Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action

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Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved October 1, 2018 (received for review May 8, 2018)

Large uncertainties still dominate the hypothesis of an abrupt large-scale shift of the Amazon forest caused by climate change [Amazonian forest dieback (AFD)] even though observational evidence shows the forest and regional climate changing. Here, we assess whether mitigation or adaptation action should be taken now, later, or not at all in light of such uncertainties. No action/later action would result in major social impacts that may influence migration to large Amazonian cities through a causal chain of climate change and forest degradation leading to lower river-water levels that affect transportation, food security, and health. Net-present value socioeconomic damage over a 30-year period after AFD is estimated between US dollar (USD) $957 billion (×10^{9}) and $3,589 billion (compared with Gross Brazilian Amazon Product of USD $150 billion per year), arising primarily from changes in the provision of ecosystem services. Costs of acting now would be one to two orders of magnitude lower than economic damages. However, while AFD mitigation alternatives—e.g., curbing deforestation—are attainable (USD $64 billion), their efficacy in achieving a forest resilience that prevents AFD is uncertain. Concurrently, a proposed set of 20 adaptation measures is also attainable (USD $122 billion) and could bring benefits even if AFD never occurs. An interdisciplinary research agenda to fill lingering knowledge gaps and constrain the risk of AFD should focus on developing sound experimental and modeling evidence regarding its likelihood, integrated with socioeconomic assessments to anticipate its impacts and evaluate the feasibility and efficacy of mitigation/adaptation options.

ecosystem services | agriculture | hydroelectricity generation | migration | adaptation

The Amazon forest dieback hypothesis (1–3) attracted attention not only in the scientific literature but also in the public media. This is because it projects a basin-wide climate-driven transition of the region's rainforests toward a drought-prone vegetation with lower biomass, a rain-green forest, savannah, or even degraded vegetation without present-day analogs. Although a few arguments support the notion that such an Amazon dieback may be improbable (4), it is premature to rule it out. While the impacts that such a large-scale forest loss would have on the carbon and water cycles and the global climate system are relatively well-studied (1–3, 5, 6), the socioeconomic impacts that could result from Amazonian forest dieback still remain superficially assessed (but see ref. 7). Nor has the matter been approached from a formal risk-analysis perspective (8), in which both the likelihood of an event as well as the potential impacts that it can cause are addressed (*SI Appendix*, Fig. S1). As such, we still lack a scientific debate that can support policy

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Author contributions: D.M.L. and P.P. designed research; D.M.L., P.P., C.A.Q., and B.B.N.S. performed research; D.M.L. and B.B.N.S. analyzed data; and D.M.L., P.P., C.A.Q., B.B.N.S., A.R., B.K., F.B., J.P.H.B.O., A.P., J.A.M., W.V., and C.A.N. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1721770115/-/DCSupplemental.

making regarding the plausibility of mitigation of or adaption to such a large-scale environmental change in the Amazon region, as well as whether taking action now is more advantageous than doing so later. In this Perspective, we briefly review the state-of-the-art scientific knowledge on the likelihood of a potential Amazon forest dieback and then assess what the impacts of such an event would be for different sectors of the Amazonian socioeconomy. This assessment particularly considers the impacts observed during recent droughts in the region (notably in the Brazilian Amazon). Our first-order evaluation provides a comparative discussion of the feasibility, timing, and costs of mitigation and resilience-building adaptation alternatives to such an event. Based on this analysis, we propose a priority research agenda for better constraining the risk of a future Amazon forest dieback (AFD) or any form of large-scale degradation of the Amazon forest driven by climatic change (hereafter AFD).

Likelihood of a Large-Scale Climate-Driven Loss of the Amazon Forest

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5) (4) states that "there is now medium confidence that climate change alone will not drive large-scale [Amazon] forest loss by 2100." Such a statement is based on four studies (5, 6, 9, 10) which a priori make strong yet tentative assumptions about potential forest resilience. The sustained forest resilience seen in these studies arises mainly from enhanced net primary productivity (NPP) due to an increased harvest of atmospheric CO_2 by photosynthesis—the so-called CO_2 fertilization effect (5, 6, 9, 11); or from the consideration of uniform soil–plant–atmosphere interactions across the basin (10, 12). In fact, several other studies using different vegetation models have also highlighted the key role of CO_2 fertilization in counteracting the likely deleterious effects of climate change on Amazonian vegetation, increasing the net carbon uptake and possibly biomass of tropical forests and their resilience to climatic extremes by enhancing water use efficiency (WUE) (13–16). However, there is no direct observational or experimental evidence of the existence, magnitude, duration, and influence of this CO_2 fertilization effect in the Amazon forest, and there is particularly no direct evidence of the stimulation of tree growth in mature forests worldwide (17, 18).

Observational studies carried out in the Amazon over the past 30 years show evidence of an already changing forest. Over time, forest productivity and tree turnover rates have increased in the Amazon—the former at a faster rate—resulting in an average net carbon sink (biomass gain) across the basin of 0.5 Pg C per year (19, 20) and changes in forest functional composition (21, 22). Invariably, such changes have been suggested to be associated with increasing atmospheric CO_2 concentrations (hereafter eCO_2) (23) while climatic extremes may also play a role in the enhanced turnover (24–26). In contrast, a recent study (27) based on a network of >300 forest plots, reported an alarming observation that the capacity of the standing Amazon forest to act as a net sink of carbon has decreased by 30% since 1990, with forest mortality rates seeming to catch up with productivity over time. Current vegetation models do not capture that slowing down of the Amazonian carbon sink whereas a linear extrapolation of that sink trend (27) would imply that, as already observed in drought years (24, 28), the world's largest tropical forest could become a source of carbon to the atmosphere in approximately 10 years from now.

In the same sense, the effects of decades-long drought on the Amazonian forest, both from experimental (29) and modeling perspectives (30), still remain undetermined (25). It is, however, unlikely that these forests can remain unchanged under a persistent change in regional precipitation patterns (12). Moreover, while reduced Amazon forest transpiration (caused by eCO_2) implies that soil moisture is conserved locally, on a basin-wide scale, it can alter the biosphere–atmosphere flux of moisture, affecting the regional recycling of precipitation (31), potentially leading to a self-amplified destabilization of large fractions of the Amazon forest (32). While much of the remotely sensed bistability of forest–savanna may be a human-produced process, notably through fire and logging (33, 34), there is no quantification of how much climate change and eCO_2 have contributed to that bistability. The same level of uncertainty is valid for nutrient limitation, in particular limitation from low phosphorus availability, which is widespread across the Amazon and which could potentially limit any forest response to eCO_2 (35, 36).

Modeling studies are unquestionably advancing our scientific understanding of the Amazonian system in light of climate change. However, several ecological processes surrounding the CO_2 fertilization effect, which are not properly considered in vegetation models, prevent us from estimating with reasonable confidence the likelihood of a future dieback-like change in the Amazon forest. A weak or transient CO_2 fertilization effect could well drive the Amazon forest, or large fractions of it, into a state of lower productivity, biomass loss, and altered forest composition and dynamics (5, 6, 13, 14, 16, 37–39)—the direction indicated by recent observational data—especially if accompanied by deforestation, fire, and selective logging (37, 40). As such, it seems likely that more severe alterations in forest structure, biodiversity, and function should occur under the climate scenarios projected for the future in the region (17). The discussion of large-scale degradation of the Amazon forest driven by climate change should therefore remain open, and there is an urgent need to reduce the uncertainties surrounding it.

Coping with the Risk of Climate-Driven Loss of Amazon Forest

Whether the aforementioned biophysical uncertainties should imply taking any sort of action now or later is a matter of balancing the impacts that such AFD could have on the Amazonian socioeconomy, with the efforts that would be involved in actions to mitigate it or to get adapted to it. Choosing a "no action" or "action later" pathway would mean enduring the cascading impacts of AFD on distinct sectors of the region's socioeconomy, such as losses in the production of hydroelectric energy. Doing something about AFD now would mean either attempting to mitigate it or to adapt the region's population to its effects. Mitigation strategies include curbing deforestation and restoring forests in southern and eastern Amazon (41). Human adaptation strategies are far less discussed but could include, for example, the decentralization of energy production with solar-dedicated infrastructure. Next, we carry out an in-depth evaluation of whether any mitigation or adaptation action should be taken now, later, or not at all in light of the uncertainties about the AFD. In that sense, we provide a first-order assessment on the feasibility and costs of mitigation and adaptation alternatives related to AFD, all of which could probably, though not yet certainly, diminish the AFD impacts.

No Action/Action Later—Impacts on the Amazonian Socioeconomy

The impacts (i.e., losses and gains) of AFD were assessed for seven sectors of the region's socioeconomy: agriculture, fisheries, transport systems and livelihoods, energy and infrastructure, other ecosystem services, cities and migration, and health. We summarized a wider spectrum of socioeconomic sectors, including those at least discussed here and also those not assessed in this study (e.g., industry) and the potential AFD-driven impacts they would be subject to (shown in *SI Appendix*, Table S1).

Quantifiable costs for all considered sectors were assessed following evidence of (positive and negative) impacts observed during past droughts or, as in the case of agriculture and energy sectors, modeling assessments. Preference was given, in order of priority, to peer-reviewed publications (e.g., ref. 42) and official and well-established statistics databases (e.g., ref. 43) but also used some informational evidence published in independent not peer-reviewed reports (e.g., ref. 44). Therefore, existing punctual impact estimates for past droughts are used here to generate a set of estimates on the long-term socioeconomic impact of AFD. "Moderate" and "extreme" estimates are presented, conditional on the severity of AFD, meaning that at least 30% and 50% of the Amazon forest area would be lost through climate change-related factors, respectively (45), and that deforestation by direct human activities would be kept below 20% of forest area (41). Keeping with mainstream economic approaches, we applied discount rates of 2% and 5% to these estimated values to reflect human preference for intertemporal choices. An average value of 3% is often used for the time horizon of ∼30 years employed here (46), and, as a sensitivity analysis, we considered values on either side of that average. In some cases, impacts were assessed outside the limits of Amazonia, such as those associated with agriculture in the La Plata basin. While the socioeconomic impacts of AFD and the drought conditions associated to it are analyzed only under future dry–warm scenarios, we recognize that disastrous floods are also becoming more frequent across the Amazon and can also contribute to socioeconomic costs (47). A simple three-level confidence analysis has been applied to results: A low level means that the majority of references used to estimate impacts came from not peer-reviewed publications; medium level used both peer-reviewed data as well as not peer-reviewed; high denotes the estimates derived from majorly peer-reviewed publications. When not mentioned otherwise, costs refer to a cumulative period of 30 years, and all values are presented in 2015-equivalent US dollars (USD). A precise description of the methods employed for estimating the impacts for each sector and an in-depth discussion of this assessment are presented in *SI Appendix* (*SI Appendix Text* and Table S1).

Other nonquantifiable costs were estimated through a qualitative (and logic) approach, also following majorly observed impacts of previous recent droughts described in the scientific literature. That was done through an ad hoc consideration of how many people would possibly be seriously affected by a given impact. A high, low, or medium nonquantifiable socioeconomic impact here refers to a situation when a high (>300,000), low (<50,000), or medium (in between) number of people are impacted through changes in income and/or alteration of life habits.

Because of either the uncertainties surrounding the financial impact estimates available at hand and/or the occasionally scarce evidence, we opted to keep the socioeconomic loss estimates presented in this study as conservative as possible—meaning that they are generally smaller or more moderate than the losses observed during past droughts. Altogether, these estimates should be regarded as a balance of derived macrosocioeconomic costs of a climate-driven degradation of the Amazon forest.

Fig. 1 summarizes the interrelation and causal chain between climate change, a dieback-like degradation of the forest, and their cascading impacts on the different socioeconomic sectors covered here—such a relational diagram is also useful for scoping cross-sectorial adaptation options (*Action Now—Adaptation*). The overall long-term quantifiable socioeconomic cost of a climate-driven degradation of the Brazilian Amazon forest would lie in the range of USD \$49 billion ($\times 10^9$) to \$456 billion [net present value (NPV)], with annual costs reaching 2.1 to 13.6% of 2015 Gross Brazilian Amazon Product (GBAP), whereas direct quantifiable economic gains are estimated between USD \$4.7 billion and \$68.5 billion (up to 2% of GBAP). These estimates do not consider the impairment of other ecosystem services not presently linked to market values (Fig. 2). Losses in this case are dominated by the agriculture and energy and infrastructure sectors due to the effects of an AFD-like climate on crop productivity and on the potential for generation of hydroelectricity, respectively. Gains would be concentrated on the agricultural sector due to a supposed relaxation of environmental rules allowing the expansion of croplands and pastures onto previously protected areas (Table 1). For some sectors, such as health, due to the severe nature of the losses, an economic gain cannot even be considered.

On the other hand, when nonmarket value ecosystem services are considered in our analysis, a range of USD \$2,529 billion to \$7,701 billion (USD \$1,616 billion to \$4,500 billion) is added to the direct socioeconomic losses (gains). In this case, total losses (gains) would be substantially higher, representing 112 to 243% (70 to 136%) of GBAP on an annual basis. This emphasizes the crucial importance of the ecosystem services the forest continuously provides but that lie outside formal economic markets. The consideration of nonmarket value ecosystem services in this cost–benefit analysis is founded on the principle that all impacts must be considered if one aims at a pervasive state of social welfare for the region. It should be noticed however that, as a sudden and widespread disappearance of these ecosystem services becomes more imminent, their marginal value would rise steeply due to a resource-scarcity effect. This would be compounded by the fact that the irreversible loss of these services may have an unacceptable and intangible cost to society (48–50). Given the lingering uncertainties about AFD, this is still not the case here. However, the extrapolation of point estimates of ecosystem services value, as carried out here and in many other studies (e.g., ref. 51), probably causes an underestimated integrated value of ecosystem services under environmental changes in the long run (52).

Other nonquantifiable socioeconomic impacts are considered high in four out of the seven analyzed sectors: fisheries (which a large human population is dependent on), transport and livelihood (strongly altered in areas where rivers are the only way of transport—e.g., western Amazon), cities and migration (it is likely that people would migrate from remote areas to large Amazonian cities under a persistent drought regime), and health (the spread of respiratory and vector-borne diseases are thought to be stimulated under an AFD future) (Table 1).

For sectors in which the quantifiable (economic) cost is estimated as relatively small or unknown (e.g., the health sector), the nonquantifiable (social) impact is invariably high and vice versa, suggesting a strong socioeconomic trade-off between effects on the macroeconomy and on people's livelihoods. It should be noted however that these estimates do not consider any savings or costs involved with adaptation actions and that they are most likely underestimated given the conservative assumptions used to achieve them. Had losses for several sectors been estimated for the entire Amazon region and not only for the Brazilian Amazon, these values would certainly be higher. In fact, due to the limited

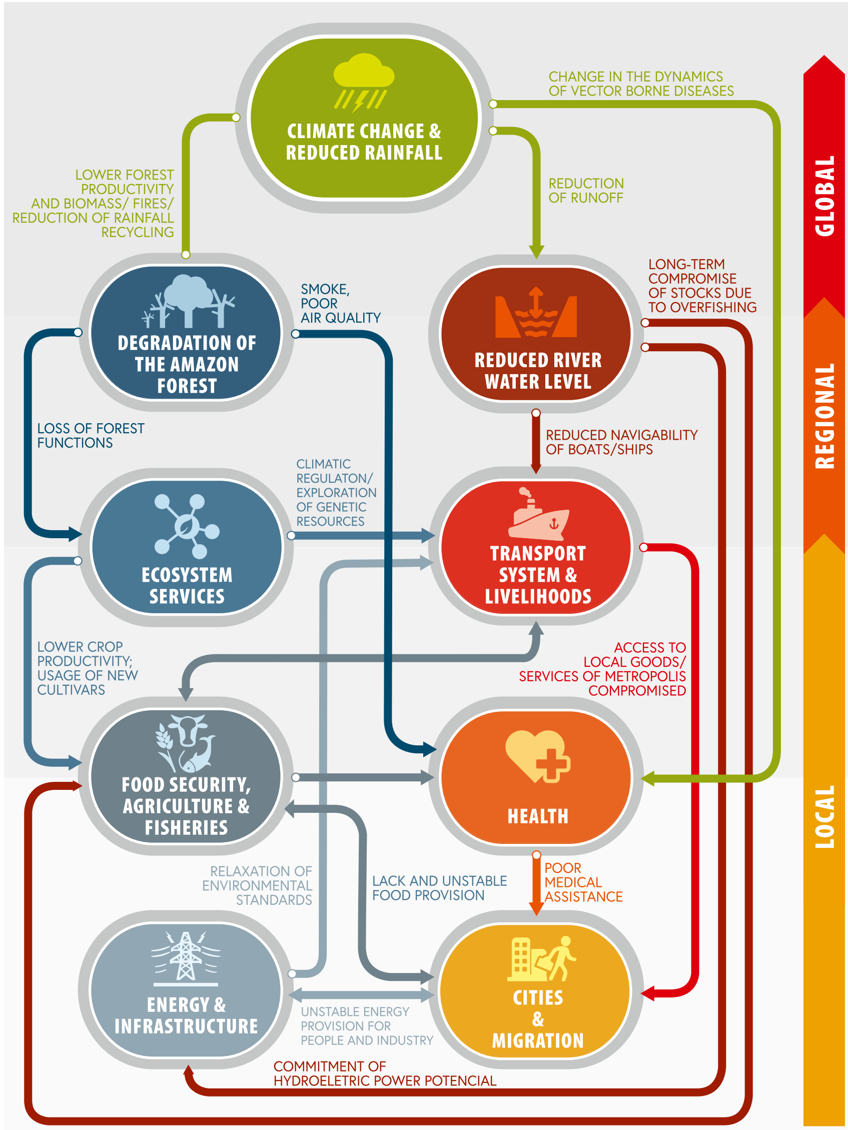

Fig. 1. Causal chain of climate change, ecological degradation of the Amazon forest, and their impacts on different sectors of the region's socioeconomy.

information available, a full reckoning of financial and social costs is well beyond the scope of this Perspective. That said, from a risk-analysis perspective (8), considering that the probability of an AFD event is not unlikely and that our current (and still sparse) knowledge suggests that the socioeconomic impact would be high, the risk that would be associated with such an event is invariably high or unacceptable (*SI Appendix*, Fig. S1).

Action Now—Mitigation

Is it possible to mitigate such large-scale degradation of the Amazon forest and its biodiversity caused by climatic changes and minimize the aforementioned socioeconomic impacts? Mitigation alternatives may be divided into two major categories: (*i*) alleviation of the cause of the dieback and (*ii*) building up the resilience of the forest to avoid drastic ecological alterations caused by global climatic change. Regardless of the category, the actions would pertain to large-scale efforts. The cause alluded to in the first category is global climate change (2, 3, 13, 14), and, from this perspective, there does not seem to be a better mitigation action for AFD other than a rapid and significant worldwide reduction in greenhouse gas (GHG) emissions (53). While the probability of rapid and significant global abatement of GHG emissions has been decreasing over the years (54), the costs of effective worldwide mitigation of climate change are estimated between USD $180,000 trillion and $260,000 trillion in the next 30 years (55). Even though it would bring about benefits far beyond the Amazon basin, this is a very high cost compared with other alternatives for AFD risk reduction. While, from a point of view of climate-change policy, it would make sense that the Amazonian countries pay only a fraction of that cost, it would be insufficient to stop global climate change and therefore prevent the AFD alone.

Potential large-scale alternatives for building up forest resilience are the most uncertain in terms of their efficacy and/or feasibility in logistical and financial terms (similarly to ref. 53). One example of such uncertain, risky, and most probably unfeasible alternatives would be to fertilize the nutrient-poor soils of the

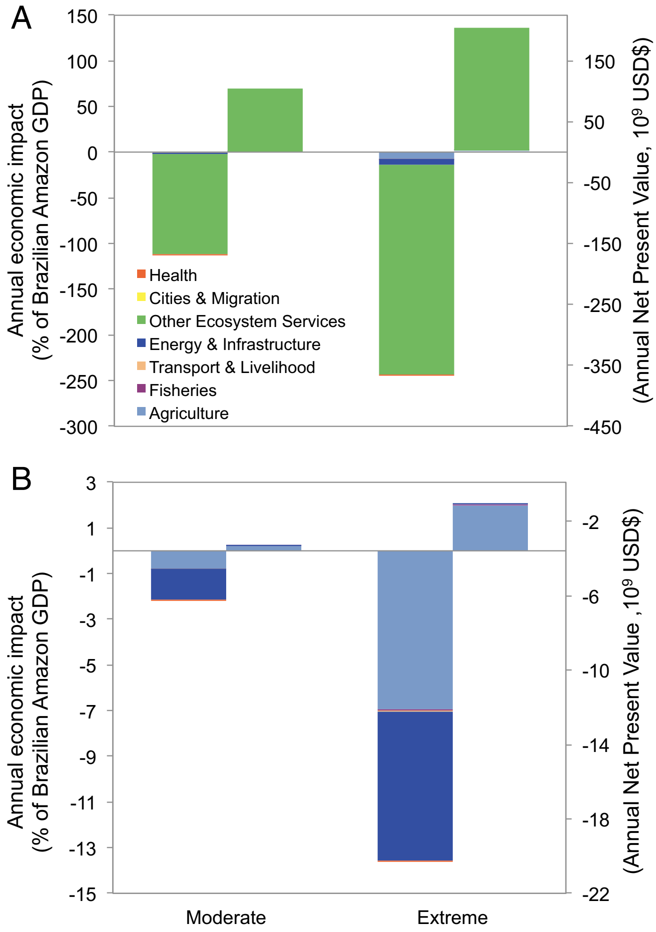

Fig. 2. Annual socioeconomic impacts (losses and gains) of moderate and extreme large-scale degradation of the Amazon forest (mainly its Brazilian portion) caused by global climatic change as a percentage of Brazilian Amazon gross domestic product (GDP) and in absolute 2015 USD$ financial cost (*A*) considering and (*B*) excluding losses and gains derived from nonmarket value ecosystem services. A discount rate of 5% and carbon value of USD $5/tCO$_2$eq (metric tons of carbon dioxide equivalent) are used in the moderate scenario whereas a discount rate of 2% and carbon value of USD $20/tCO$_2$eq are employed under the extreme case. See Table 1 for the quantitative definition of moderate and extreme scenarios.

Amazon forest to reduce the limitation they impose on forest productivity. The amount of fertilizer (triple superphosphate) necessary for such an endeavor would reach nearly 200 million metric tons in three to five years, resulting in an initial cost of USD $54 billion (*SI Appendix*). The enormous negative impacts that such a fertilization could cause (for example, the eutrophication of freshwater systems throughout the basin) make this measure prohibitive. Another example in this category of large-scale and probably unrealistic interventions would be to irrigate the forest to levels that would nullify the projected rainfall reduction. A superficial example considering only the costs of irrigation systems (*SI Appendix*) implemented in half of the Amazon forest area would result in an exorbitant initial price of USD $846 billion. This estimate does not consider the availability of sufficient water or the labor costs involved.

Other large-scale interventions in the forest structure and functioning cannot be completely disregarded for use in the near future but are, at this moment, unreachable with the available knowledge and technology. An example of such intervention would be large-scale genetic engineering aiming at the maintenance of existing forest taxa under the AFD climate.

On the other hand, more realistic measures, such as the reduction of deforestation, landscape restoration, and adoption of environmentally rational agricultural practices, are certainly more feasible and desirable as they would contribute to reduce—but not eliminate—the probability of AFD (41, 56–58). The cost of halting deforestation in the Brazilian Amazon has been previously estimated as USD $5.5 billion to $18 billon within an assumed 10-year-long program (59) (2009 values inflated to 2015 and applied a 5% and 2% discount rate, respectively). Moreover, the restoration of at least half of the already deforested area [381,232 km^2 in 2014, representing 7.6% of the Brazilian Amazon (60)] would cost between USD $22 billion and $46.2 billion (on a time horizon of 10 years, with 5% and 2% discount rates applied to low- and high-end estimates, respectively), with landscape benefits accruing to as much as four times that value over a 50-year period (57).

A realistic first-order estimate on the overall costs of feasible actions for mitigating the AFD by increasing forest resilience (including only stopping deforestation and restoring a large fraction of the deforested area) would lie in the range between USD $27.5 billion and $64.2 billion, but the efficacy of these measures in mitigating an AFD-like event is currently unknown.

Action Now—Adaptation

As a consequence of the uncertainties surrounding the AFD and our limited knowledge of its potential socioeconomic impacts, there has not been any dedicated research about adaptive actions that could effectively alleviate its impacts on Amazonian society, economy, culture, and conservation systems. Despite the uncertainties involved in the likelihood and impact of the AFD, "no-regrets" adaptation actions (61) could diminish the problems faced today by Amazonian society and bring about benefits, even if severe climatic change and its effects on the forest do not materialize in the future. We suggest here an initial list of 20 key no-regrets measures aiming at adaptation to a potential AFD, as well as an initial estimate of costs for their implementation. Their efficacy, precise costs, wider benefits, and methods for implementation are yet to be subject to in-depth investigation. Given that the impacts of AFD would bring consequences in nonforest areas (such as croplands), urban livelihoods, and people's health, some of the proposed adaptation actions go far beyond forest management interventions (*No Action/Action Later—Impacts on the Amazonian Socioeconomy*). These 20 adaptation measures are first presented here in a concise way but are further discussed in *SI Appendix*, alongside with the assumptions used to calculate a first-order estimate on their implementation costs.

Agriculture. (*i*) Reduce the vulnerability of farming with better (early) warning systems for droughts and floods, enabling farmers to adapt management or to allow subsistence communities to prepare accordingly. This should be accompanied by the development and/or usage of warmer–drier-climate crop varieties and livestock adapted to such conditions, including those used in subsistence farming or even nonconventional alimentary plants. Many of these varieties are known by local small-scale farmers but are neither widely used nor have been systematically assessed with regard to what extent they can endure climatic extremes. (*ii*) Implement strong incentive policies/campaigns that stimulate a "no-fire" culture across the Amazon, both in the outskirts of urban areas and distant rural areas, jointly with the development of low-tech

Table 1. Direct quantifiable and nonquantifiable socioeconomic impacts incurred by (moderate and extreme scenarios of) a climate-driven degradation of the Amazon forest

Sector	Nature of losses	Quantifiable direct loss (10^9 USD$)	Nature of gains	Quantifiable direct gain (10^9 USD$)	Nonquantifiable impacts	Confidence level
Agriculture	Long-term effect of 1 to 20% decrease of crop yields on Amazonian agricultural 2015 GDP; 10 to 50% effect on value of La Plata basin agriculture that is dependent on Amazon-originated rainfall	18 to 233	"Drier climate" cultivars replacing low yield crops. Agriculture occupying previously protected areas (1 to 10% increase in agricultural GDP)	4.6 to 67.2	Medium/high: food security of small-holder farmers to be affected	Medium
Fisheries	5 to 30% long-term reduction of fishing stocks and/or diversity, including reduction of productivity in aquaculture	0.2 to 1.9	Short-term (three years) increase (5 to 30%) of fishing yield	0.04 to 0.24	High: income and/or subsistence of large number of fishermen affected	Medium
Transport & livelihood	10 to 30% long-term reduction of shipping activities in the Madeira waterway	0.3 to 1.3	(See energy & infrastructure gains)	—	High: no access to goods, education, health for people outside large urban centers	Low
Energy & infrastructure	10 to 50% long-term reduction of the hydroelectric potential of plants in operation and planned	30 to 220	Relaxation of standards for the implementation of infrastructure, such as roads, ports, and railways affecting 1 to 20% of IIRSA projects	0.05 to 1.06	Medium: loss of energy potential affects a relatively small number of Amazonians; generation of jobs; impacts of new infrastructure for forest dwellers	Medium
Ecosystem services	Loss of ecosystem services value in 30 to 50% of basin area (carbon stocks; water quantity and quality; biodiversity; others)	2,529 to 7,701	Maintenance of same ecosystem services but with values typical to Cerrado savannah in 30 to 50% of basin area	1,616 to 4,499	Medium: relative loss of ESS affecting a limited number of people	Medium
Cities & migration	Migration of people in the Manaus polygon to Manaus and Boa Vista	Not quantified	None	—	High: migrants occupying marginal spaces and vulnerable jobs in major cities	N/A
Health	Treatment costs of long-term higher incidence of malaria (5 to 15%) and respiratory diseases (20 to 50%)	0.03 to 0.13	None	—	High: diseases affecting people's ability to carry out their day-to-day activities	High
Total (no ESS)		49 to 456		4.7 to 68.5		
Total (with ESS)		2,578 to 8,157		1,621 to 4,568		

Long-term refers to a period of 30 years. Dieback extent of 30% and 50% of current forest area and discount rates of 5% and 2% are applied to lower- and upper-end estimates, respectively. The confidence level of quantitative estimates based on the share of peer-reviewed data used to derive estimates is also shown. See *SI Appendix* for methods employed to assess cost estimates. ESS, ecosystem services; GDP, gross domestic product; IIRSA, Initiative for the Integration of the Regional Infrastructure of South America. A dash is placed in the financial estimate of sectors for which a positive impact could not be identified, or is considered together with another sector (Transport & livelihood and Energy & infrastructure).

solutions that can substitute for the role of fire in these areas. This would concomitantly lead to a reduction in the incidence of respiratory diseases. (*iii*) Restore forests and diversify agricultural/agroforestry production in deforested landscapes as a way of making farmers more resilient to future climate extremes.

Fisheries. (*iv*) There should be well-planned management of fishing stocks with stricter control over the amount caught seasonally/annually. (*v*) Further develop fish farming technology, including other fish species resistant to a future warmer climate. Such technology should aim at sustainable standards: e.g., by minimizing water pollution and sourcing fish feed from low-impact sources.

Transport & Livelihood. (*vi*) Improve basic infrastructure and services (e.g., health care and schools) in smaller cities to reduce dependence on the navigability of rivers during drought crises. This could include the implementation or maintenance of local facilities dedicated to the storage of goods. (*vii*) The environmental impacts and financial demands of any intervention on major rivers (such as dredging) could be minimized or avoided, for example, with the use of ships adapted to navigate in shallow waters.

Energy & Infrastructure. (*viii*) Energy provision planning should consider the effects of climate change and potential alterations of the hydrological cycle. This could include the planning and implementation of multiple-use water reservoirs near urban areas, with the aim of securing water and energy provision during drought extremes. (*ix*) Decentralize energy sources across Amazonia, focusing on small-scale hydro- and solar-powered energy plants. (*x*) Expand energy saving policies and incentives, starting with more efficient air-conditioning (see measure *xvii*) and the insulation of buildings (*SI Appendix*, Fig. S2).

Other Ecosystem Services. (*xi*) Improve the governance and planning of water resources in the region: for example, through subsidy-oriented water-saving policies and full implementation of water basin management committees across the Amazon. (*xii*) Develop innovative practices for planning, implementation, and management of protected areas in the Amazon, which consider that the ecosystems within them may be deeply altered by climatic changes. (*xiii*) Long-term projects in the scope of carbon storage-based policies [e.g., Reduction of Emissions from Deforestation and Forest Degradation (REDD)] should account for a potentially reduced sink or even a source of carbon from the standing Amazon forest to the atmosphere in the coming years/decades. In that sense, new biotechnological pathways for the active capturing of atmospheric carbon by the forest could be explored. (*xiv*) Accelerate the implementation of genetic and traditional knowledge databases aiming at securing the sustainable usage of biodiversity for industrial purposes. Harness biological and biomimetic assets of the forest with the assistance of modern technologies.

Cities & Migration. (*xv*) Implement community disaster/emergency aid management nuclei throughout the Amazon. (*xvi*) Minimize disorderly occupation and optimize the transportation systems of the metropolitan areas. The master plans of cities should not only be reviewed but also enforced, with strong citizen participation. (*xvii*) Set up incentives to increase the greenness of cities or other low-energy cooling solutions (e.g., clean open water bodies and better building materials) that would reduce the need for air-conditioning while improving people's well-being. (*xviii*) Develop well-elaborated emergency evacuation plans to be used when other measures are insufficient to guarantee people's safety and living conditions.

Health. (*xix*) Develop participatory campaigns to eliminate at least the peaks of incidence of vector-borne diseases (i.e., malaria and dengue fever) seen during climatic extremes. (*xx*) Eliminate open-air sewage as a way to reduce the spread of water-borne diseases during climatic extremes, improving urban quality of life in general.

Overall first-order estimated cost for the implementation of these 20 measures is USD $122 billion in NPV, or 3.6% of annual GBAP if amortized over a period of 30 years (even though many of these actions could be executed in a period of 10 years or fewer). A summary of the costs for each individual action is shown in *SI Appendix*, Table S2 (except for actions *xii* and *xiii*, the costs of which are not determined in this study). Although certain, the benefits originating from several of these adaptation measures are intricate (actions may permeate and feed back in different socioeconomic sectors) and/or intangible (e.g., action *xvii*). Nevertheless the quantification of these benefits, not carried out here, could reveal that many of these are in fact cost-neutral measures, making them even more attractive as AFD response actions. It is crucial, however, that further investigation of such adaptation possibilities is carried out in a participatory way, involving actors of different social instances. This kind of multisector mitigation/adaptation-oriented governance (e.g., cutting access to credit to deforesters, creation of public protected areas, soybean sector moratorium on deforestation) has been successful in reducing Brazilian Amazon deforestation by 76% from 2004 to 2017 (62, 63). Such an experience suggests that a latent capacity exists, at different governmental and societal levels, to tackle mitigation and adaptation to the large-scale degradation of the Amazon forest caused by climate change.

Filling Research Gaps to Constrain the Risk

The AFD hypothesis is now nearly 20 years old, and, given the uncertainties surrounding its likelihood and impacts, it is not surprising that it has not since then permeated governance debates or public policies. We need to articulate guidelines for future research that can change this situation, both in terms of reducing uncertainties and helping to put this critical topic on the political agenda. It is not only unfulfilled scientific curiosity that is at stake with such a knowledge gap but also the fate of at least ~30 million

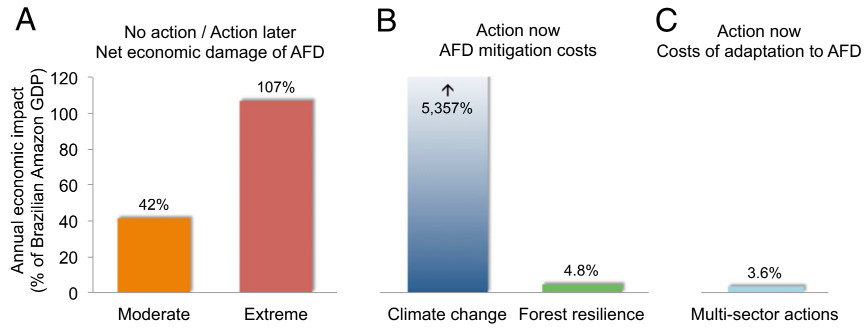

Fig. 3. Comparative quantifiable costs of (*A*) the net socioeconomic damage of moderate and extreme large-scale degradation of the Amazon forest caused by climatic change (AFD) considering nonmarket value ecosystem services, (*B*) AFD mitigation costs, split into mitigation of AFD cause—global climate change—and mitigation through the strengthening of Amazon forest resilience (the latter has high uncertainty regarding the efficacy of the proposed actions), and (*C*) estimated cost for the implementation of the 20 adaptation actions mentioned in the text. Moderate (extreme) estimates in *A* make use of a discount rate of 5% (2%) and a carbon value of USD \$5/tCO_2eq (\$20/tCO_2eq) (metric tons of carbon dioxide equivalent). An upper-end discount rate of 2% is used in *B* and *C*.

people that directly or indirectly depend on the forest for their well-being.

The major insights derived from this first-order assessment are as follows:

i) The likelihood of occurrence of an AFD is not sufficiently understood, and, as such, it is premature to rule it out, especially in view of recent observational data.

ii) If no action is taken or if action is postponed, there will be considerable socioeconomic losses, which are estimated to be more pronounced than the eventual gains under an AFD-like future, making AFD a high-risk event.

iii) Costs of acting now to curtail the impacts or to mitigate the AFD are lower than the socioeconomic losses involved in a "no action or action later" pathway (Fig. 3). This is true even including the uncertainties in the estimated cost of adaptation and at triple its total value.

iv) Even though reachable mitigation options have a cost that is comparable with the set of adaptation measures, their efficacy in increasing forest resilience to the point of preventing AFD is highly uncertain. The efficacy of adaptation measures in reducing the socioeconomic impacts is also yet to be determined. However, the essence of these adaptation measures being no-regrets implies that they would be beneficial (and maybe cost-neutral), even if the AFD does not occur, as they would make both the ecosystem and society more resilient and safe.

However, many uncertainties that hinder an objective and well-informed choice of action to be taken remain to be addressed. We suggest that efforts to move beyond the fragmented knowledge represented by the aforementioned IPCC-AR5 statement on the AFD (4) should be catalyzed via a research agenda for constraining the risk of the AFD and increasing the resilience of the Amazon system to climate change.

If we are to make robust assessments of actions to take or not take regarding AFD, then we have to focus on improving our understanding first of the ecological susceptibility of the Amazon forest to climate change and eCO_2. In that sense, it is crucial to obtain ecosystem-scale experimental evidence on the effects of elevated atmospheric CO_2 on Amazon forest functioning, structure, and composition. Experimental evidence is also needed on the limitation of forest productivity by phosphorus and possibly other nutrients, as well as the concomitant interplay of these processes with increased atmospheric temperature and changing rainfall. The Amazon Free-Air CO_2 Enrichment (FACE) experiment and the Amazon Soil Fertilization Experiment (AFEX) in central Amazonia, as well as the continuation of other long-term monitoring experiments (e.g., the throughfall exclusion drought experiments and forest inventory networks), will help advance our understanding of these relationships (64).

Second, as our knowledge of the susceptibly of the forest to climate change advances, we will be able to better anticipate the impacts of such climate-driven alterations of the forest on the Amazonian socioeconomy. In this regard, the most urgent research questions are to understand the ecological processes that determine ecosystem services supply and quantify the costs incurred in securing such a supply. Additional questions would include the impacts of AFD on agriculture, on the generation of hydroelectric energy, and the associated social consequences such as regional migration.

Such scientific advancement is necessary to support participatory research on the most adequate mitigation and adaptation measures that could be taken to avoid AFD or reduce its impacts within and outside the Amazon. To achieve this, we must pay attention to understanding the feasibility, efficacy, and financial costs and benefits of the mitigation and adaptation actions discussed in *Action Now—Mitigation* and *Action Now—Adaptation*. It is yet to be determined, for example, whether the complete curbing of deforestation would make the forest sufficiently resilient to climate change or if the recovery from current forest degradation levels could largely revert the forest–savanna bistability currently observed in Amazonia (34). On the other hand, assessing the feasibility and efficacy of adaptation measures may demand innovative ways for on-the-ground testing of alternatives, taking advantage that current droughts in the region can be predicted several months in advance (26)—allowing the planning of intervention-prone research on climate change adaptation.

In light of these needs, it becomes clear that any future research program related to climate change in the Amazon must include the intrinsic connections between the natural and social sciences. This integrated research agenda should be regarded as a major scientific ambition for the region in the years to come, given the potential impacts on vulnerable populations and the enormous latent economic potential of the world's largest tropical forest.

Acknowledgments

We thank A. Cattaneo, E. D. Assad, M. L. Ruffino, L. E. O. C. Aragão, P. J. B.Santilli, T. Jacaúna, and D. R. Braga for helpful suggestions and comments on the manuscript. This study was funded by the Inter-American Development Bank through a technical cooperation agreement with the Brazilian Ministry of Science, Technology, Innovation and Communications (Grant BR-T1284), by Brazil's Coordination for the Improvement of Higher Education Personnel (CAPES) Grant 23038.007722/2014-77, by Amazonas Research Foundation (FAPEAM) Grant 2649/2014, by São Paulo Research Foundation (FAPESP) Grants 2015/02537-7, 2014/50627-2, and 2014/50848-9, by Brazil's National Council for Scientific and Technological Development (CNPq) Grants 465501/2014 and 458020/2013-3), and by Serrapilheira Institute Grant Serra-1708-15574.

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