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Spatially explicit valuation of the Brazilian Amazon Forest's Ecosystem Services

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The Brazilian Amazon forest is tremendously important for its ecosystem services but attribution of economically measurable values remains scarce. Mapping these values is essential for designing conservation strategies that suitably combine regional forest protection with sustainable forest use. We estimate spatially explicit economic values for a range of ecosystem services provided by the Brazilian Amazon forest, including food production (Brazil nut), raw material provision (rubber and timber), greenhouse gas mitigation (CO_2 emissions) and climate regulation (rent losses to soybean, beef and hydroelectricity production due to reduced rainfall). Our work also includes the mapping of biodiversity resources and of rent losses to timber production by fire-induced degradation. Highest values range from US\$56.72 ± 10 ha^{-1} yr^{-1} to US\$737 ± 134 ha^{-1} yr^{-1} but are restricted to only 12% of the remaining forest. Our results, presented on a web platform, identify regions where high ecosystem services values cluster together as potential information to support decision-making.

Given the declining capacity of tropical forests to provide local, regional and global ecosystem services[1–4], decision-makers' ability to evaluate trade-offs and to prioritize budgetary resources to protect the remaining forest has become ever more necessary. Since the late 1990s, scholars have emphasized the importance of ecosystem services provided by tropical forests[5], such as biodiversity[3] and regulation of regional[6] and global climates[7]. Some studies have identified these and other distinct ecosystem services that contribute to human wellbeing without explicitly quantifying these services or valuing their importance[8,9], while others advocate the attribution of monetary values to encourage their conservation[8–10]. Without monetary values for unpriced services, stakeholders tend to over-emphasize benefits from deforestation or degradation, which are usually quantifiable, promoting exploitative land uses (for example provision of raw materials or foodstuffs) and ignoring values of other long-term ecosystem services (for example climate regulation or genetic resources). Such perspectives have the undesirable effect of inhibiting precautionary forest conservation[11]. Valuing ecosystem services may inform the implementation of mechanisms, including payment for ecosystem services but its importance is further reaching. Monetary valuation of forest ecosystem services can assist policy-makers in managing different elements of human wellbeing, thus providing the basis for both economic and environmental sustainability[9,12]. In a spatially explicit context, it can complement biodiversity assessments[3] to more precisely identify forest areas that are key to protect.

The importance of monetary valuations has inspired several scientific endeavours to generate total value estimates for ecosystem services of the Amazon forest[8,9]. More recent work has emphasized the importance of calculating marginal ecosystem service values: the cost (benefit) of destroying (preserving) an additional unit area of forest[13,14]. Prevailing assessments, however, vary widely and value levels have increased dramatically in recent years. On the basis of the valuation of 11 ecosystem services categories, the Brazilian Amazon forest was assessed to have a total marginal value of US\$1,175 ha^{-1} in 1993[15] and between US\$431 and US\$3,135 ha^{-1} in 1995[13]. The main problem with these studies is that their estimates draw on aggregate values from meta-analysis of various studies. Moreover, several of these value components were derived by transferring data referring to tropical forests in countries other than Brazil, thus not reflecting the real regional Amazon. A more recent study[10], synthesizing 665 value estimates for 2007, reaches a total average value of US\$5,264 ha^{-1} yr^{-1} for 22 ecosystem services categories in all tropical forests, with Costanza et al.[2] reaching similar (US\$5,382 ha^{-1} yr^{-1}) conclusions. These studies usually present average values for tropical forests as a whole without accounting for differences in land use and ecological systems between regions. All studies mentioned here use value homogenization to account for methodological differences across referenced valuation studies. No study has yet attempted to aggregate monetary benefits from multiple ecosystem services categories in a comprehensive and spatially explicit way that either accounts for methodological differences or builds on a singular methodological approach.

Estimating ecosystem services values is challenging. The connections between ecosystem functions and human wellbeing are complex and many benefits of ecosystems are difficult to recognize, measure and value, due to imperfect information of their functioning, measurement inaccuracy or imperfect understanding of human–nature relations[9]. Some ecosystem services, such as those emanating from biodiversity, are particularly challenging to value economically and tend to rely on revealed or stated preference techniques[16]. Others, such as cultural and aesthetic benefits involve a

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variety of value judgements[17]. Therefore, most ecosystem services in studies aforementioned (for example watershed protection and biodiversity) still have no economic value estimates attached to them, leading to gross under-representation of total forest values. Furthermore, while some studies provide marginal values, most derive average value estimates assumed to be constant across entire biomes or ecosystem categories. One exception[12] demonstrates how information on the geographical distribution of ecosystem services values in the United Kingdom could support planning for cost-effective land use. Similar work has not yet been undertaken for tropical forests.

Research approach and value components

Rather than aggregating average values from various sources, we here estimate differentiated marginal economic values for a limited range of ecosystem services and their geographic distribution in the Brazilian Amazon at an unprecedented level of spatial detail. While overall spatial forest values are underassessed, our approach focuses on estimating the impacts of forest losses (Supplementary Section 1) on the values added by four ecosystem services: food production, raw materials provision, greenhouse gas mitigation (that is CO_2 emissions) and climate regulation (reduced rainfall)[8]. Our results highlight the added value of forest protection and deforestation reduction. Our value components for the first two ecosystem services include rents (net revenues) from reduced impact logging (RIL) as well as from the collection of Brazil nuts and rubber. For the climate regulation function, we calculate the value added by rainfall reliant on Amazon forests to rents of soybean cropping, beef production and hydroelectricity generation. For greenhouse gas mitigation, we estimate the value of potential payments for emissions reductions in regions under immediate threat of deforestation. Our analysis also presents unprecedented results on economic losses from forest degradation, represented by rent losses to RIL production by forest fires. In addition, our analysis identifies highly biodiverse areas as a fifth ecosystem services with an explicit spatial representation due to the importance of the Amazon forest as one of most biodiverse regions of world[18], although these are only mapped biophysically and were not inserted as a value component. We attempt to apply a singular methodological rationale (that is rent losses from additional deforestation and forest degradation) to justify aggregation of ecosystem services values. The rigour and precision of the available economic valuation methodologies[19] as well as the wide relevance of the ecosystem services have been decisive for selecting these value components, as specified in the remainder of this section. Details on the methodologies used for each value component, including data sources, data accuracy and methodological challenges, are briefly discussed in the Methods and thoroughly elaborated in the Supplementary Information.

Our RIL analysis (Supplementary Sections 1 and 2) includes forms of harvest planning and logistics that maximize productive efficiency while minimizing the impacts on timber production. RIL reflects the norms and practices proposed by the Brazilian government for timber concessions. In this case, Brazilian resolution 406/2009 determines that (1) timber production may not exceed $0.86\,m^2\,ha^{-1}\,yr^{-1}$ and involves adoption of forest management units, (2) annual harvest areas are defined, and (3) protections exist against reducing the harvest cycle[20]. The same resolution prohibits timber harvest in protected areas or indigenous lands. The biomass and tree species distribution data for the Amazon constitute inputs to our SimMadeira+ model that runs in 'RIL mode' to provide spatially explicit rent estimates over a single 30-year logging cycle for the Brazilian Amazon[21]. These rents reflect the marginal ecosystem services value (US$ $ha^{-1}\,yr^{-1}$) that would be lost with each hectare of additional forest loss in those areas.

In addition to deforestation, RIL values may also be lost or seriously undermined by forest degradation from forest fires, especially in a context of higher drought frequency[22] and reduced canopy cover[23,24]. By some estimates, forest fires in the Brazilian Amazon between 1996 and 1999 led to economic losses of US$$0.09$–$5\times10^9\,yr^{-1}$(ref. [25]). Although forest fires impact on physical assets, biodiversity and habitat, CO_2 emissions and human health, we restrict valuation to the losses to RIL as a complement to this valuation item whose value is affected by fire-induced degradation in addition to deforestation. As such, our work includes an analysis of future forest fire occurrences simulated using the Fire Ignition, Spread and Carbon (FISC) model and their impact on RIL values, calculated by the Economic Costs of Fire (EcoFire) model[21] (Supplementary Section 3).

The extraction of non-timber forest products (NTFPs) contributes to the livelihoods of over 6,000,000 households living in the Brazilian Amazon. Despite its socioeconomic importance, there are no comprehensive studies that differentiate NTFP values across the entire Brazilian Amazon. Challenges relate to major limitations in comparing estimates from specific community-based case studies that use contrasting methodological approaches and only provide a fragmented view of the socioeconomic situation in the Amazon as a whole. Our analysis uses a unique spatially explicit approach for mapping rent distribution across the biome for two important NTFPs: rubber and Brazil nut (Supplementary Section 4). Their selection was motivated by their stable presence on markets, their widespread collection across the Amazon, production and price statistics for all the Amazon municipalities and the availability of a large forest inventory and production cost data for the states of Acre and Pará where production chains are more widely consolidated[26–28]. These two states are largely representative of the range of NTFP collection conditions found in the Amazon as a whole.

Our climate regulation analysis (Supplementary Section 5) addresses three economic activities in the Brazilian Amazon that are usually associated with deforestation: soybean cropping, beef production and hydroelectricity generation[29]. Conversely, these activities are heavily dependent on the climate regulative functions provided by forests, mainly rainfall, which depends on forest cover[6,30]. Stable upwind forests act as a steady source of evapotranspiration that irrigate downwind economic activities, whereas decreases in forest cover are usually non-linearly translated into decreased rainfall downwind. Motivated by increasing production levels, deforestation driven by agricultural expansion could therefore feedback adversely, affecting its own productivity due to harmful effects on vital ecosystem functions[6]. Our analysis estimates the share of rents from three economic activities that stem directly from the climate regulation functions that would be lost with each hectare of additional forest loss. Although the changes in climate are calculated by a climate model, deforestation effects essentially depend on wind trajectories that carry water vapour to the regions and watersheds that contain soybean crops, beef production and hydroelectricity generation[31]. Calculations of the changes in rents consider average commodity and energy prices for the 12-month period from June 2015 to May 2016. Economic losses are then traced back to the individual Amazon forest areas (cells of about $100,000\,km^2$) where forest is lost using reverse calculations.

Recognizing the effects of multiple greenhouse gas emissions on climate change, our analysis of greenhouse gas mitigation is restricted to CO_2 emissions due to their central role in international and national climate politics[32]. Brazilian climate policies are committed to reduce greenhouse gas emissions by 37% below 2005 levels by 2025, which represents an 80% reduction in CO_2 emissions from Amazon deforestation. Moreover, historical emissions reductions have been valued and rewarded at US$5 per tonne of CO_2, mainly through the Norwegian–Brazilian Amazon Fund agreement[33] but rising deforestation rates may lead Brazil to miss such opportunities[32]. To value reduced CO_2 emissions, our model simulates realis-

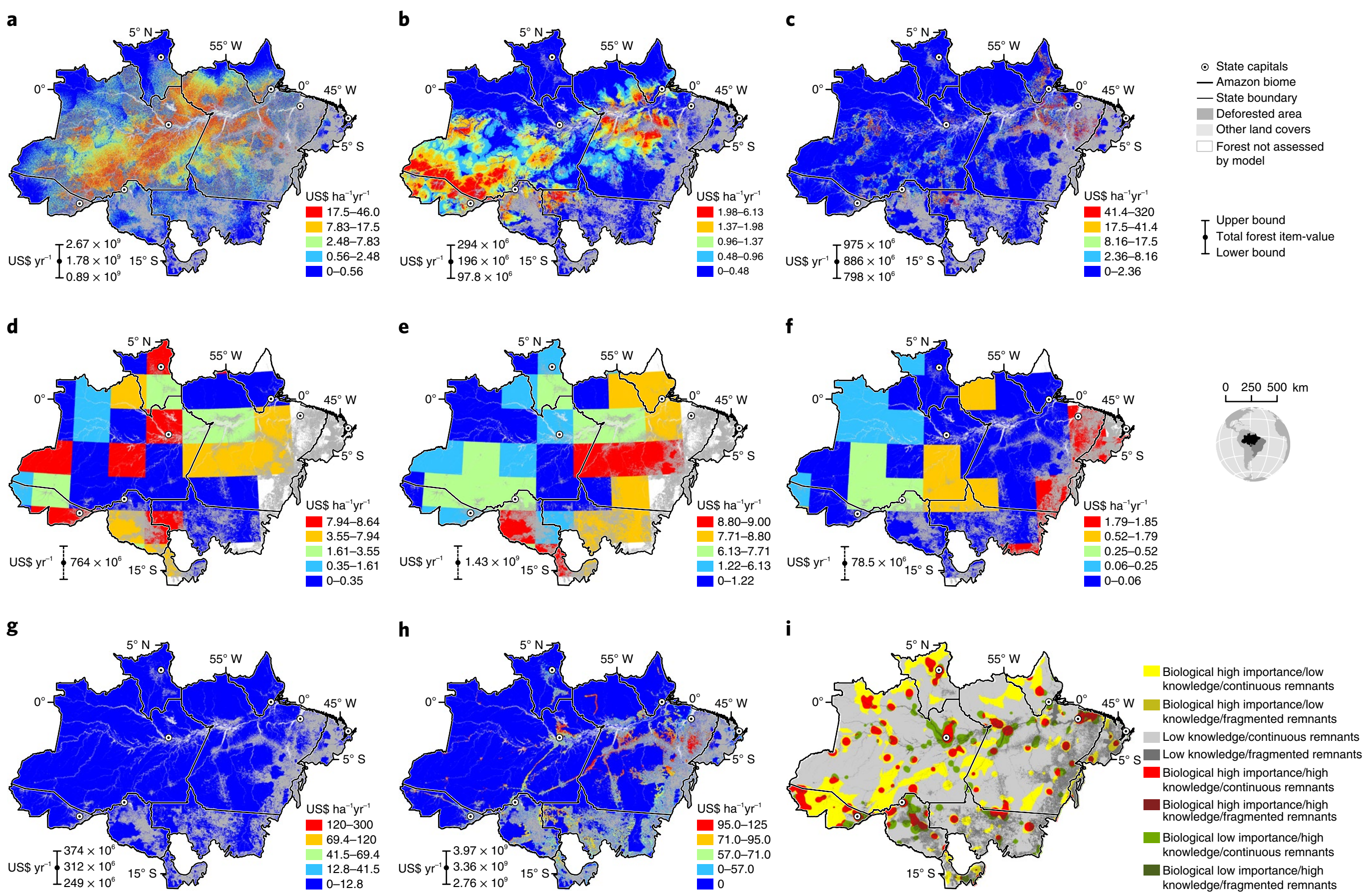

Fig. 1 | Forest values for individual value components a–i, Value maps for brazil nut (**a**), rubber (**b**), timber (**c**), soy* (**d**), livestock* (**e**), energy* (**f**), fire losses to timber (**g**), CO_2 emission reductions (**h**) and biodiversity relevant areas (**i**). Values are presented in EAA (30-year period with a discount rate of 5%). The value of CO_2 abatement is set at US$5 per tonne. Soy*, Livestock* and Energy* refer to their marginal value not lost by keeping vegetation standing. Bar diagrams depict overall value for valuation component and associated uncertainty bounds when available.

tic spatial patterns of future deforestation under a business-as-usual scenario[1,34] as a means to highlight the most threatened regions and their potential CO_2 emissions. The results therefore reflect the values of CO_2 emissions that could be avoided if Brazilian climate policies succeed[32,35] and for which monetary compensation may occur if the simulated reductions are verified under the forest component of the Paris climate agreement.

Although our analysis does not include a valuation of biological resources and functions due to methodological limitation, we recognize that the Amazon forest has more distinct and unique species than any other similarly sized geographical region on Earth[36]. Many species can be expected to go extinct when additional forest is lost before their usefulness, or even existence, to humans or to ecosystem equilibrium has been discovered[37]. The biological resources of the Amazon have non-use (existence and preservation) values to humanity, inside and outside the region, for generations to come. These resources also provide other services including pollination[38] and bioprospecting (harvesting genetic resources for pharmaceutical and other productive uses). To acknowledge the importance of biological resources and functions, our biodiversity analysis (Supplementary Section 6) identifies highly biodiverse areas where these resources and functions abound and are more valuable from an economic point of view. We focus on composite biodiversity metrics that equally emphasize a set of biodiversity parameters: weight endemism, areas of endemism, phylogenetic endemism, beta-diversity, phylogenetic beta-diversity and species richness[39]. The geographical differentiation of these quantitative variables is presented in maps that account for both heterogeneity and irreplaceability measures (Supplementary Figs. 6.4 to 6.10) and our approach also includes analysis of uncertainty due to lack of knowledge about biological data, pointing out where further inventories should be conducted (Fig. 1). The outcome of this analysis involves the spatial identification of highly biodiverse areas that is superimposed on our value map (Fig. 2).

Results

Our value maps (Figs. 1 and 2) show a scattered distribution of high-value ecosystem services that is concentrated in the centre of the Legal Amazon and extends from the western Brazilian border to the eastern Amazon. Hotspots of ecosystem services were mostly found in southern and eastern Amazon and western and central Pará, where high monetary values tend to overlap with highly biodiverse areas (Fig. 2). High values were also found in northern Mato Grosso, albeit more clearly interspersed with areas of lower value and without much overlap with highly biodiverse areas. By contrast, low-value areas are found in remote regions such as the state of Roraima, western Acre and northwestern Amazon but these regions partially overlap with highly biodiverse areas. The highest value regions, ranging from US$56.72 ± 10 $ha^{-1} yr^{-1}$ to US$737 ± 134 $ha^{-1} yr^{-1}$, amount to merely 12% of the remaining forest. Monetary values greater than US$17 ± 2 $ha^{-1} yr^{-1}$ occur only over a span of 35% of the forest. Conversely, roughly 65% of the

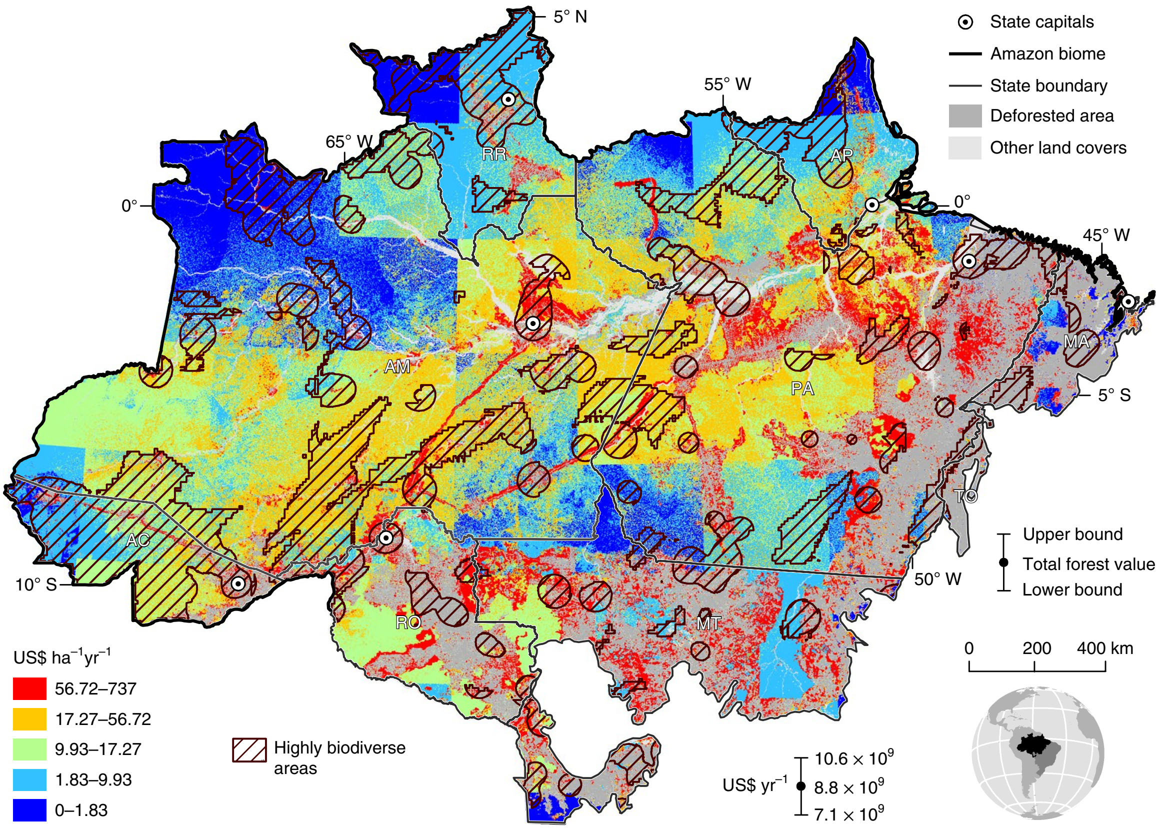

Fig. 2 | Forest values overlaid with highly biodiverse areas. Values are presented in EAA (30-year period with a discount rate of 5%). Overall value map is a linear sum of value items cell by cell. Bar diagram depicts overall forest value and associated uncertainty bounds.

Amazon forest present total values for measured components below US$$17\pm2$ ha^{-1} yr^{-1} (Fig. 3).

Reduced impact logging. Although the Brazilian Amazon forest contains about 5.3×10^9 m^3 of commercial roundwood at an average of 15 m^3 ha^{-1}, only a small fraction is profitable due to land use zoning constraints as well as current and foreseeable investments in infrastructure and milling capacity. As such, timber production is most valuable in regions where transport costs are low due to proximity and easy access to milling centres and where commercial values are high. Hardwood production, accounting for 11% of commercial volumes and 19% of gross revenues, is mostly found in central and north Pará, northwestern Mato Grosso and Amapá. Softwood production, accounting for 89% of commercial volumes and 81% of gross revenues, is mostly located in Amapá, northeastern Pará, northwestern Mato Grosso and central and west Amazon (Supplementary Figs. 2.11 and 2.12). RIL rents average US$$20\pm2.8$ ha^{-1} yr^{-1} but can reach up to US$$320\pm17$ ha^{-1} yr^{-1} in these regions (Figs. 1c and 3 and Supplementary Fig. 2.16).

Interactions between fire and timber harvest indicate that fire could damage roughly 2% of the production areas projected to be harvested between 2012 and 2041, reducing returns by an average of US$$39\pm2$ ha^{-1} yr^{-1} in burnt areas (Fig. 1g and Supplementary Fig. 3.16). Losses could reach up to US$$183\pm30$ ha^{-1} yr^{-1} in areas around timber milling centres hit by recurrent fires in southern and eastern Amazon. Estimated Net Present Value (NPV) of economic losses is approximately US$$689\pm184\times10^6$, representing 4% of total net revenues from sustainable timber extraction in the region. Yet potential losses could be significantly larger, since few burnt areas are eventually logged. If all burnt areas would have been logged in the near future, economic losses could hypothetically reach US$$7.6\pm2.4\times10^9$.

Non-timber forest products. Our analysis shows that rents of Brazil nut production, on the one hand, may reach up to US$46 ha^{-1} yr^{-1} (average rents are US$$5.05\pm7.49$ ha^{-1} yr^{-1}) in highly productive areas (hotspots) with yields around 30 kg ha^{-1} yr^{-1} (Fig. 1a). Such hotspots have been observed in southern Amazon as well as in northwestern and southwestern Pará (Calha Norte). On the other hand, rents from rubber extraction average only US$$0.56\pm0.7$ ha^{-1} yr^{-1}, even in areas with yields above the mean (yields $\geq$3.53 kg ha^{-1} yr^{-1}) that receive governmental subsidies (for example minimum guaranteed price). The highest rents of rubber extraction are found in the westernmost part of the Brazilian Amazon, particularly in Acre, southern Amazon and central Pará (Figs. 1b and 3), where values reach up to US$$6.13\pm2$ ha^{-1} yr^{-1} partially due to the strong government policy aimed at promoting the native rubber production chain[27,40]. For both Brazil nut and rubber production, rents tend to be higher near villages/towns that have better access to industry and larger populations (Fig. 1a–b, Fig. 3 and Supplementary Fig. 4.16). Nonetheless, the extractivist livelihoods for rubber extraction under current market prices are barely possible in most cases because of the unfair competition with rubber plantations in regions outside the Amazon[41].

Reduced rainfall. Overall, regions that are both upwind and close to pasture and soybean production areas are those that have benefited most from climate regulation functions. For soybean and beef production, reductions in productivity and rents due to diminishing climate regulation functions from deforestation average US$1.81 and 5.43 ha^{-1} yr^{-1}, respectively, but can be as high as US$9 ha^{-1} yr^{-1} (that

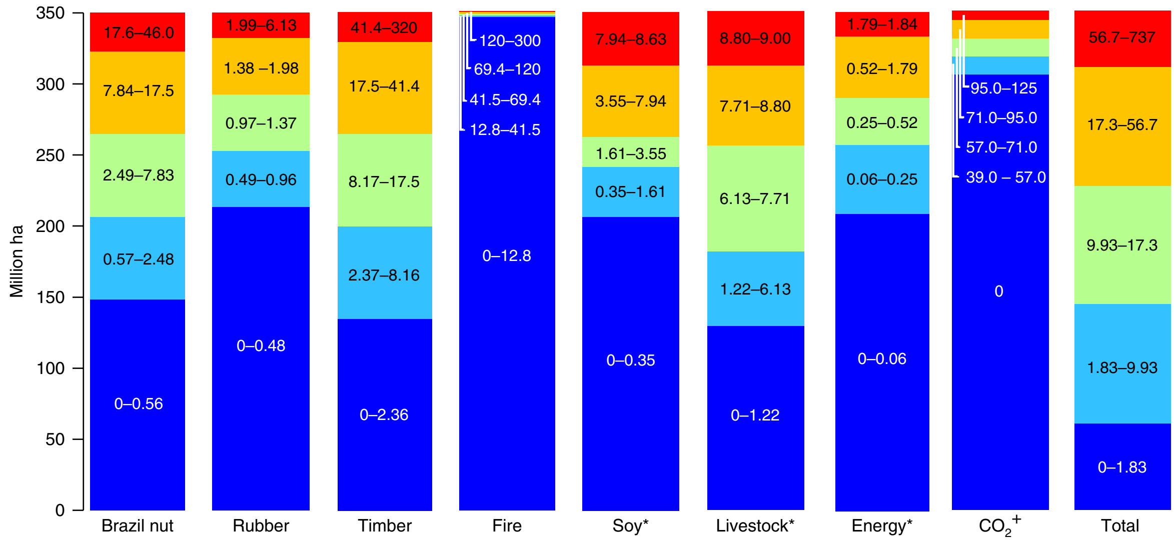

Fig. 3 | Areal extent of intervals of forest values in US\$ ha^{-1} yr^{-1} for each valuation component and for the total value map (see Figs. 1 and 2). Area of remaining forest is approximately 350 Mha. Soy*, Livestock* and Energy* refer to their marginal value not lost by keeping vegetation standing.

is 30% of total rents). Such reductions are mostly concentrated on the fringes of the Amazon forest, particularly in downwind production areas in northern Mato Grosso (soybean, Fig. 1 and Supplementary Figs. 5.2–5.4), Rondônia and eastern and southern Pará (livestock, Figs. 1d,e and Supplementary Figs. 5.6–5.8). Changes in hydroelectricity generation are only US\$0.32 ha^{-1} yr^{-1} on average, although economic losses may reach up to US\$1.84 ha^{-1} yr^{-1} depending on the extent of deforestation. These changes are mostly concentrated in the wet-to-dry and dry-to-wet season transition months (Figs. 1f and 3 and Supplementary Figs. 5.9–5.12). By contrast, forests in the northwest region do not provide relevant amounts of water vapour to form rains in the downwind soybean/cattle producing regions, and have therefore benefited the least from the climate regulation functions of the Amazon forest.

Greenhouse gas emissions. Reductions of CO_2 emissions are valued only in areas under threat of deforestation along the deforestation frontier from southwestern to eastern Amazon as well as western Pará and eastern Amazon (Figs. 1h and 3). In these regions, REDD+ (Reduced Emissions from Deforestation and forest Degradation) international agreements, at US\$5 per tonne CO_2, could generate up to US\$$48 \pm 9 \times 10^9$ for Brazil until 2025 if reduction targets are met. Monetary values could reach up to US\$$100 \pm 20$ ha^{-1} yr^{-1}, particularly in the eastern Amazon, northwestern Mato Grosso, near Manaus and along the region's major roads.

Discussion and conclusion

Our results indicate that the added value from ecosystem services in Amazon forests is not evenly distributed over space. The high values mostly reflect the partially overlapping effects of potential CO_2 emissions along the arc of deforestation, rubber production in the southwestern Amazon and Brazil nut production in Pará. While high rents from RIL are found in south and central regions near established milling infrastructure, economic impacts from losses of climate regulation functions in these forests are largely absent. The same value components also have impacts in Pará, albeit distributed differently. Conversely, in regions where agricultural expansion occurs, most notably in Rondônia, Mato Grosso and eastern Pará, we find that losses of climate and greenhouse gas regulation functions have the most impacts. Soybean and beef production in these regions show the largest decrease in rents due to reduced rainfall, while timber production is mostly impacted by forest fires.

The emphasis on high-value regions does not imply that other regions are less important. For example, while ecosystem services values in Acre are slightly lower than in southern Pará, the majority of the state was identified as a highly biodiverse area. Even in the remote northern regions, where overall values are relatively low due to sparse production chains, there are still vast expanses of highly biodiverse areas (Roraima) that are undervalued here as well as substantial carbon stocks (northeastern Amazon). These are not accounted in our analysis as we focus solely on deforestation reduction under REDD+ agreements in place, for example the Amazon Fund[33]. Although these regions are not immediately at risk of deforestation, they should be considered as a potential source of CO_2 emissions due to degradation by droughts and associated fires[23]. The strength of our approach is the ability to identify regions where value components cluster together and aggregate value to standing forests. Some high-value areas in central Pará, for example, reflect the combined values of RIL, NTFP and beef production as well as emissions reductions.

These results build on a far more refined approach to ecosystem services valuation than those adopted by most studies, despite their much broader scope. Previous studies have reported much higher ecosystem services values due to higher number of ecosystem services categories, poor detail on value components or methodologies used and heterogenous data sources, among other limitations[10,13]. By contrast, the relatively low values found in our study stem from the adoption of a singular methodological approach (that is rent losses from additional deforestation) and the selection of value components for which rigorous and precise economic valuation methodologies are available. This methodological approach therefore provides highly reliable information on the spatial distribution of ecosystem services values in the Brazilian Amazon. Our spatially explicit aggregation of several key forest value components (Figs. 1 and 2) substantially enhances our capacity to conduct land use planning where priorities are needed regarding protection or sustainable use for different forest areas. Our spatial mapping is particularly useful when these values exceed the opportunity cost of forestland (often illegal logging followed by agricultural conversion) and the forest should unambiguously be saved when measured in a purely economic sense. While opportunity values still often exceed demonstrable protection values[42], economically measurable values amount to only a small fraction of the immeasurable overall value of the Amazon forest, given that most of its ecosystem services are intangible and we map only (a fraction of) 4 of 17 documented ecosystem services[8,9].

Our work reflects the preliminary outcomes of a broader effort to build a user-friendly, interactive valuation platform (amazones.info) that provides a useful tool for policy-makers in forming their assessments of the spatially differentiated values for conserving the Amazon. In addition, our platform provides an adequate environment for exploring and advancing further developments on ecosystem services valuation as well as for showing opportunities to combine forest conservation with sustainable forestry development in key areas where resources from bilateral or multilateral financing mechanisms would make the most difference.

Policy makers need to remain cautious about two aspects of our work. First, our maps represent values for different groups at different levels of society. Deforestation may incur economic losses to individual production activities (for example timber, Brazil nuts, rubber, soybean and beef) or miss opportunities to capture societal benefits (that is finance for emissions reductions, hydroelectricity production yields and highly biodiverse areas). Policy makers need to account for these differences when using our maps, since our valuation platform does not yet incorporate decision-making guidelines to resolve such conflicts. Second, and partially related, our maps do not provide sufficient guidance in cases of overlapping value components that may contradict. For instance, regions with high values of timber may overlap with highly biodiverse areas, which benefit different social groups. Policy makers therefore need to decide as to where each group has preference.

There is still much work to be done. As already mentioned, our study has quantified only a fraction of the overall value of the Amazon forest. Spatially explicit valuation of biodiversity is currently missing; several other ecosystem variables, including recreation and tourism, health impacts, nutrient retention, watershed and flood protection, freshwater supplies and fish catches, are not mapped either. As such, our maps are less useful for identifying areas where protection values are small. Policy makers should be cautious in using our maps to justify forest conversion in such areas. Including the aforementioned additional elements will go further toward a complete economic mapping of Amazon forest. Our study also identifies shortfalls that require addition of value components. One such component involves the values held by populations outside the region, not counted here. Separate work has shown that these values can be substantial[14], justifying large global investments in Amazon conservation (Supplementary Section 7). Future research also needs to continue refining valuation methods to account for the complex and intertwining deforestation dynamics, including the adverse effects of agricultural expansion and the infrastructural developments that often follow pioneering economic activities[43].

Methods

Our valuation builds on methods developed by project participants over an extensive period, which include a number of models and model applications described at greater length in the Supplementary Information and related literature[6,7,14,19,21,24,26–28,30–32,39,40,44,45]. All valuation items are based on flow (US$ ha^{-1} yr^{-1}). To compare rents and to sum up values, we use Equivalent Annual Annuity (EAA). The annual net rents are transformed into NPV using a discount rate of 5% and converted into EAA to facilitate comparison given that EAA represents the annual uniform value of a project/activity that is evenly spread over its lifespan. Our value maps (Figs. 1 and 2) build on base maps for indicating state capitals[46] and boundaries[47], deforested areas and other land cover[48] and the Amazon biome[49]. In this section we present a brief outline of our methodology by highlighting the most important features discussed in the Supplementary Information.

Our analysis of spatial forest value is based on a marginal valuation principle (Supplementary Section 1), where one considers the economic loss sustained when a small value of the Amazon is lost, at alternative sites of standing forest, notwithstanding losses due to degradation. As discussed in Supplementary Section 1, however, this is a difficult principle to maintain for the overall analysis, as the distinction between marginal and average forest values is complicated to operate and to ensure accuracy. In addition, the calculations of marginal values can be demanding. Marginal values of particular forest attributes are often lower than average values, as is typical for biodiversity and tourism. But in other contexts, it is the opposite, due to negative external impacts of forest losses on forest fires and forest dryness[14]. Supplementary Section 1 discusses this issue and suggests the use of multipliers, derived for all locations in the Brazilian Amazon, to reflect the negative external effects of local forest losses in terms of increased risks of losing forests in the direct vicinity. These multipliers enhance the marginal economic value of preventing forest losses by also preventing forest fires and excessive dryness. Deriving such a set of multipliers is a target for future research on ecosystem services valuation in the Amazon.

For the reduced impact logging (RIL) analysis (Supplementary Section 2), a simulation model, SimMadeira+, developed to evaluate the economic impact of RIL was applied[21]. The model consists of a partial equilibrium dynamic spatial simulation model of the Amazon timber industry, which calculates a residual stumpage value of forested land, annual harvest volume and value, potential tax revenues and forecasts primary industrial capacity (Supplementary Fig. 2.1). Simulations encompasses a 30-year period for timber harvesting in the entire Brazilian Amazon, with temporary logging centres being established sequentially over time, and moving as allowable and exploitable timber is depleted locally. The model embeds assumptions about local logging costs and assumes that timber prices will grow at 2% annually over this 30-year period. Occurrence maps are created for the entire biome for 40 commercial tree genera/species that the Brazilian government permits to be harvested under RIL (Supplementary Fig. 2.4). That only one 30-year forest harvesting cycle is analysed in the valuation leads to a conservative measure of RIL with an overall under-valuation of discounted forest returns by around 40%. Because rents from logging occur over time, the annual net rents are transformed into NPV and then converted into EAA. Our valuation approach leads to a spatially explicit commercial value map for the entire biome for RIL at 1 km^2 spatial resolution. It is recognized that RIL is not allowed in protected and indigenous areas, so for such areas this value is set at zero (Supplementary Figs. 2.15 and 2.16).

The forest fire analysis (Supplementary Section 3) is done by using three separate models developed for this task: (1) the EcoFire (Economic Cost of Fire) model which estimates fire-related losses to RIL returns; (2) the SimMadeira+ model for RIL timber value distribution across the biome; and (3) the FISC (fire, ignition, spread and carbon components) model developed to simulate fire ignition and propagation across the Amazon biome at 25 ha spatial resolution[21]. The EcoFire is a spatially explicit model developed to estimate the economic losses in the forestry sector caused by forest fires between 2002 and 2041 (Supplementary Fig. 3.2). To this end, the EcoFire processes and combines occurrence and intensity of forest fires simulated from FISC with data on the impact variation on different tree species and economic data on timber production in the Amazon to estimate the economic losses. To establish the relationship between fire and timber, EcoFire includes a set of empirical parameters that represent the economic impact of different fire intensities on different commercial tree species. In this way, losses from fire are estimated separately for softwood and hardwood, recognizing that hardwood damages are significant only in cases of reoccurrence of fires (Supplementary Fig. 3.9).

For the NTFP analysis (Supplementary Section 4), our valuation is concentrated on two such products, Brazil nut and rubber, which are mapped for the entire Brazilian Amazon. For Brazil nut production, we use Brazilian Geographical and Statistics Institute (IBGE) data by municipality for 1994–2013 to estimate maximum production volume per municipality (Supplementary Fig. 4.1). Price data per municipality come from IBGE data and the Brazilian National Supply Corporation (Supplementary Fig. 4.2). We begin the model by estimating Brazil nut tree density and productivity using large forest inventory data from Acre and Pará case studies[27,28,40]. We then extrapolate the resulting yield maps (Supplementary Fig. 4.6) to the entire Brazilian Amazon building first a favorability map by integrating the effects of a set of biophysical variables on production volume (as a proxy for yield) through the weights of evidence (WofE) method (Supplementary Fig. 4.5); finally we convert the favorability map into the yield map (Supplementary Fig. 4.7) by using a Probability Distribution Function (PDF) transformation, whereby the yield PDF is derived from the case study areas[27,40]. Collection and transport costs are estimated and modelled based on case studies from Acre and Pará and then extrapolated for the entire Brazilian Amazon using detailed information on infrastructure and processing centre location data to arrive at the rent map (Fig. 1a). Net returns from rubber production (Fig. 1b) are also modelled for the entire Brazilian Amazon using the same methodology as that of the Brazil nut map, which is also based on observations from Acre and Pará (Supplementary Fig. 4.1). Minimum prices to rubber extractors include government subsidies. Production and transport costs are also estimated from field surveys in Acre and Pará[27,28]. To create the value maps (annual rents in US$ ha^{-1} yr^{-1}), we coupled biophysical and economic spatially explicit models at 1 km^2 spatial resolution for Brazil nut and rubber collection, as follows:

$$\mathrm{Rent}_j = (Q_{xy}{}^*\mathrm{P_n}) - (Q_{xy}{}^*\mathrm{CTprd_n}) - (Q_{xy}{}^*\mathrm{Ctr_{n\_}d_z}) \quad (1)$$

where Q_{xy} is the simulated production for a cell with coordinates (x,y) in kg ha^{-1} yr^{-1}; P_n and CT_{prdn} correspond to, respectively, selling price and cost of production in US$ per kg of product n and cost of secondary transportation (Ctr_n) in US$ per kg of product n by modes of transport (car, donkey, on foot) (d_z) from the location (x,y) to the nearest cooperative.

To simulate production (Q_{xy}), we first use WofE method[50] for estimating the spatial determinants of productivity of Brazil nut and rubber based on bioclimatic and production data (Supplementary Figs. 4.5 and 4.14). For the production and transportation costs, we carried out field surveys in Acre and Pará states to collect up-to-date data through semistructured interviews and focus group. We interviewed 30 people in Acre including 6 extractivists, 10 NGOs and 10 governmental agencies, as well as 4 academics at the Acre Federal University. In Pará, we interviewed 9 extractivists, 2 cooperatives, 5 governmental bodies, 2 scientists and 1 representative of the Brazil nut exporting industry (Supplementary Information Section 4). Through semistructured interviews, we collected market prices (from cooperatives), production costs (from extractivists) and transport costs (from both cooperatives and extractivists and their associations). Based on the network of contacts established during fieldwork we collected data on harvesting activities of over 11,000 families in Acre and Pará. Although limited to two states (Acre and Pará), this study uses the most comprehensive dataset on these NTFPs available to date[27,40].

The climate regulation analysis (Supplementary Section 5) is based on the National Center for Atmospheric Research (NCAR) Community Climate Model 3 (CCM3), coupled with an updated version of the Integrated Biosphere Simulator (IBIS). The coupled model (CCM3–IBIS) has been extensively used for projecting the impacts of changes in land use on climate of South America, at a spatial resolution of $300 \times 300\,km^2$. Rainfall results used here have been previously analysed[31,44]. These changes in climate are used to estimate the impacts of deforestation on production and net returns of soybean production (for Argentina, Uruguay, Bolivia, Paraguay and Brazil), beef production (Brazil only) and hydroelectricity generation from four Brazilian facilities, using the Integrated Model of Land Surface Processes (INLAND), an evolution of the Agro–IBIS model. Reverse calculations are made whereby economic losses, at stipulated (current) output prices, can be traced back to the individual (large) Amazon forest cells where forest is lost. Loss magnitudes in US\$ $ha^{-1}\,yr^{-1}$ are calculated for each cell output. Climate results are the average of five ensembles but since a single suite of climate and agroecological models was used, uncertainty related to model diversity cannot be quantified. Adaptation through changing planting dates is considered but calculations assume that crop management and other farm practices remain fixed. Other limitations include the use of fixed prices of commodities and invariant soy and pasture areas.

For calculating CO_2 emissions from reduced deforestation, we applied SimAmazonia-2 (ref. [7]) to simulate spatially explicit deforestation under a baseline scenario of annual deforestation rates of $19{,}600\,km^2\,yr^{-1}$, that is the annual average between 1996 and 2005 and under the target scenario of 80% reduction from the baseline by 2025. SimAmazonia-2 begins by regionalizing the overall annual rates using an econometric model; next, the rates are allocated in a spatially explicit form based on the influence of a set of spatial determinants. Spatial determinants represent either proximate causes of deforestation (the opening or paving of a road) or are simply preferable, for example more fertile soil, low slope or land use zoning, such as outside protected areas. To calculate potential CO_2 reduction, the model annually sums the carbon stocks[1] of cells that are deforested under the prescribed scenario, assuming that 85% of their forest carbon is released to the atmosphere with deforestation[51]. To come up with the total emission reductions, the model deducts the amount of emissions that would occur under the target scenario from emissions that would occur under the baseline scenario. To account for spatial uncertainties, we ran SimAmazonia-2 50 times, recalculating the emissions figures each time. In this way, our approach considers which areas might be more vulnerable to deforestation if deforestation continues unabated, therefore presenting a realistic picture of potential CO_2 emission reduction.

The biodiversity mapping (Supplementary Section 6) uses a large number of species occurrence datasets, including GBIF, CRIA, Herpnet, Nature Serve and Orthoptera Species File, as well as data from the taxonomic literature. From these datasets, we have created a database comprising more than 110,000 geo-referenced records for the Amazon, the most comprehensive to date. Our model seeks to identify within unique biota regions the smallest possible areas that contain the most species as well as highest phylogenetic diversity, endemicity and phylogenetic endemism. To this end the model first interpolates into map representation six biodiversity dimensions: (1) phylogenetic and (2) species compositions, (3) species richness and (4) endemism, (5) areas of endemism and (6) phylogenetic endemism (Supplementary Figs. 6.3–6.7). To map highly biodiverse areas, our model stratifies the Amazon into regions (Supplementary Fig. 6.8). We use species (β-diversity) and phylogenetic (β-phylodiversity) compositions to identify biogeographic regions with unique combination of species and lineages. Next, for each biogeographic unit, the model sums the quantitative biodiversity variables (species richness, species endemism, areas of endemism and phylogenetic endemism) after re-scaling their minimum and maximum values within each region to 0 and 1. Finally, the model adds the sampling effort and stamps the native vegetation remnants to generate the final set of classes that combine biological relevance, sampling density and regional vegetation coverage (Fig. 1i). Hence, the biodiversity relevant map integrates the level of knowledge on the region's biota with its degree of biological relevance and level of vegetation fragmentation. No monetary valuation is performed.

Model typologies, uncertainties and validation — while some of our models are based on production functions, that is NFTPs, SimMadeira+ and EcoFire, others simulate complex process-based systems, such as the fire propagation (FISC), the CCM3–IBIS and INLAND models. In turn, SimAmazonia+ and OTIMIZAGRO are spatial optimization models whose rates of changes are exogenous. As modelling approaches are becoming increasingly hybrid, new versions of these models could also include decision-making process (for example agent-based models) and be coupled to, for example, computable equilibrium models to simulate the impact of production volume on input prices. Modelling uncertainties stem from various sources and uncertainty bounds when available are depicted as bar diagrams in Figs. 1 and 2 for overall value of valuation components. For example, in our RIL model, the commercial timber volume for each tree species is based on volume data provided by Merry et al.[45]. Since these data are remotely sensed biomass maps, these values intrinsically embody about 20% uncertainties. Furthermore, they only represent indirect measurements of commercial timber volumes and timber prices are estimated as a weighted average value for a small sample of genera and species, since the available literature does not provide standardized data on variation in species, class and density of trees across the entire Amazon. Regarding fire assessment, our model incorporates uncertainties from the Natural Environment Research Council (NERC)[52] together with temperature and humidity products that FISC uses to calculate the Vapour Pressure Deficit (VPD) data. In addition, the spatially explicit analysis of EcoFire assumptions are constrained by absence of parameters related to field experiments and scarce literature on the degree of damage by varying intensity of fire to specific tree species. We acknowledge that a more comprehensive valuation related to fire losses should also encompass the costs of physical assets damages, biodiversity and habitat degradation, CO_2 emissions and effects on human ailments, which remain as items for future work on our valuation platform. NTFP assessments are limited by the scarcity of data on tree density and productivity. Although our database is the most comprehensive to date, its forest plots were derived basically from two case studies in Acre and Pará. The same applies to biodiversity analysis due to knowledge shortfalls in large regions of the Amazon (see grey areas in Fig. 1i). Limitations of hydrological analyses are mentioned above. Lastly, CO_2 emissions calculations mainly suffer from uncertainties related to biomass estimates. Notwithstanding the various sources of uncertainties in our calculations, our models have been properly validated when developed for previous applications, for example rents of rubber[27], Brazil nut[40] and timber[45] and deforestation simulation[7].

Data availability

The data that support the findings of this study are available at http://amazones.info. Further description of how the data were processed and analysed is presented in the SI.

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Author contributions

J.S., B.S.F. and M.C. designed the project, conducted research and wrote the manuscript. G.P., U.O., S.R., R.R. and A.O. conducted research and helped write the manuscript. J.S. and R.M. conducted research. P.M., M.T. and R.H. helped write the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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