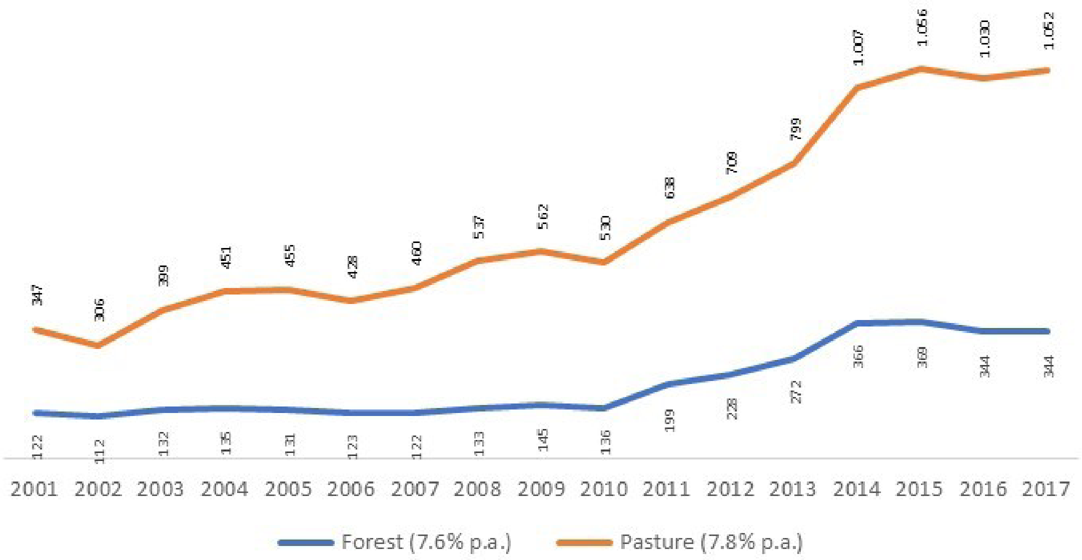

Figure S3. Evolution of land prices in the Brazilian Amazon from 2001 to 2017 (prices in USD). Source: FNP, Agriannual several years (IEG FNP | Agribusiness Intelligence). Values in BRL from each year were adjusted to 2019 value by the IGP-FGV index (Brazil) and converted to USD by the exchange rate of 31 Dec 2019.

Appendix S4. Climate challenges faced by Amazonian farmers

Current challenges faced by farmers, particularly smallholders, of annual and perennial crops call for better dissemination of climate information and forecasting, sharing and diffusion of adaptive solutions, and better integration of existing production, processing, trading and consumption systems that improve economic return for farmers:

1 - While the Amazon has experienced catastrophic flood and drought events, for producers, the main hazards are localized extreme hydro-climatic disturbances that have increased in frequency and intensity (Espinoza *et al.* 2019; List *et al.* 2019). The provision of information on timing, frequency and intensity of severe floods, droughts, strong wind and other disturbances are needed to promote sustainable production of annual and perennial crops.

2 - Information on adaptive responses is as critical as information on climatic disturbances and the impact of changes in urban markets. In all Amazonian countries there are examples of families that are successfully producing annual and perennial crops by innovating and adapting farming and marketing systems. A process for documenting, evaluating and promoting alternative agricultural strategies can help to achieve the Sustainable Development Goals (Brondizio and Moran 2008).

3 - The fields of farmers who are successfully producing annual and perennial crops are reported to have high levels of agrobiodiversity (includes all landraces, varieties and species of annual and perennial crops) that help them to reduce the losses produced by floods and droughts (Astier *et al.* 2011). Programs such as agricultural credits should focus on promoting crop diversity rather than promoting a single species. In general, monocrops for small farmers have been highly vulnerable to climate extremes, and agriculture credit programs for the production of rice, corn, *açaí*, *cacao* and other single crops systems have been demonstrated to be unsustainable and highly risky to climate changes (Flores et al. 2017; List *et al.* 2019).

Programs to foster the production of annual and perennial crops should integrate existing adapted production systems, techniques, practices and other forms of local agrodiversity (including production systems, techniques, practices and strategies used by farmers to produce, process, trade and consume annual and perennial crops) as technological resources for managing vulnerability and risks associated with hydro-climatic disturbances and changes in urban markets (Kawa 2011; Sherman *et al.* 2016; Futemma *et al.* 2020).

4 - Urban expansion has attracted private investors in the food market to supply the demand for rice, beans, corns and other products to the urban Amazon. Private investors have established supermarkets that are bringing grains, vegetables and other food staples that are produced outside the Amazon which can undermine local production. Large supermarkets often rely on more distant suppliers of products like rice and beans, while small shops sell more local products, a pattern which may have changed with the impact of small farmer declines (Roberts 1991). While urbanization has had mixed effects on the demand for locally produced annual crops, it has created markets for perennial crops such as fruits. For instance, an increase of taste and preference for rural food and diets of urban residents have created regional, national and international markets for fruits such as *açaí, cupuaçu, graviola*, and a variety of other perennial crops.(Slinger 2000, Barbieri and Carr 2005; Nardoto *et al.* 2011; Goncalves *et al.* 2014; Dal'Asta and Amaral 2019; Ribeiro *et al.* 2022).

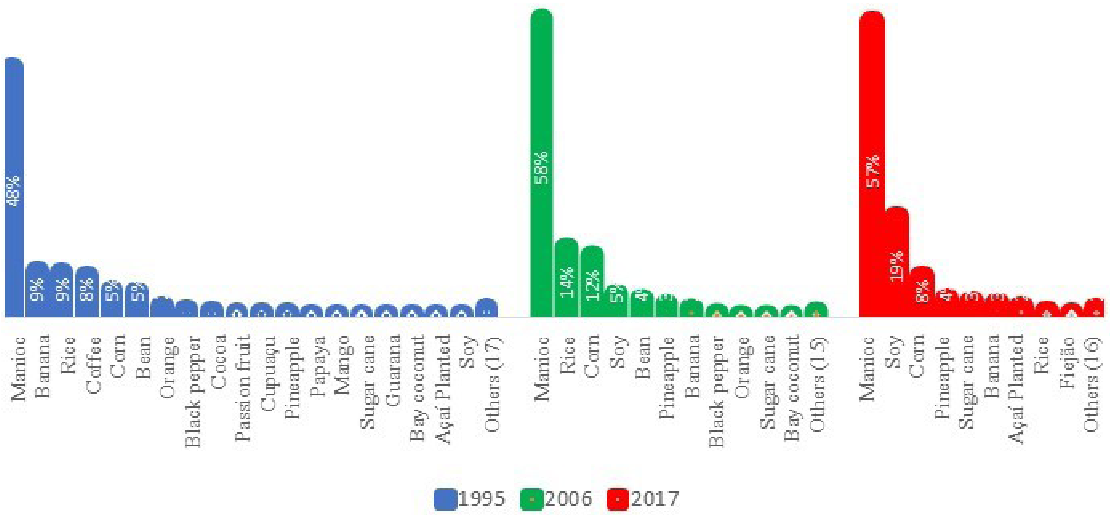

Figure S4. Evolution of family-based agriculture production (% of GVP) in the Brazilian Amazon from 1995 to 2017.

Appendix S5. Challenges to fisheries development

Progress in fisheries management in the Brazilian Amazon reached its peak with the creation of the Ministry of Fisheries and Aquaculture (MPA) in 2009. However, the creation of the MPA also marked the beginning of the disruption of the government fisheries sector. With the creation of the MPA, responsibility for fisheries management was to be shared between the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) and the MPA, despite the fact that the new Ministry lacked the technical and institutional capacity to manage Brazilian fisheries (McGrath *et al.* 2015). Then, in 2015, MPA was abolished and its functions transferred to another agency. Over the next few years, the federal government fisheries sector became a pawn in the alliance-forming strategies of two presidents, finally ending up in a Secretary in the Ministry of Agriculture and Ranching. Subsequently, responsibility for managing fisheries was transferred to state governments, with varying interest and capacity for managing their fisheries.

Contrasts in state-level commitment to fisheries management and development are illustrated by the states of Amazonas and Pará, which have the lion's share of the fisheries resources of the Amazon. Amazonas embraced its fisheries early, implementing co-management policies largely through the network of state and federal reserves. In contrast, the state of Pará has rarely invested in the fisheries sector (McGrath *et al.* 2015). Amazonas also developed policies for *pirarucu* management based on the management system developed by the Mamirauá Institute (Castello *et al.* 2009). As a result, while sustainably managed *pirarucu* production is growing in Amazonas, *pirarucu* populations in Pará are declining due to unregulated fishing (Castello *et al.* 2014).

In addition to the lack of government effort in managing fisheries, two other issues exacerbate the problem: 1) the absence of monitoring programs to collect data on commercial fish landings that can be used to analyze trends in fish stocks and fishing activity (Cooke *et al.* 2016), and 2) the absence of state inspection facilities to ensure that fish entering Amazon urban markets meet legal, sanitary and fiscal requirements (McGrath *et al.* 2015). The major exception to the latter issue is the industrial fisheries sector, which is required to register and inspect fish entering cold storage warehouses or *frigoríficos*, and to pay any taxes and fees owed to the government. Consequently, the Amazon's small-scale fisheries are an invisible sector, with no information on the legality or quality of Amazon fish supplied to consumers, nor data to assess the economic importance of the fisheries sector to the regional economy and inform government policies and private sector investment decisions (Bartley *et al.* 2015; Cavole *et al.* 2015).

In addition to the direct impacts of uncontrolled fishing pressure, Amazon fisheries are vulnerable to the range of impacts that have led to the decline of inland fisheries throughout the world (Cooke *et al.* 2016). These include large-scale land-use change that can affect water quality and discharge, and pollution from urban centers and mining, especially placer mining (*garimpos*) and oil extraction (Castello *et al.* 2013; Lobo *et al.* 2016, Caballero Espejo *et al.* 2018; Cortes-McPherson 2019, Diringer *et al.* 2019; Guiza *et al.* 2020; Kalamandeen *et al.* 2020)). Dams on major tributaries can disrupt the migration routes of major commercial fish species, accelerating their decline. In addition, six major Andean dams scheduled for construction could capture 70% of the sediment transported by Amazon rivers, with major long-term impacts on the productivity of Amazon rivers, their floodplains and fisheries (Forsberg *et al.* 2017).

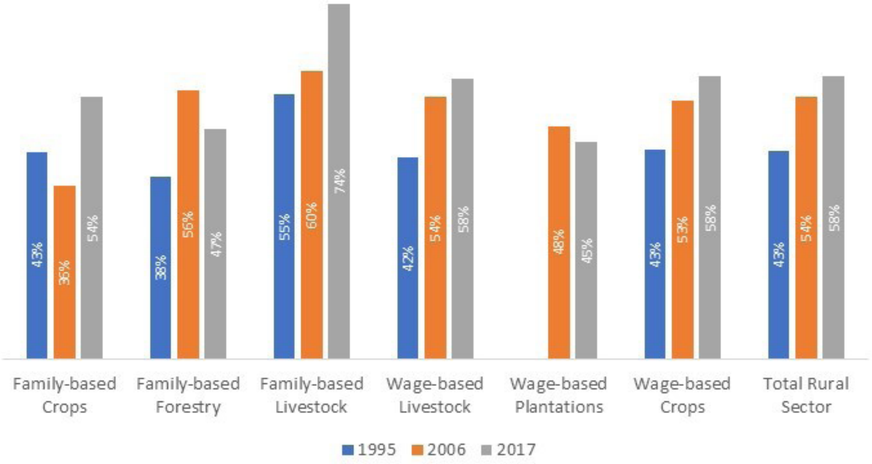

Figure S5. Ratio of used land to total owned land by productive trajectory in 1995, 2006 and 2017 (in %). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017.

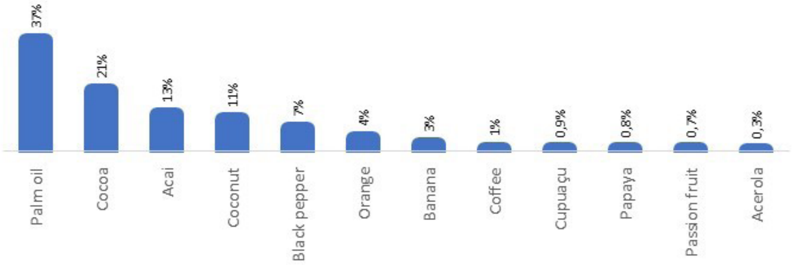

Figure S6. Order of importance of different permanent crops in wage-based productive trajectories in 2017. Source: IBGE, Agricultural Census 2017.

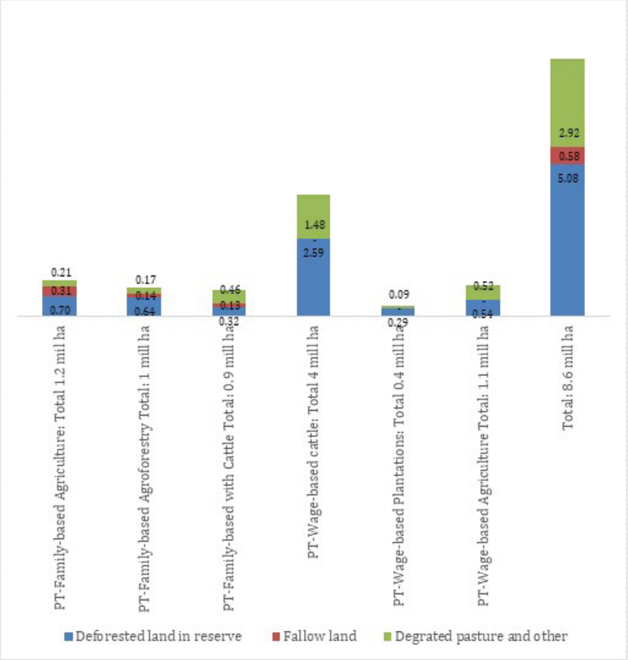

Figure S7. Lands with secondary vegetation in productive trajectories (PTs): fallow land, deforested land in reserve and degraded land by PT in 2017 (in mill ha). Source: IBGE, Agricultural Censuses 1995, 2006 and 2017; Costa 2016.

Table S1. Key variables of the agrarian sector by Productive Trajectories (PT), 1995, 2006 and 2017.

Variable	Family-based agriculture	Family-based agroforestry	Family-based livestock	Wage-based livestock	Wage-based plantations	Wage-based agriculture	Total
1995							
. Dairy cattle (R$ 1,000)	561,710	109,780	1,003,871	-		-	1,675,362
. Beef cattle (R$ 1,000)	459,316	81,498	509,311	3,032,217		979,522	5,061,865
. Small animals (R$ 1,000)	595,352	57,312	152,729	96,711		98,517	1,000,622
. Permanent cultures and forestry (R$ 1,000)	1,247,072	155,612	182,645	475,471		166,014	2,226,813
. Annual crops and vegetables (R$ 1,000)	3,189,688	583,663	708,084	1,336,611		3,057,473	8,875,518
. Timber extraction (R$ 1,000)	202,581	352,475	55,976	171,527		373,832	1,156,390
. Non-timber extraction (R$ 1,000)	148,180	443,832	38,994	28,065		20,653	679,723
Gross Value of Production (GVP) (R$ 1,000)	6,403,898	1,784,171	2,651,610	5,140,602		4,696,012	20,676,293
Production Costs (R$ 1,000)	1,665,024	381,528	560,625	2,990,419		3,073,907	8,671,504
Net Income (R$ 1,000)	4,738,874	1,402,643	2,090,985	2,150,182		1,622,105	12,004,790
Family workforce (Man/Year)	1,038,688	376,380	386,541	73,408		32,740	1,907,756
Net income by family worker (R$ 1,000)	4,562	3,727	5,409				
2006							
. Dairy cattle (R$ 1,000)	41,447	71,704	869,435	329,427	42,921	24,296	1,379,231
. Beef cattle (R$ 1,000)	175,638	263,941	1,708,231	6,223,744	564,486	709,894	9,645,933
. Small animals (R$ 1,000)	79,005	104,129	406,514	160,862	413,274	398,871	1,562,654
. Permanent cultures and forestry (R$ 1,000)	138,889	952,900	769,424	226,421	482,890	38,783	2,609,307
. Annual crops and vegetables (R$ 1,000)	2,826,327	1,662,753	1,530,223	1,468,098	213,891	11,137,391	18,838,683
. Timber extraction (R$ 1,000)	86,539	214,476	14,103	20,574	16,543	436	352,672
. Non-timber extraction (R$ 1,000)	47,873	646,262	44,107	18,613	54,949	2,134	813,938
. Other (R$ 1,000)	136,674	125,678	238,511	193,054	59,373	17,107	770,397
Gross Value of Production (GVP) (R$ 1,000)	3,532,390	4,041,843	5,580,549	8,640,793	1,848,328	12,328,911	35,972,815
Production Costs (R$ 1,000)	492,406	604,558	2,228,207	7,171,241	1,160,447	12,737,960	24,394,819
Net Income (R$ 1,000)	3,039,984	3,437,285	3,352,342	1,469,552	687,881	-409,049	11,577,996
Family workforce (Man/Year)	247,839	415,395	596,593	99,043	42,375	18,638	1,419,882
Net income by family worker (R$ 1,000)	12,266	8,275	5,619				
Credit (R$ 1,000)	132,121	154,180	638,872	864,314	226,368	2,940,086	4,955,941
2017							
. Dairy cattle (R$ 1,000)	255,073	322,799	1,482,096	432,675	25,208	71,841	2,589,692
. Beef cattle (R$ 1,000)	836,086	852,264	3,994,923	12,568,519	574,120	4,714,785	23,540,698
. Small animals (R$ 1,000)	151,455	267,418	403,673	939,152	366,003	1,944,365	4,072,065
. Permanent cultures and forestry (R$ 1,000)	206,055	861,195	641,039	198,455	666,954	199,739	2,773,437
. Annual crops and vegetables (R$ 1,000)	2,395,535	1,115,688	752,617	14,767,285	163,158	24,846,193	44,040,476
. Timber extraction (R$ 1,000)	55,547	4,164	810	70,631	1,696	11,813	144,661
. Non-timber extraction (R$ 1,000)	176,968	725,786	51,642	72,640	112,612	15,271	1,154,921
. Other (R$ 1,000)	444,659	255,783	157,468	1,056,395	176,530	863,347	2,954,183
Gross Value of Production (GVP) (R$ 1,000)	4,521,378	4,405,097	7,484,269	30,105,752	2,086,281	32,667,355	81,270,132
Production Costs (R$ 1,000)	1,517,396	1,308,509	2,905,299	15,235,613	1,935,703	18,264,487	41,167,006
Net Income (R$ 1,000)	3,003,983	3,096,589	4,578,969	14,870,139	150,579	14,402,868	40,103,127
Family workforce (Man/Year)	368,044	372,982	377,669	160,605	37,917	45,891	1,363,108
Net income by family worker (R$ 1,000)	8,162	8,302	12,124				
Cattle Herd (Head)	2,556,723	2,885,369	12,257,778	25,381,569	1,261,688	7,624,153	51,967,280
Establishments with technical assistance (U)	13,826	15,381	19,953	15,121	2,552	7,120	73,953
Credit (R$ 1,000)	381,293	387,181	1,861,172	8,592,448	286,084	9,300,500	20,808,678

Source: IBGE, Censo Agropecuário 1995, 2006 and 20017. Current values in BRL were restated for 2019 by the IGP-FGV index.

Table S2. Shifts in resources among productive trajectories (PT), 1995 to 2006.

Productive trajectories in 19951	Productive trajectories in 2006						
	Family-based agriculture	Family-based agroforestry	Family-based livestock	Wage-based livestock	Wage-based plantations	Wage-based crops	Total
Number of establishments							
Family-based agriculture	76.709	71.418	112.778				260.905
Family-based agroferestry	30.700	93.529	50.307				174.536
Family-based livestock	2.752	14.858	88.359				105.969
Wage-based livestock				33.128	10.963	2.402	46.493
Wage-based plantations							-
Wage-based crops				16.928	9.466	5.706	32.100
Total in 2006	110.161	179.805	251.444	50.056	20.429	8.108	620.003
Total in 1995	337.328	125.160	128.806	31.916		13.518	636.728
A1. output/input 1995-2006	-76.423	49.376	-22.837	14.577	-	18.582	-16.725
Owned land							
Family-based agriculture	1.899.647	1.965.371	4.885.993				8.751.011
Family-based agroferestry	1.221.676	2.038.089	2.522.317				5.782.082
Family-based livestock	202.937	720.193	5.008.967				5.932.097
Wage-based livestock				29.559.020	4.760.842	2.425.397	36.745.259
Wage-based plantations							-
Wage-based crops				15.994.728	3.041.896	9.392.199	28.428.823
Total in 2006	3.324.260	4.723.653	12.417.277	45.553.748	7.802.738	11.817.596	85.639.272
Total in 1995	9.328.999	2.681.381	6.305.316	45.512.245		22.234.571	86.062.512
B1. output/input1995-2006	-577.988	3.100.701	-373.219	-8.766.986	-	6.194.252	-423.241
Used land							
Family-based agriculture	989.942	1.053.982	3.010.549	-	-	-	5.054.472
Family-based agroferestry	715.128	1.264.991	1.640.660	-	-	-	3.620.779
Family-based livestock	101.463	475.814	3.419.155	-	-	-	3.996.432
Wage-based livestock	-	-	-	17.522.566	2.318.352	1.439.745	21.280.663
Wage-based plantations	-	-	-	-	-	-	-
Wage-based crops	-	-	-	8.792.158	1.641.412	5.191.736	15.625.305
Total in 2006	1.806.534	2.794.786	8.070.363	26.314.723	3.959.764	6.631.481	49.577.652
Total in 1995	3.994.032	1.010.636	3.454.891	18.932.626		9.612.089	37.004.274
C1. output/input 1995-2006	246.517	2.312.298	232.646	1.152.548	-	5.078.685	9.022.694
Workers							
Family-based agriculture	185.934	176.401	275.509				637.843
Family-based agroferestry	69.019	224.057	127.933				421.008
Family-based livestock	7.921	33.120	216.084				257.124
Wage-based livestock				167.493	39.247	17.777	224.517
Wage-based plantations							-
Wage-based crops				83.588	31.750	32.183	147.521
Total in 2006	262.873	433.577	619.525	251.081	70.997	49.959	1.688.013
Total in 1995	1.179.601	402.468	433.550	195.743		86.816	2.298.177
D1. output/input1995-2006	-541.758	18.541	-176.425	28.774	-	60.705	-610.165

Source: IBGE, Agricultural census 1995, 2006 and 2017.

Table S3. Shifts in resources among productive trajectories (PTs) 2006 to 2017.

Productive trajectories in 2006	**Productive trajectories in 2017**						
	Family-based agriculture	Family-based agroferestry	Family-based livestock	Wage-based livestock	Wage-based plantations	Wage-based crops	Total
Number of establishments							
Family-based agriculture	58,737	19,686	20,478				98,901
Family-based agroferestry	63,652	120,452	17,830				201,934
Family-based livestock	56,369	46,203	160,496				263,068
Wage-based livestock				56,312	4,205	11,369	71,886
Wage-based plantations				12,362	12,151	4,721	29,234
Wage-based crops				6,361		4,924	11,285
Total in 2017[3]	178,758	186,341	198,804	75,035	16,356	21,014	676,308
Total in 2006[4]	110,161	182,671	257,122	50,354	20,429	8,108	628,845
A2.Output/Input 2006-2017[2]	-11,260	19,263	5,946	21,532	8,805	3,177	47,463
Owned Land							
Family-based agriculture	1,345,416	855,908	775,777				2,977,101
Family-based agroferestry	1,737,640	3,178,188	789,207				5,705,035
Family-based livestock	2,360,995	2,339,976	10,082,631				14,783,602
Wage-based livestock				38,320,000	1,380,387	12,488,372	52,188,759
Wage-based plantations				5,262,008	2,401,016	1,242,953	8,905,977
Wage-based crops				5,600,370		8,687,250	14,287,620
Total in 2017[3]	5,444,051	6,374,072	11,647,615	49,182,378	3,781,403	22,418,575	98,848,094
Total in 2006[44]	3,324,260	4,745,295	12,634,788	45,650,989	7,802,738	11,817,596	85,975,666
B2.Output/Input 2006-2017[2]	-347,159	959,740	2,148,814	6,537,770	1,103,239	2,470,024	12,872,428
Used Land							
Family-based Agriculture	694,879	325,945	468,944				1,489,768
Family-based Agroferestry	902,669	1,306,313	568,665				2,777,647
Family-based Livestock	1,358,786	1,392,813	7,527,743				10,279,342
Wage-based Livestock				22,623,879	683,138	7,234,174	30,541,190
Wage-based Plantations				2,730,326	1,013,622	658,062	4,402,010
Wage-based Crops				3,107,664	-	5,196,324	8,303,988
Total in 2017[3]	2,956,334	3,025,071	8,565,352	28,461,868	1,696,760	13,088,560	57,793,945
Total in 2006[4]	1,806,534	2,794,786	8,070,363	26,314,723	3,959,764	6,631,481	49,577,652
C2.Output/Input 2006-2017[2]	-316,766	-17,139	2,208,979	4,226,467	442,246	1,672,507	8,216,294
Workers							
Family-based Agriculture	126,356	42,733	50,176				219,265
Family-based Agroferestry	140,057	263,997	38,660				442,714
Family-based Livestock	126,155	97,247	320,513				543,915
Wage-based Livestock				238,452	22,320	53,194	313,966
Wage-based Plantations				47,546	43,848	16,377	107,771
Wage-based Crops				24,473		32,767	57,240
Total in 2017[3]	392,568	403,978	409,348	310,470	66,168	102,338	1,684,870
Total in 2006[4]	262,873	439,493	634,235	252,016	70,997	49,959	1,709,574
D2.Output/Input 2006-2017[2]	-43,608	3,221	-90,320	61,949	36,774	7,280	-24,704
Total Output/Input 1995-2017							
Establischment (A1+A2)	-87,683	68,639	-16,891	36,109	8,805	21,759	30,738
Owned land (B1+B2)	-925,147	4,060,441	1,775,595	-2,229,216	1,103,239	8,664,276	12,449,188
Used Land (C1+C2)	-70,249	2,295,159	2,441,625	5,379,014	442,246	6,751,192	17,238,987
Workers (D1+D2)	-585,366	21,761	-266,746	90,723	36,774	67,985	-634,868

Source: IBGE, Censo Agropecuário 1995, 2006 and 2017.

[1] For each year t there are two sets of data, one with elements that describe the rural peasant economy (Bct), and the other with elements that describe the wage-based rural economic (Bpt). In each of the data sets, each row describes a place and each place is associated in that year with only one PT, e.g. PT1t of the Bpt. If we add to each row the information about the PT that was in force in that place in year t-1, e.g. such as PT2t-1, then all the information in that row refers to the PT1t in year t and

the PT2t-1 in year t-1. If it refers to a resource, such as land (L), the value reported (Lt) refers to the current domain of the PT1t and the past domain of the PT2t-1 over this resource: Lt came from PT2t-1 and is found with PT1t. Aggregating Lt in a matrix (like those that make up Table Annex 15.2a) whose rows are PTt-1's and columns are PTt's, leads to a special reading of the distribution of Lt by current PTt's in t, still considering the Pt-1's that originally (in year t-1) controlled resource L. In each cell, a value such as Lt(1,1), for example, means that Lt came from the PT1 in year t-1 and currently is under the domain of the same PT1 in year t; if Lt(2,3), it means that it came from the PT2 in year t-1 and is found under the domain of the PT3 in year t, and so on.

[2] Each line of this matrix offers information on the exits of the resource from the PT in question. Considering that the exit flows, or use, in year t are made in relation to the stock of resources in year t-1, there is a final "balance" that is:

Lt-1(PT1) – Lt(1,1) – Lt(1,2) – ... – Lt(1,n) = Lt(1,x) (1)

This "balance," if negative, means that between the two moments the PT1 used more than the resource received from year t-1 and, therefore, had to acquire L outside of the systems described by Bpt (therefore, acquired from peasant PTs, or from the land market, or through direct appropriation of public lands) in the amount of Lt(1,n). If is positive, on the other hand, an amount Lt(1,n) was transferred by the PT1 outside the system (to peasant PTs, or to the urban system). These terms permit the reproduction of the practice of the process in the following relationship:

Lt-1(PT1) – Lt(1,2) – ... – Lt(1,n) – Lt(1,x) = Lt(1,1) (2)

Literally: from the stock of lands of the PT1 proceeding from t-1 parcels of L were transferred to the other PTs of Bpt and to other systems if Lt(1,x) is positive; if negative, Lt(1,x) was added to form the initial stock of L in t, equivalent to Lt(1,1). In Table Annex 13.1a and in the graphs based on it Lt(1,x) has the sign it acquired in the relationship (2).

[3] To the initial stock in t, parcels are added from the L resource transferred by the other PTs of the system to the PT1 to form the final stock in year t. Thus:

Lt(1,1) + Lt(2,1) + ... + Lt(n,1) = Lt(PT1) (3).

[4] From Table S3.