Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm

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For half a century, the process of economic integration of the Amazon has been based on intensive use of renewable and nonrenewable natural resources, which has brought significant basin-wide environmental alterations. The rural development in the Amazonia pushed the agricultural frontier swiftly, resulting in widespread land-cover change, but agriculture in the Amazon has been of low productivity and unsustainable. The loss of biodiversity and continued deforestation will lead to high risks of irreversible change of its tropical forests. It has been established by modeling studies that the Amazon may have two "tipping points," namely, temperature increase of 4 °C or deforestation exceeding 40% of the forest area. If transgressed, large-scale "savannization" of mostly southern and eastern Amazon may take place. The region has warmed about 1 °C over the last 60 y, and total deforestation is reaching 20% of the forested area. The recent significant reductions in deforestation—80% reduction in the Brazilian Amazon in the last decade—opens up opportunities for a novel sustainable development paradigm for the future of the Amazon. We argue for a new development paradigm—away from only attempting to reconcile maximizing conservation versus intensification of traditional agriculture and expansion of hydropower capacity—in which we research, develop, and scale a high-tech innovation approach that sees the Amazon as a global public good of biological assets that can enable the creation of innovative high-value products, services, and platforms through combining advanced digital, biological, and material technologies of the Fourth Industrial Revolution in progress.

Amazon tropical forests | Amazon sustainability | Amazon land use | Amazon savannization | climate change impacts

A number of complex problems threaten our geopolitical, environmental, social, and economic stability: the links between global food and energy markets; the unsustainable depletion of natural resources and biodiversity stocks; the increasing water insecurity around the world; and, above all, the urgent need both to decarbonize the energy systems of the world to avoid catastrophic climate change and to adapt to unavoidable climate change underway. The scale and reach of the risks associated with climate change, together with their potentially irreversible nature, make this probably the greatest market failure and the starkest example of a "tragedy of the commons" the world has ever seen. To put this comparison in perspective, the net benefit to the world economy of a 50% reduction of tropical forest deforestation and degradation has been estimated at US $3.7 trillion (1).

Of particular importance is the continued deforestation in the Amazon, which could lead to the irreversible change of its tropical forests (2, 3) and the major loss of its biodiversity (4). The Amazon ecosystems harbor about 10 to 15% of land biodiversity (5, 6); its abundant rainfall of about $2.2\ \mathrm{m \cdot y^{-1}}$ makes the region an important heat source for the atmosphere (7), generating an estimated $210{,}000\ \mathrm{m^3 \cdot s^{-1}}$ to $220{,}000\ \mathrm{m^3 \cdot s^{-1}}$ of river discharge (8, 9), which is ~15% of the freshwater input into the oceans (10); it stores an estimated 150 billion to 200 billion tons of carbon (11–15); and it presents a mosaic of ethnological and linguistic diversity (16, 17).

A number of large-scale drivers of environmental change are operating simultaneously and interacting nonlinearly in the Amazon, namely, land-use change and climate changes due to global warming and to deforestation, which may, in turn, induce higher frequency of extreme climate events and of vegetation fires, adding to increased tropical forests' exposure and vulnerability. Our scientific understanding has increased about the risks associated with these drivers of change acting synergistically (18, 19). By and large, environmental change in the region is a response to the global economy. Global market demand growth for animal and vegetable protein (20–22), new transportation and energy infrastructure projects (23), and weak institutions (24) can be cited as some of key drivers in this process.

The prevailing model for rural development in the Amazon over the last half century—replacing forests with agriculture, cattle ranching, and large-scale hydropower generation—has long been outdated for a number of environmental, economic, and social reasons (25–27). For instance, for Brazil, the gross agricultural product of the Amazon represents 14.5% of Brazil's agriculture sector gross domestic product (GDP), using a deforested area of about $750{,}000\ \mathrm{km^2}$. In contrast, São Paulo state accounts for 11.3% of the agriculture sector GDP, using an area of approximately $193{,}000\ \mathrm{km^2}$ (see Tables S1–S3 in *Datasets Used to Derive Agricultural Sector GVA for the Brazilian Amazon*). The conclusion is

Significance

The Amazonian tropical forests have been disappearing at a fast rate in the last 50 y due to deforestation to open areas for agriculture, posing high risks of irreversible changes to biodiversity and ecosystems. Climate change poses additional risks to the stability of the forests. Studies suggest "tipping points" not to be transgressed: 4° C of global warming or 40% of total deforested area. The regional development debate has focused on attempting to reconcile maximizing conservation with intensification of traditional agriculture. Large reductions of deforestation in the last decade open up opportunities for an alternative model based on seeing the Amazon as a global public good of biological assets for the creation of high-value products and ecosystem services.

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inescapable: Over 50 y of a deforestation-based development model have not resulted in wealth creation or better quality of life for those living in the Amazon—the Amazônidas (28, 29). Moreover, in terms of development policy pathways for the Amazon, two modes have historically dominated: (*i*) a valuable nature conservation approach with large swathes of territory legally protected from any economic and human activity outside indigenous peoples and (*ii*) an approach that has focused on conversion or degradation of forests for the production of either protein commodities or tropical timber at the forest frontier and the build-out of massive hydropower generation capacity—which, together, have been historically responsible for massive deforestation of the Amazon (30, 31) and generated other significant negative externalities. We argue therefore that there is a "Third Way" within reach that sees the Amazon as a global public good of biological assets and biomimetic designs that can enable the creation of innovative high-value products, services, and platforms for current and for entirely new markets.

It is urgent to halt deforestation, keeping in mind that almost 1 million square kilometers of the Amazon tropical forests have already been deforested and another equal portion finds itself in the process of degradation (27). The rate of deforestation has declined in the last several years; this decline is conspicuous in the Brazilian Amazon, where deforestation rates have been cut down by almost 80% since 2005 (32–34) at the same time that the agricultural output in the region has been increasing significantly (35). It is therefore becoming clear that economic growth is decoupled from deforestation as demonstrated by ample facts, such as the case of the reduction of deforestation rates observed between 2005 and 2014, which are opposed to the growth of the values of agricultural gross value added (GVA) in North Brazil, which almost tripled during this period (32). Since 2005, deforestation rates in Brazilian Amazon have decreased from almost 30,000 km^2·y^{-1} to a rate of around 6,000 km^2·y^{-1}, on average, from 2011 to 2015 (33), indicating the difficulties of zero deforestation targets (36). This sharp decline of deforestation was enabled by several factors, including purpose-built satellite monitoring capabilities, effective law enforcement and compliance, industry value chain initiatives like the soy moratorium, restrictions on access to credit for farms located in deforested areas, and expansion of protected areas and indigenous territory encompassing 47% of the entire Brazilian Amazon region (37). Long-term-demand growth for agricultural commodities in the emerging markets, weak institutions, and large energy infrastructure projects may potentially contribute as underlying and proximate drivers to the return of high deforestation rates in the absence of alternative development pathways (27, 30, 38–40).

The present economic scenario continues to conspire against the Amazon by placing a higher premium on agricultural commodities such as soybeans, meat, and tropical timber than on standing forests. The long-term success of antideforestation policies must rest on firmer ground besides command and control measures to curb illegal deforestation.

The challenge, therefore, is to reconcile the current development model with a new paradigm for sustainable development of the Amazon. A corollary to this greater challenge is the urgent need to deploy a high-tech innovation ecosystem approach to serve as the basis for this new model of sustainable development for the Amazon.

In this review, we assess scientific knowledge on climate variability and extremes, on anthropogenic drivers of environmental change in the region, and on the impacts and risks for the future of the tropical forests, and we propose a paradigm for the sustainable development of the Amazon, a model that intrinsically depends on the existence of the forests.

Climatic Variability and Extremes, and the Lengthening of the Dry Season

Precipitation Variability and Extremes. A suite of geographical, geomorphological, and climatic factors makes the Amazon basin an area with high precipitation. The average basin-wide annual precipitation is on the order of 2,200 mm, ranging from 3,000 mm in the west, due to the influence of the Andes, to values around 1,700 mm over the southeast of the basin, areas of intense land-use and land-cover change, known as "deforestation arc" (41). High precipitation rates are maintained both by moisture flows from evaporation in the tropical Atlantic Ocean and by forest evapotranspiration (ET) recycling (7, 42). Precipitation seasonality varies markedly across the basin: minimum monthly precipitation of >150 mm·mo^{-1} and short or absent dry season in the west and northwest, in contrast to a very seasonal regime in the south and southeast with longer dry seasons (>4 mo with monthly values of <100 mm) (43, 44). Given average forest ET of 3.5 mm·d^{-1} to 4 mm·d^{-1} (45), below about 100 mm·mo^{-1} of precipitation, ET is assumed to exceed incoming precipitation, and the forest is in water deficit (46).

Precipitation pattern in the Amazon basin has a strong interannual and interdecadal variability, largely influenced by fluctuations in sea surface temperature (SST) of the tropical Pacific (related mostly to El Niño−Southern Oscillation) and tropical Atlantic (Atlantic "Dipole" Mode) Oceans. Severe droughts are associated, in general, with the occurrence of strong El Niño events affecting mostly the central and eastern portions of the Amazon, as was the case in 1906, 1912, 1926, 1983, 1992, 1998 (47), and 2015 (33). On the other hand, the warmer tropical North Atlantic and cooler tropical South Atlantic affect also the west and northwest of the basin and were responsible for the severe droughts that occurred in 1964, 2005 (48), and 2010 (49), which was recognized as one of the strongest and extensive droughts of recent decades: The 2005 drought affected about 1.9 million square kilometers, whereas the 2010 drought affected around 3 million square kilometers (50).

Although droughts and floods are part of the Amazon natural climate variability, the extreme drought and flood events that took place in the past decade (2005, 2010, and 2015 droughts; 2009 and 2012 floods) have been unusual and may have long-term implications. Global warming is projected to increase the frequency and even the intensity of extreme events (51). Drought extreme events have the potential to increase the mortality of forests, and the synergistic association between severe droughts, deforestation, and fire can be highly deleterious to the Amazon forest (see *CO$_2$ Fertilization and Forest Mortality*).

The Lengthening of the Dry Season. Another important aspect of the functioning and maintenance of the Amazon forest is the dry season length being shorter than about 4 mo. There is growing evidence of lengthening of the region's dry season, primarily over southern and southeastern Amazon (49, 52, 53). The reasons for this lengthening are still not very clear. It has been suggested that large-scale influence of SST gradients of the North and South Atlantic (49, 54, 55), or a strong influence of dry season ET (56, 57), in response to a seasonal increase of solar radiation (58), may play a role.

In particular, this apparent lengthening of the dry season has been quantified: The dry-season length has been observed to have increased [(6.5 ± 2.5) days per decade] over southern Amazonia since 1979, primarily owing to a later onset of the wet season, and is accompanied by a prolonged fire season (53). These changes cannot be simply linked to the interannual variability of the tropical Pacific and Atlantic Oceans and may indicate that, in addition to the moisture transports from the oceans, soil moisture from continental areas could act as an important precondition for the onset of the wet season (59–61).

Therefore, understanding the forests' ability to maintain high ET rates during low-precipitation periods is an important element to better understand not only the drought-forest response, but also aspects that influence the transition from dry to wet season.

Seasonal Variability in ET. Considering a wide range of climate variability patterns in the Amazon, it could be expected that other hydroclimatic variables also exhibited a large spatial and temporal variability. In fact, it is known that seasonal and interannual variations of the ET in tropical forests are mainly controlled by variations in the light (radiation) and soil moisture (62). Data from flux towers installed in the region as a result of the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) and the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) indicated the occurrence of ET rates as high in the dry season as in the wet season (45). However, in regions such as eastern and southern Amazon, this was not the case (63). From data obtained from the LBA flux towers networks, it was observed that, in experimental sites where the average annual rainfall exceeds 1,900 mm and the average dry season length is less than 4 mo (e.g., Manaus, Santarém, and Rondônia), ET rates tend to increase in the dry season in response to an increase in solar radiation, reaching values of around 4 mm, similar to wet season ET values (64). On the other hand, regions with average annual rainfall below 1,700 mm and longer dry seasons (>4 mo), such as in southern and southeastern Amazon, showed clear evidence of decreasing ET during the dry season, with maximum values of around 2.5 $\text{mm}\cdot\text{d}^{-1}$. A similar threshold of close to 2,000 mm of annual rainfall was identified in the photosynthesis and ET patterns along the Amazon forest and for tropical forests in Africa and Asia (65). In regions where the annual rainfall is above this value, water stored in the soil during the wet season seems to be able to supply ET and photosynthesis for the subsequent dry season. However, this normally is not the case for regions where the average annual rainfall is below this value, highlighting a clear spatial and seasonal pattern of ET and photosynthesis variability (66). The ET's controlling mechanisms also varied over this rainfall gradient, with climate demands (particularly radiation and vapor pressure deficit) controlling ET rates in wetter areas and soil moisture deficit controlling ET in the driest areas (64).

Due to the Amazon's huge dimension and diversity, some Amazon regions could present high values of ET during the dry season even when annual precipitation, on average, is smaller than 2,000 mm. In Paragominas, for example, at the northeast flank of the Amazon, the mean annual precipitation of 1,800 mm can sustain high ET rates even during a dry season lasting for about 5 mo (67). Storage of water in deep, clay-rich soil layers may presumably be the reason for maintenance of ET in periods of absence of rain (67–70).

Despite some exceptions, in general, the driest regions in the Amazon are found in the southern and southeastern portions, presenting a climate pattern similar to a savannah, where the vegetation responds with loss of leaves and dormant state in response to water stress of the prolonged dry season (64). This region, known as the "Arc of Deforestation," is experiencing heavy anthropogenic change and could be presenting signals of change in the equilibrium state, in the sense of the prevalence of a dry vegetation type (71).

Climate Change: Global and Regional Perspectives

Global Climate Change. Climate change resulting from increased emissions of greenhouse gases, and from other anthropogenic forcings, has the potential to increase air temperature and cause complex changes in precipitation patterns (51). Despite the importance of understanding how climate affects the structure and functioning of the tropical forest as we know it today, it has not been an easy task to identify current and plausible future changes in climate variables—especially those related to the hydrological cycle—in these regions. For the Amazonian forest, this difficulty is due, in part, to the scarcity of historical data and, in part, to the natural variability of precipitation (72).

The Amazon—similarly to all continental areas of the world—has warmed about 1 °C during the last century (51, 73, 74). The temperature increase was more pronounced since the 1970s and was attributed to the global temperature increase caused primarily by greenhouse gas emissions (51, 75, 76). Temperature increases are more pronounced in deforested areas during the dry season and can reach between 1 °C and 1.5 °C, on average, solely due to the effect of deforestation, because the surface energy budget is altered and sensible heating is higher for areas covered with pastures in the Amazon (77).

It has been more difficult to identify long-term changes in rainfall patterns in the Amazon. This is due to the large natural variability, relatively small number of weather stations, and important gaps in time series (72, 78). To complement these studies, some assessments have been based on river discharge data, rather than precipitation, due to their better integrative nature and dataset consistency (79, 80). Although some studies indicated a decreasing trend in rainfall (drying) in the Amazon, in recent decades (80–83), others pointed to a wetting trend for the region, as a result of an intensification of the hydrological cycle (79, 84, 85). These wetting trends (up to 80 $\text{mm}\cdot\text{mo}^{-1}$ in the period 2000–2009 compared with period 1981–1990) are not homogeneously distributed around the basin, and they tend to occur during the wet season over the northwestern part of the basin. On the other hand, the decreasing wet season rainfall trend (-20 $\text{mm}\cdot\text{mo}^{-1}$ for the same period) was observed in the southern and southeastern parts of the basin (79).

Precipitation reductions observed in the last two decades over southern and southeastern Amazon cannot, as yet, be fully explained, but one possible explanation could be the effects of extensive land-use change in this region and relative changes in the albedo (79, 86). The increasing precipitation trend observed during the rainy season was attributed to a gradual warming of the tropical North Atlantic SST and the resulting increase of water vapor supply from the ocean toward the continent (79). The influence of the tropical North Atlantic SST anomalies, however, is more gradual and has a different pattern from that observed during 2005 and 2010 droughts, when North Atlantic SST anomalies resulted in changes in the Intertropical Convergence Zone (ITCZ) position (79). The important point here is that, even for wetter conditions, the southern and southeastern Amazon forest presented drying trends in the last two decades. Observed interdecadal trends in precipitation (87) have been associated with natural climate variability—somewhat different from the apparent lengthening of the dry season in Amazonia—and sharp shifts in precipitation patterns in the mid 1940s, 1970s, and 2000s are likely linked to phase shifts of the Pacific Decadal Oscillation (72, 80, 88, 89).

In summary, the observed absence of a significant long-term trend in Amazon river discharge—a proxy of basin-wide precipitation variations—highlights the difficulty of detecting clear long-term, anthropogenic climate change impacts in precipitation. In contrast, the observed increase in the frequency of extremes over the past decade (see *Precipitation Variability and Extremes*) could be an early manifestation of global climate change (90), because there have been both positive and negative precipitation extremes, which, however, did not alter significantly the long-term basin-wide averages.

Tropical Deforestation and Regional Climate Change. Deforestation can affect vegetation through changes in the regional climate. Modeling studies suggest that a decrease in the ET rates and an increase in atmospheric temperature were caused by the large-scale replacement of the Amazon forests by pasture (7, 91, 92). It is estimated that these changes will lead to changes in local precipitation patterns, but how large these changes will be is still uncertain. Small-scale deforestation can lead to an increase in local precipitation by the so-called "wind effect" (93, 94). On the other hand, large-scale deforestation may act to decrease the precipitation rate. Increases in nonprecipitation clouds and a decrease in the dry season precipitation have been observed over deforested areas in Amazonia (95). Modeling studies simulating the rainforest replacement by pasture also showed a decrease in rainfall with an increase in deforested areas (7, 91, 92, 96–98). The extent of total deforested area also matters, with greater effects occurring for deforested areas exceeding 40% of the total area covered by forests (91). Complete deforestation could cause eastern Amazonia to warm by more than 3 °C, and precipitation from July to November could decrease by up to 40%. Crucially, these changes would be in addition to any change resulting from global warming.

Regional climate models with higher spatial resolution (25-km grid) project a smaller decrease of regional precipitation ($-62\ \mathrm{mm \cdot y^{-1}}$) for a complete deforestation scenario (96). Some regional models also show that low levels of deforestation (up to around 20%) increase calculated precipitation over the deforested area as a result of a heterogeneous heating of the land surfaces, which increases mesoscale convection ("vegetation breeze") and cloud formation (96, 99). However, the importance of this effect varies according to the size and pattern of the deforestation patches (100) as well as the model considered. Most regional models agree that the effect of the vegetation breeze vanishes beyond a certain area of deforestation (around 30%) for which a decrease of regional precipitation is expected, especially during the dry season (99, 101). It is important to highlight that examples of land-use change that has been sufficiently widespread to detect its effect on river discharge over and above the effects of interannual variation or trends in precipitation patterns are currently limited to watersheds that were dominated by neighboring Cerrado vegetation, with only small fractions of Amazon forest vegetation (102, 103). It may be necessary to have a similar magnitude of land-use change in forest-only subbasins of the Amazon in order for its effect to be unequivocally established.

A key to risk analysis for the maintenance of the Amazon ecosystems is that the impacts of deforestation are greater under drought conditions, as fires used for forest clearance frequently get out of control and burn larger areas (see *Extreme Droughts, Deforestation, and Fire*). The impact of land-use change on simulated precipitation and temperature occurs primarily during the dry season and in regions of relatively low annual mean precipitation, projecting precipitation reductions and temperature increases (104). Reducing deforestation may help to boost forest resilience under a changing climate. Forest fires, drought, and logging increase susceptibility to further burning, and deforestation and smoke can inhibit precipitation, exacerbating fire risk (see *Extreme Droughts, Deforestation, and Fire*). The likely continuation of strong El Niño episodes (e.g., 1997−1998 and 2015–2016 episodes) into the near future and the possibility that the pattern of intense Amazon droughts seen in the last decade continues into the future, keeping business as usual policies, means that a large fraction of the forest will be cleared, logged, damaged by drought, or burned in the next few decades (105).

In sum, we can say that reducing deforestation could minimize these impacts as well as mitigate emissions of greenhouse gases. It has been suggested that there may be thresholds or "tipping points" that should not be transgressed for the maintenance of the Amazonian tropical forests: 40% of area deforested, beyond which forest loss causes climate impacts that cause further forest loss (91); global warming of 3 °C to 4 °C may also lead to a similar tipping point (106, 107). Although the existence of these tipping points still requires further research, interaction between climate change due to global warming and due to large-scale deforestation may make them more likely.

In sum, the observations of changes in hydroclimatic factors (e.g., the lengthening of the dry season and the enhanced occurrence of precipitation extremes)—added to global warming scenarios of increased temperatures and continued deforestation and forest fires—may wreak havoc on the stability of tropical ecosystems (see *Third Way as Paradigm of Sustainable Development for the Amazon*).

Impacts of Anthropogenic Drivers of Change in the Amazon

Extreme Droughts, Deforestation, and Fire. Despite coming from different anthropogenic drivers, which act upon different scales, deforestation and extreme drought events may damage tropical forest ecosystems in an analogous way: Both have the potential to enhance mortality selectively, creating degraded areas in which the equilibrium state of the humid forest can be disrupted.

A great number of studies and advances were made in recent decades, to better understand the impacts of drought extreme events on tropical forests. However, important questions still remain. In fact, the ability of some areas of the Amazon rainforest to maintain high ET rates and, eventually, keep growing or begin leaf flushing (108) during the dry season does not guarantee that humid forest could be resilient to extreme and prolonged droughts. In situ observations of the impact of "natural" extreme droughts (109) and artificially induced droughts for several years (110–112) showed that forest responds with interruption of growth and mortality of some species during a prolonged drought period. The results of artificially induced and natural droughts have shown that the larger trees [diameter at breast height (dbh) $>$ 30 cm], together with lianas, are the most vulnerable ones (112). This behavior is contrary to the hypothesis, previously assumed, that the larger trees would be more resilient to droughts as a result of a deeper root system, allowing them to capture water from the deeper soil layers as a drought survival strategy. It was observed, however, that these large trees could be under water stress due to a significant exposure to solar radiation, eventually dying by cavitation and embolism (113) during extreme droughts.

The vulnerability of the larger trees is a critical aspect of forest functioning and maintenance. It implies that droughts can act selectively, changing species composition and endangering local biodiversity (109). In addition, mortality of the highest species reduces the shading over lower canopy, litterfall, and soil. The increasing incident radiation in these areas enhances temperature and dryness, increasing vulnerability to subsequent droughts as well as to ignition sources and fire. Although the drought effects on stem growth could cease as soon as the drought finishes (3), this is not the case for tree mortality. In addition, the increase of dead biomass can result in a number of negative aspects: loss of habitat of endemic species, changes in the composition and biome structure, and changes in carbon budget and energy fluxes between the land surface and the atmosphere, besides potentially acting as a positive feedback to climate change.

Extreme events and deforestation can act synergistically in a two-way mode. Deforested areas can affect regional climate, and the regional climate, in its turn, can amplify the impact of deforestation, by increasing tree mortality far beyond the limits of the deforestation edges. In both situations, fire occurrence and spreading is greatly amplified. It has been observed that the forest fire scars in the Amazon increased substantially during extreme droughts years, particularly in the edges between intact forest and deforested areas. The association between a dry forest environment (soil and litterfall) and ignition sources from the anthropic activities (mainly the agricultural practices of slash and burn) promotes the leakage of fires toward the intact forest areas. The absence of rainfall, typical of the drought years, facilitates its propagation (46, 114–120).

Under normal conditions of high precipitation amounts and high atmospheric moisture, spontaneous occurrence of fire in the Amazon rainforest is quite rare (121). As a result, most of the local species are not adapted to fire, which hampers their recovery after recurrent burns. Forest areas submitted to successive fires over the years experience a change in the prevalence of secondary vegetation (119). Huge and successive fires have substantially increased tree mortality and favored the occurrence of short-life-cycle pioneer species. Invasive grasses observed in the burned areas act as a potential source of ignition during subsequent events of droughts, potentially indicating a change in the biome composition (71). This transition is more likely to occur in fragmented forest areas where disturbances are frequent and the dry season is longer (>4 mo to 5 mo) (71), or, in other words, at the southern region of the Amazon forest.

CO_2 Fertilization and Forest Mortality. In a CO_2-enriched atmosphere, one of the few potentially resilience-increasing aspects for forests seems to be the effect known as "CO_2 fertilization" (122). The increasing concentration of this gas in the atmosphere has been recognized as being responsible for faster growth of trees, a fact that has been proven in large-scale experiments (123–126). However, there are large uncertainties about the long-term response of the tropical forests to this effect (127), although modeling of this effect for the Amazon indicates that the impact of high degrees of climate change are attenuated, but not to the extent of avoiding forest loss (128). In a CO_2-enriched environment, the plants can respond with stomatal closure to capture the same amount of CO_2 required for photosynthesis (129). As a consequence, transpiration rates could decrease, potentially returning a lower amount of vapor to the atmosphere, or, in other words, altering ET rates (130). Ultimately, this behavior could impact precipitation in the Amazon, which, as shown above, plays an important role in generating dry season precipitation. Another unexpected unfavorable effect of CO_2 fertilization could be the increase of mortality rates of adult trees in the tropics (131).

Terrestrial ecosystems and, in particular, tropical forests have been recognized as strong carbon sinks, comparable to the oceans (132–134). However, the potential connections between sinks of carbon and the spatial patterns of soil and tree characteristics across the region are also noteworthy. In the west, younger fertile soils (135) associated with enhanced plant growth coexist with higher tree mortality, complicating the interpretation of carbon sink (13, 136). In the eastern and central portions of the region, weathered and relatively infertile soils (135) host trees that live longer and grow taller (13, 136). Although these locations may potentially stock larger carbon pools in the long term, the responses to CO_2 fertilization may be limited due to relative low nutrient availability (137). Despite uncertainties, it has been recognized that the mature forests of the Amazon store around 150 PgC to 200 PgC in their biomass (15), and the forest seems to be acting as an overall carbon sink, with assimilation rates estimated at 0.4 $PgC \cdot y^{-1}$ (109) over the recent past. Carbon stored in forests each year occurs in the form of growth of branches and trunks, new leaves and roots, and increase of soil organic matter (138). However, from field inventories carried out in 321 plots from 1983 to 2011, it was observed that the Amazon forest could be moving from a carbon sink to a carbon source ecosystem (131). Although the tree growth data confirmed the Earth's surface as a strong carbon sink, the same data show a decline in the growth rate of carbon accumulation and a one-third decline in net increase in aboveground biomass in the 2000s compared with the 1990s. Factors explaining this behavior are still not clear, but the main hypothesis is that the increase in forest productivity in recent years due to CO_2 fertilization effect could have accelerated the life cycle of trees, anticipating their death when still young (131, 139–142). To reduce the uncertainties about the effect of increasing atmospheric CO_2 concentrations on tropical ecosystems, a group of international scientists are proposing to carry out a Forest Free-Air CO_2 Enrichment-type experiment in the Amazon (143).

Impacts of Hydropower Dams in the Amazon. Major anthropogenic land-use change in the Amazon historically has been a consequence of either growing international demand for agricultural commodities or of growing energy demand domestically. In this context, the Amazon has been historically identified as a source of massive growth in hydropower capacity, and all Amazonian countries have made plans for its use in the present and in the foreseeable future. For instance, the Brazilian government has planned the expansion of hydroelectric power generation in the Brazilian Amazon to make it a large net exporter of electricity to the rest of the country. The plan calls for 30 new large dams in the next 30 y (23), with the associated flooding of ∼12,000 km^2 (144). The flooding of these areas will cause a series of environmental impacts: significant increases of greenhouse gas emissions (145), disorders to local wildlife by blocking mass fish migration patterns and changes in ichthyological diversity (146, 147), loss in connectivity between upstream and downstream (148), decreased productivity in lowland Amazon floodplains due to the retention of nutrients by reservoirs (149), hydrological alterations through the water level change (150), deforestation and degradation of forests near the reservoir (27), transmission of parasitic diseases to humans such as malaria and leishmaniasis (151, 152), social impacts with the displacement of traditional populations and indigenous peoples (153, 154), and reduction of fish catch potential (155).

Climate Change, Forest−Climate Equilibrium States, and the Future of the Amazon Forests. Taken alone, the drought impacts could be harmful enough for the ecosystem maintenance and integrity. Their joint action and the synergic effects with other anthropogenic drivers such as deforestation and fire have the potential to strongly amplify these impacts, so that the collapse of tropical rainforest (156, 157) and its transformation into a drier and impoverished savanna-like biome (7, 158) have been anticipated by computational models, and have been continuously validated by field observations. Studies in forest sites, in fact, support the assumption of a positive feedback between relatively frequent (1 to 3 y) fires and degradation (71, 115), which favor the presence of grasses and shrubs (115), secondary vegetation (119), and pioneer species that do not take long to become flammable (71). Controlled fire experiments carried out in the transition forests of northern Mato Grosso showed great incidence of lianas and tree mortality, supporting, according to the authors (71), the likelihood of "savannization" of parts of the Amazon. Depending on the scale, these changes could ultimately drive changes in the local climate, pushing the ecosystem toward a different forest−climate equilibrium state (159), that is, the one where most of the tropical forests in southern, southwestern, and southeastern Amazon are replaced by degraded savannas as predicted by models (91, 106, 158, 160). Evidence that the relationship between degraded forest, regional climate change, and a change in the equilibrium would lead to a tipping point in the Amazon region is described as a medium-confidence likelihood (161), but is already being observed in the Xingu basin (71).

At this point, it is important to assess the trends of the drivers of change conducive to savannization or forest dieback risk. In recent years, deforestation rates fell by about 80% in the Brazilian Amazon since 2005 (33). As mentioned above, the Amazon has experienced a succession of extreme climatic events since 2005 (see *Precipitation Variability and Extremes*). However, increased floods do not compensate fully for an increase of droughts in terms of forest vulnerability, especially due to increased fire frequency during droughts, which wreak havoc to forest resilience (18). This is supported by a trend of increasing observed forest mortality (131), together with the fact that forest fires have not decreased as expected (162). Another important driver is, of course, global warming. The Amazon region has experienced a temperature increase of close to 1 °C (51, 73), mostly due to global warming. It is estimated that 3.5 °C of global warming (that corresponds to about 4 °C temperature increase in the Amazon) could disrupt the forest–climate equilibrium, leading to substantial loss of tropical forests (106, 160, 161). In addition, as mentioned above, there is some observational evidence of a lengthening of the dry season in southern–southeastern Amazon, and this is the most important driver of forest transitioning to savanna as claimed by the hypothesis of Amazon savannization (7) because the climate envelope for tropical forests requires a dry season (less than 100 $\mathrm{mm{\cdot}mo^{-1}}$) no longer than 4 mo.

There have been attempts to use climate and vegetation models to quantify the impact of changes in climate due to global warming and due to deforestation on the distribution of major biomes in the Amazon as summarized in *Modeling Efforts and Advances*, including analysis (Figs. S1 and S2 and Table S4). The results show that the calculated area of tropical forest remaining, for simulations of biome distribution when only climate change forcing is considered, is about 15% smaller by 2050 for Intergovernmental Panel on Climate Change (IPCC) scenario Representative Concentration Pathway 8.5 $\mathrm{Wm^{-2}}$ (RCP8.5) in comparison with the change for scenario RCP2.6, given that the amplitude of climate change is vastly larger for the former scenario, and the effect increases in time (Fig. S1). For more drastic changes, taking into account the combined effect of climate change scenarios, regional climate change due to large-scale deforestation, and the effect of forest fire making tropical forests more vulnerable, the calculations project a substantial reduction of over 60% in the forest area in the Amazon by 2050. Most of the biome type changes occur over eastern and southern Amazon, with replacement of tropical forest by seasonal forest and tropical savanna (Fig. S2). The effect of fire in this region is important in all scenarios in further decreasing the area of tropical forest. Northwest Amazon presents the smallest changes in reduction of tropical forest, indicating that, even for substantial land-use and global climate changes, the resulting climatic conditions would still support tropical forest in that region (Fig. S2). All of the calculations assume the so-called CO_2 fertilization effect (see *CO_2 Fertilization and Forest Mortality*). In the absence of this moderating effect, the forest replacement would be considerably higher for all scenarios.

Summing up, it has been established by modeling studies that the stability of Amazon forests may have at least two tipping points that, once one or both are transgressed, would entail irreversible large-scale forest dieback and a tendency for drier seasonal forests or impoverished tropical savanna to prevail over 30 to 50% of the basin, especially in the southern and eastern portions.

That is, we have identified the risks of land-use and climate change. Are there solutions to eliminate or mitigate those risks? Or, alternatively: Is the fate of the Amazon predetermined, given the likely risks to the Amazon ecosystems spelled out in *Impacts of Anthropogenic Drivers of Change in the Amazon*, or can we nudge a better outcome leveraging humanity's limitless ingenuity in scientific discovery and solving seemingly intractable problems with an innovation model that has, as its foundations, a number of scientific and technological revolutions quietly transforming the world economy?

The Amazon development debate has been torn between attempting to reconcile maximizing conservation versus intensification of traditional agriculture and expansion of hydropower capacity. In *Third Way as Paradigm*, we argue for a Third Way based on aggressively researching, developing, and scaling up a new high-tech innovation approach that sees the Amazon as a global public good of biological and biomimetic assets that can enable the creation of innovative high-value products, services, and platforms for current and for entirely new markets through combining advanced digital, biological, and material technologies of the Fourth Industrial Revolution in progress.

Third Way as Paradigm of Sustainable Development for the Amazon

In terms of development policy pathways for the Amazon, two modes have historically dominated: (*i*) a valuable nature conservation approach with large swathes of territory legally protected from any economic and human activity outside indigenous peoples—which comprise 2.1 million $\mathrm{km^2}$, or about 43% of Brazilian Amazon (153, 163, 164); and (*ii*) an approach that has focused on conversion or degradation of forests for the production of either protein commodities (e.g., meat and soya) or tropical timber at the forest frontier and the build-out of massive hydropower generation capacity—which together have been historically responsible for massive deforestation of the Amazon (30, 31) and generated other significant negative externalities.

Recently, there have been suggestions of promoting grain agriculture intensification (165) and higher intensification of cattle ranching to substantially increase meat production (22) in areas already deforested through recovery of degraded pastures. However, even though these approaches can potentially provide a "transition bridge" toward a safer sustainable development model, they are inconsistent with the rigorous zero-deforestation target necessary, among other things, for climate change stabilization, because the exponential demand growth of these commodities by the emerging middle class in the emerging markets, in the end, will likely depend to a greater or lesser extent on continuously expanding the agricultural frontier.

Given Brazil's huge underexploited central and distributed renewable energy generation and energy efficiency potential in regions much closer to the consumption centers (166, 167) versus energy demand in the Amazon that can be met by local renewable sources (168–170), we argue that it should be feasible to plan for energy generation capacity increases that do not rely on new hydropower capacity from the Amazon.

On the other hand, the Amazon biological (e.g., biomimetic) assets may hold promise for advanced energy production innovations. In nature, photosynthesis generates energy for plants, and microorganisms generate their own energy from other sources (e.g., sulfur-fixing bacteria). These processes have inspired innovations in advanced microbial fuel cells (171). In addition, the Tungara frog species that creates long-lived foams has inspired new energy generation and carbon dioxide sequestration technologies (172). Finally, plants have also directly inspired solar cell design, potentially generating much cheaper alternatives to silicon-based photovoltaics (173).

We argue therefore that there is a Third Way within reach in which we aggressively research, develop, and scale a new high-tech innovation approach that sees the Amazon as a global public good of biological assets and biomimetic designs that can enable the creation of innovative high-value products, services, and platforms for current and for entirely new markets by applying a combination of advanced digital, material, and biological technology breakthroughs to their privileged biological and biomimetic assets (please refer to *Implications of the Fourth Industrial Revolution for the Sustainable Development of the Amazon* for more details on the Fourth Industrial Revolution).

Biological systems in the Amazon are the result of millions of years of evolution. Humanity, as a whole, has long relied on observing and learning from nature, just as the famous Icarus tried mimicking bird flight from his prison island in ancient Greek mythology. Fast forward, and the search for biomimetic applications has developed into a scientific discipline leading inevitably to a large number of biomimicry-based innovations.

Biomimicry innovations in the Amazon should focus on learning from and then emulating Amazonian natural forms, processes, and ecosystems to create more sustainable designs and innovations (174). We are rapidly gaining understanding on how things are created in nature (materials), how organisms sense their surroundings (sensors), how they move in their environment (biomechanics and kinetics), and how they behave and function (processes) (175). In addition, there is significant innovation potential to focus on learning from the Amazon in biomimicry-enabled nanoscience, reproducing complex biological systems to solve problems on a nanomolecular scale (176, 177), create environmentally friendly process and pollution prevention/remediation technologies, design bioinspired textile structures (178), aid in energy production, and provide insight in behavioral and cognition—artificial intelligence robotic—applications (179), which are in the early phase of the innovation cycle.

In the short term and with a low-tech approach, we estimate that it is quite feasible to develop a number of biodiversity-based product value chains capable of reaching global markets with unique differentiation (180, 181). This new economy has the potential to become much larger than the present one that is based on the unsustainable use of natural resources in the Amazon. A number of biodiversity products from the Amazon, such as babassu (*Attalea speciosa*), cupuaçu (*Theobroma grandiflorum*), and the Brazil nut have already impacted the local economies, and there are plenty more to be discovered and commercialized (182). Pioneering illustrations of this new biodiversity-based economy are the recent emergence of assai (*Euterpe oleracea*) production that has reached the multibillion-dollar scale (183–186). The spilanthol alkaloid found in the leaves, branches, and flowers of jambu (*Spilanthes oleracea*) is described in patents as appropriate for anesthetic, antiseptic, antiwrinkle, toothpaste, gynecological, and antiinflammatory uses (187). Other products of the Amazon biodiversity are essential oils of species such as rosewood (*Aniba rosaeodora*), nhandiroba (*Carapa guianensis*), and copaiba (*Copaifera langsdorffii*) that are amenable for end-to-end processing in the Amazon and can be alternatives in the formation of a fluorine–xylo–chemical hub for cosmetic and pharmaceutical products in the Amazon (188). The bacuri (*Platonia insignis*) is an Amazonian fruit in increasing demand for ice cream, candy, and juice products. The oil extracted from its seeds is used as an antiinflammatory substance in traditional folk medicine and in the cosmetics industry (189). New uses of biodiversity-based products are being developed and patented more often [e.g., ucuuba (*Virola Surinamensis*) (188) and murumuru (*Astrocaryum murumuru*) butter (190)] in the cosmetics industry.

Beyond these new developments in the right direction, however, the Fourth Industrial Revolution opens a new paradigm of seeing tropical regions not only as potential sources of natural resources and biodiversity but also as reserves of precious biological biomimetic knowledge that can fuel a new development model that can benefit both local/indigenous populations and the world at large.

Our view is that transitioning to this sustainable development model will require an Amazon-specific Fourth Industrial Revolution innovation “ecosystem” that is able to rapidly prototype and scale innovations that apply a combination of advanced digital, biological, and material technologies to the Amazon’s renewable natural resources, biomimetic assets, environmental services, and biodiverse molecules and materials. This sustainable development model would then provide a basic foundation to nurture a biomimetic innovation ecosystem model for the region that would be capable of capturing synergies between private and public R&D laboratories, public–private partnerships, private and social entrepreneurs, venture capital, and innovative corporations—much like in Silicon Valley. For this innovation ecosystem to be developed over time, a new Amazon-specific innovation public–private partnership needs to be in place, together with an enabling regulatory framework that deals with good practice in dealing with biomimetic knowledge and assets. In particular, the Amazon requires an aspirational type “man on the Moon” mission that draws on frontier knowledge across digital, biological, and advanced materials to attain the goal of big science deployed to meet big problems. The role of the government and high-tech start-ups will be particularly important in the first-stage capital-intensive high-risk domains that the corporate sector tends to shy away from. Just as the development of the Internet was funded initially by the US government that, in time, created a platform for innovation for social, private, and public entrepreneurs around the world, so should the path be set for the Amazon innovation ecosystem that we aspire to develop.

The Amazon region presents limited potential for knowledge generation and capacity building partly due to a limited number of research institutions and researchers (191, 192). In this context, a critical missing element for transforming local development toward sustainability is human capital in the region. Brazilian Amazon universities produce only 2% of Ph.D.s trained in Brazil every year (330 out of 16,745 in 2014)—in contrast, the Brazilian Amazon has about 11% of the population (see Tables S5 and S6 in *Datasets Used to Derive the Fraction of Ph.D.s Trained in Brazilian Amazon Universities*)—and very few are trained in innovative research areas of advanced digital, biological, and material sciences that should serve as pillars of the Fourth Industrial Revolution in the region. Developing a locally innovative research capacity and attracting human capital are essential elements for long-term sustainability. This should include creating new research institutions across the region, taking notice of subregional potential of renewable natural resources and also enhancing connectivity through broadband satellite-based* and fluvial fiber optics Internet (191) [Connected Amazon Project (Amazônia Conectada) was established by Ministerial Ordinance 596, published in Brazilian Federal Register on July 23, 2015, issued by the Ministry of Science, Technology and Innovation] and through provisioning a common high-performance computing infrastructure for the region.

Transforming the current regional developmental model presents multidimensional challenges, which cannot be achieved through science, technology, and innovation alone. It has become vital and indeed urgent to instigate a real scientific, high-tech, and innovation revolution in the Amazon. The enormous institutional and governance challenge is to find the pathways to transform this vast and mostly unknown natural capital into a global common public good that provides a foundation for public, private, and social entrepreneurs to develop and scale innovations as a basis for a novel high-tech regional sustainable development model for the Amazon.

Concluding Remarks

Overcoming the risks to the integrity and functionality of Amazon ecosystems does not depend exclusively on a new local, standing forests sustainable development paradigm such as the one put forth in *Third Way as Paradigm of Sustainable Development for the Amazon*. Reducing tropical deforestation to nearly zero is necessary for biodiversity conservation, provision of ecosystems services, and, to some extent, climate mitigation by reducing land-cover change emissions, but it is not sufficient at all to avert the risk of global climate change. Unchecked climate change poses a great danger of exceeding tipping points for the forests. Therefore, a gargantuan global effort of decarbonizing the world

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*The geostationary satellite will be the first satellite fully controlled by the Brazilian government, and the project involves the Ministries of Defense, Communications, and Science, Technology and Innovation. The Telebras and Visiona Space Technology companies were responsible for the construction if equipment, which started in 2014; equipment should be ready for release in the first half 2016. The project was funded through the National High Speed Internet Program (Programa Nacional de Banda Larga-PNBL), which was established by Ministerial Decree 7.175, by the Ministry of Communications.

economy is called for to avoid transgressing these boundaries and to meet the safeguards of maximum 2 °C global warming as set by the recent Paris Agreement during the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change.

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