REVIEW SUMMARY

TROPICAL FOREST

Human impacts outpace natural processes in the Amazon

James S. Albert*, Ana C. Carnaval, Suzette G. A. Flantua, Lúcia G. Lohmann, Camila C. Ribas, Douglas Riff, Juan D. Carrillo, Ying Fan, Jorge J. P. Figueiredo, Juan M. Guayasamin, Carina Hoorn, Gustavo H. de Melo, Nathália Nascimento, Carlos A. Quesada, Carmen Ulloa Ulloa, Pedro Val, Julia Arieira, Andrea C. Encalada, Carlos A. Nobre

BACKGROUND: The Amazon is a critical component of the Earth climate system whose fate is embedded within that of the larger planetary emergency. The Amazon is the most species-rich subcontinental-scale ecosystem and is home to more than 10% of all named plant and vertebrate species, concentrated into just 0.5% of Earth's surface area. The Amazon rainforest is also a critical component of the Earth climate system, contributing about 16% of all terrestrial photosynthetic productivity and strongly regulating global carbon and water cycles.

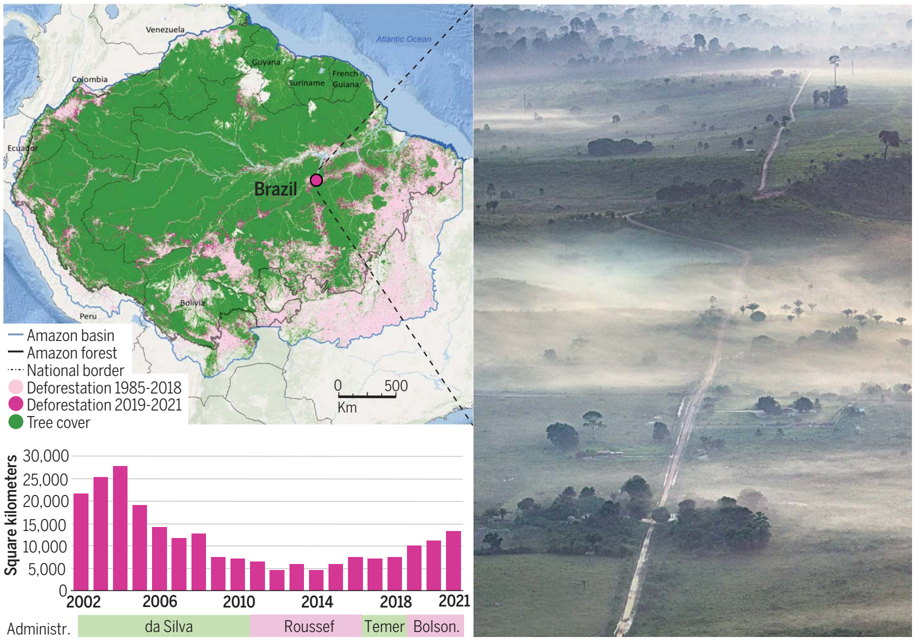
Amazonian ecosystems are being rapidly degraded by human industrial activities. A cumulative total of 17% of the original forest have already been cleared, and 14% replaced, by agricultural land use. After millions of years serving as an immense global carbon pool, under further warming the Amazon rainforest is predicted to become a net carbon source to the atmosphere. Some regions have already made the transition, with forest respiration and burning outpacing forest photosynthesis.

ADVANCES: In this Review, we compare rates of anthropogenic and natural environmental changes in the Amazon and South America and in the larger Earth system. We focus on deforestation and carbon cycles because of their critical roles on the Amazon and Earth systems. Data for South America were compiled for the Science Panel for the Amazon (SPA) Assessment Report, which details the many dimensions of the Amazon as a regional entity of the Earth system. The SPA report, coauthored by 240 scientists from 20 countries, documents epoch-scale transformations in Amazonian biodiversity, ecosystem function, and cultural diversity.

We found that rates of anthropogenic processes that affect Amazonian ecosystems are up to hundreds to thousands of times faster than other natural climatic and geological phenomena. These anthropogenic changes reach the scale of millions of square kilometers within just decades to centuries, as compared with millions to tens of millions of years for evolutionary, climatic, and geological processes. The main drivers of Amazonian habitat destruction and degradation are land-use changes (such as land clearing, wildfires, and soil erosion), water-use changes (such as damming and fragmenting rivers and increased sedimentation from deforestation), and aridification from global climate change. Additional important threats come from overhunting and overfishing, introduction of invasive exotic species, and pollution from the mining of minerals and hydrocarbons.

OUTLOOK: Given the outsized role of the Amazon in our planetary hydrological cycle, large-scale deforestation of this region is expected to push the whole Earth system across a critical threshold to a qualitatively different global climate regime. Quite aside from biodiversity losses, such a transformation will have multifarious and catastrophic consequences for human welfare, including widespread water and food insecurity that will lead to mass migrations and political instability. The key message is that Amazonian environments are being degraded by human industrial activities at a pace far above anything previously known, imperiling its vast biodiversity reserves and globally important ecosystem services.

The Amazon is now perched to transition rapidly from a largely forested to a nonforested landscape, and the changes are happening much too rapidly for Amazonian species, peoples, and ecosystems to respond adaptively. Policies to prevent the worst outcomes are known and must be enacted immediately. We now need political will and leadership to act on this information. To fail the Amazon is to fail the biosphere, and we fail to act at our peril. ■



Amazon deforestation is accelerating from a combination of anthropogenic drivers, including drier climatic conditions and policies that favor industrialized agriculture. (Top left) Map of Amazon showing location of wildfires, 1985 to 2021. (Right) Recently burned primary forest near Rurópolis, State of Pará, Brazil, 17 September 2020. (Bottom left) Rate of deforestation in the Brazilian Amazon is now rising rapidly under environmental policies of the Bolsonaro administration. After millions of years serving as an immense global carbon pool, the Amazon rainforest is becoming a net carbon source to the atmosphere.

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REVIEW

TROPICAL FOREST

Human impacts outpace natural processes in the Amazon

James S. Albert[1]*, Ana C. Carnaval[2], Suzette G. A. Flantua[3], Lúcia G. Lohmann[4], Camila C. Ribas[5], Douglas Riff[6]†, Juan D. Carrillo[7], Ying Fan[8], Jorge J. P. Figueiredo[9], Juan M. Guayasamin[10], Carina Hoorn[11], Gustavo H. de Melo[12], Nathália Nascimento[13], Carlos A. Quesada[14], Carmen Ulloa Ulloa[15], Pedro Val[16,17,18], Julia Arieira[19], Andrea C. Encalada[20], Carlos A. Nobre[21]

Amazonian environments are being degraded by modern industrial and agricultural activities at a pace far above anything previously known, imperiling its vast biodiversity reserves and globally important ecosystem services. The most substantial threats come from regional deforestation, because of export market demands, and global climate change. The Amazon is currently perched to transition rapidly from a largely forested to a nonforested landscape. These changes are happening much too rapidly for Amazonian species, peoples, and ecosystems to respond adaptively. Policies to prevent the worst outcomes are known and must be enacted immediately. We now need political will and leadership to act on this information. To fail the Amazon is to fail the biosphere, and we fail to act at our peril.

The Amazon is a critical component of the Earth climate system, whose fate is embedded within that of the larger planetary emergency. Along with the two polar ice sheets and coral reefs, the Amazon [as defined in (*1*)] is one of four major ecosystems of the Earth system that are rapidly approaching or surpassing the threshold to a qualitatively degraded state (*2*, *3*). The Amazon is by far the most species-rich subcontinental-scale ecosystem, being home to more than 10% of all named plant and vertebrate species concentrated into just 0.5% of Earth's surface area (*4*). Yet Amazonian biodiversity is grossly underestimated, with perhaps only about 10% of the species yet described (*5*). Amazonian biodiversity is the evolutionary source for much of the world's plants and animals (*6*, *7*), serving as the core of a biogeographic realm that hosts about one-third of all known species on Earth (*8*).

The Amazon is also a crucial provider of global ecosystem services, contributing about 16% of all terrestrial photosynthetic productivity (*9*) and strongly regulating global carbon and water cycles (*10*, *11*). Yet global warming is rapidly increasing climate variability in the Amazon. Extreme droughts and record floods have occurred in nine of the past 15 years, compared with just four extreme droughts and three record floods in the previous century (*11*). These extreme weather events are substantially lowering the threshold for wildfires at the rainforest margins; altering biogeochemical cycles; and leading to widespread deforestation, habitat degradation, and wetland loss (*9*, *12*).

Given the outsized role of the Amazon in our planetary hydrological cycle, large-scale deforestation threatens to push the whole Earth system across a critical threshold to a qualitatively different global climate regime (*13*). Quite aside from biodiversity losses, such a transformation will have multifarious and catastrophic consequences for human welfare, including widespread water and food insecurity (*14*–*16*), leading to mass migrations and political instability (*16*).

In this Review, we compare rates of anthropogenic and natural environmental changes in the Amazon and other regions of South America and also compare these rates with other processes in the larger Earth system. Data for South America were compiled from the Science Panel for the Amazon (SPA) Assessment Report (*1*), which details the many dimensions of the Amazon as a regional entity of the Earth system. The SPA report—coauthored by 240 scientists from 20 countries, including members of Indigenous Peoples and Local Communities (IPLCs)—documents epoch-scale transformations in Amazonian biodiversity, ecosystem function, and cultural diversity. The report also summarizes the major social and ecological transformations of the Amazon through human history and presents sustainable development pathways for the Amazon into the near future. The key messages of this Review are that multiple strong changes to the Amazon being driven by modern human activities are happening far too fast for the survival of its species and ecosystems (*17*) and that widespread Amazon deforestation would be an irreversible catastrophe for the global climate system (*9*, *18*).

Amazon in motion

The Amazon is perched to transition rapidly from a largely natural to degraded and transformed landscape, under the combined pressures of regional deforestation and global climate change (*19*, *20*). As of 2019, a cumulative total of about 17% of the pre-Columbian Amazon forest had been cleared, and 14% replaced, by human agriculture landscapes—89% for pasture and 11% for crops (*21*). After millions of years serving as an immense global carbon pool, under further warming the Amazon rainforest is predicted to become a net carbon source to the atmosphere [for example, (*22*, *23*)]. Some parts of the Amazon have already made the transition, with forest respiration and burning outpacing forest photosynthesis (*24*).

As we enter the third decade of the 21st century, portions of the southern and eastern Amazon are changing to a disturbance-dominated regime (*25*, *26*). Under global drivers of climate change, much of the Amazon is experiencing pronounced increases in the frequency and severity of floods, droughts, and wildfires (*12*, *27*). The basin-wide impacts of landscape desiccation have far surpassed the variability of natural hydrological and biogeochemical cycles since the start of the current climate epoch, the Holocene, ~11,700 years ago (*28*). Further, several other ecologically and biodiversity-rich regions of the Neotropics outside of the Amazon (such as the Atlantic Rainforest or Mata Atlântica, Caatinga, Cerrado, Chocó, and Puna) are also facing accelerating threats from modern human activities (*1*, *7*).

Before the Anthropocene (starting around 1950), the Amazon had maintained natural humid and tropical environments, including forests and wetlands, over most of lowland northern South America for tens of millions of years (*4*). Amazonian ecosystems have persisted

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through many profound climatic and evolutionary transformations, including the formation and draining of inland seas and mega-wetlands during most of the Miocene (~23 million to 10 million years ago), and transitioned into a fluvial landscape in the late Miocene to Pliocene (~10 million to 2.3 million years ago) (*29*), alternated ice-age and interglacial climates during the Pleistocene (~2.6 million to 0.01 million years ago) (*29*, *30*), and shifted land-use practices of Indigenous peoples during the Holocene (*31*).

Thus, quite unlike the expansive temperate and boreal forests of the northern hemisphere, which were repeatedly cleared and pushed southward by low temperatures and continental glaciers during the Pleistocene and then regenerated in the Holocene, Amazonian rainforests have never previously confronted regional-scale deforestation (*32*, *33*). This ecosystem persistence over evolutionary time scales resulted in the Amazon becoming both a center and source of biodiversity for the whole Neotropical region (*6*, *34*).

In the Amazon, more than in most other regions, forest-rainfall feedback is required to maintain the current forest cover (*35*). About half of the precipitation over the Amazon is recycled from evapotranspiration, with about 14.1 trillion cubic meters of water per year falling as precipitation over the whole basin, compared with the Amazon River discharge of about 7.3 trillion cubic meters per year. Amazonian forest cover buffers the ecosystem against variations in precipitation and fire (*36*, *37*). This dependence of the state of the system on its history (hysteresis) is a common feature of many ecological systems at large spatial and temporal scales, in which the observed state of a system cannot be predicted on the basis of current conditions alone.

Amazon forest extent and structure is therefore highly sensitive to widespread forest degradation and removal (*38*, *39*). Clearcutting parts of the Amazon forest exposes the landscape to an irreversible regime shift, from a forested to a nonforested landscape, with a wide range of deleterious consequences (*12*, *40*). Beyond a certain threshold, deforestation and regional aridification will become locked in a vicious cycle that drives a runaway transformation of lush rainforests to degraded savanna-like agricultural landscapes (*25*, *41*).

Drivers of Amazon destruction and degradation

The main regional-scale drivers of Amazonian habitat destruction and degradation arise from land-use changes (such as deforestation, wildfires, or soil erosion), water-use changes (such as damming and fragmenting rivers, increased sedimentation from deforestation, pollution from the mining of minerals and hydrocarbons, or ground-water extraction), and aridification from global climate change (*5*, *18*). The main effects of climate change today are precipitation changes, and sea level rise will likely have major effects in the near future. Overhunting and overfishing (*42*), the introduction of invasive exotic species (*43*), and pollution (*44*) are additional important threats to biodiversity and ecosystem function at local to regional scales in the Amazon and other ecosystems. Here, we focus on deforestation and carbon cycles because of their critical roles on the Amazon and Earth systems.

The most rapid environmental changes in the Amazon today are driven by land converted from forests and degraded pastures into soy and livestock production, primarily for export (*45*, *46*). By 2019, about 867,000 km^2 or about 14% of the Amazon forest had been cleared, especially in the Brazilian states of Pará, Mato Grosso, Rondônia and Amazonas, in order of greatest contribution to deforestation (*21*). Between 1995 and 2017, 17% of the Amazon rainforest was degraded by logging, fire, windthrow, or road expansion (*47*). Under the auspice of globalization, Amazonia is being integrated into global commodities markets, mostly soybean, beef, and timber (*48*).

The immediate crisis is driven by the logging and burning of closed-canopy tropical rainforests to clear land for agriculture and pasture. Agricultural expansion is the leading cause of regional deforestation worldwide and in South America (*49*, *50*). The legal construction of roads, dams, and other infrastructure, combined with many illegal activities (such as forest clearcutting, logging and burning, mining, illicit crops, and clandestine roads) have driven the agricultural frontier deep into the Amazon margins over the past 20 years (*51*, *52*). During this same period, soybean exports from Brazil to China surged by 2000%, primarily as animal feed to supply rapidly increasing meat consumption in China, and South America is currently the largest source of biomass imports to the European Union (*53*).

The great soybean plough-up of South America during the early 21st century is the farthest outlier of anthropogenic changes from the regression lines for South America in Fig. 1. This landscape transformation is roughly comparable in total area and proportion of landscape surface with other regional-scale "great plough-ups" of history, such as the spread of grain culture across monsoon Asia from about 3000 to 1000 years ago; the Northern European plains from about 1500 to 1000 years ago; the Russian Steppes in the 18th and 19th centuries; the Great Plains of North America in the late 19th and early 20th century; and the ongoing expansion of palm oil plantations in Indonesia, Malaysia, and many other countries.

Effective forest-protection policies act by removing the international financing of market-driven land-conversion projects. Two of the largest funding sources are the Inter-American Development Bank (IDB), based in Washington, DC (*54*), and the Belt and Road Initiative (BRI) of the Chinese government. The Initiative for the Integration of the Regional Infrastructure of South America (IIRSA) is a massive infrastructure program of road and dam construction launched in 2000. Most IIRSA environmental impacts derive from road construction in the Brazilian states of Amazonas and Acre and the Colombian states of Caquetá and Guaviare, providing increased access for accelerated expansion of beef production, oil extraction, and mining (*55*).

BRI-financed hydroelectric and water-diversion projects are planned to dredge and canalize hundreds of river kilometers in Ecuador and Perú (*56*). BRI-supported water diversion projects will expand soybean cultivation on more than 74,000 km^2 and hydrologically link Amazonian tributaries to neighboring drainages. Once completed, these projects will convert major southern tributaries (such as Tapajos and Xingu rivers) into a network of artificial reservoirs with poorly known but negative impacts to local biodiversity and IPLC livelihoods and the function of regional hydrological systems (*57*).

The effectiveness of forest-protection policies has varied over the past 20 years (*52*, *58*). The Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), launched in 2004, improved the deforestation

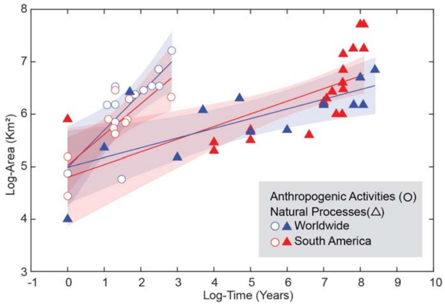

Fig. 1. Temporal and spatial scales of anthropogenic and natural processes in the Earth system. Data for 55 cases, with references in Table 1. Circles and triangles indicate anthropogenic and natural processes, respectively; red and blue symbols indicate processes from South America and globally, respectively. All regressions are power functions represented as linear curves on a log-log plot. Anthropogenic South America (n = 10 activities), y = 106,443 × 0.5853, coefficient of determination (R^2) = 0.2455. Anthropogenic global (n = 12 activities), y = 96,870 × 0.7071, R^2 = 0.8214. Natural South America (n = 21 activities), y = 102,364 × 0.185, R^2 = 0.4565. Natural global (n = 13 activities), y = 97,678 × 0.1849, R^2 = 0.4669. Anthropogenic processes occur at rates several orders of magnitude faster than those of natural processes.

monitoring system, reinforced environmental inspections, and promoted land tenure for IPLCs in legally protected areas. These actions were strengthened over time by the Soy Moratorium (from 2006) and the Black List of municipalities with highest deforestation rates (from 2008). Together, these actions substantially reduced access of industrial farming interests to international markets and financial credit (*53*, *58*). Whereas the Temer and Bolsonaro administrations (2016–2022) undermined the PPCDAm, weakened the new Brazilian Forest Code, dismantled environmental agencies, and suppressed the Sugarcane Agroecological Zoning Act of 2009 (*59*), markedly increasing deforestation rates, one of the first acts of the new Lula administration was to reestablish the PPCDAm.

Global climate change represents the other imminent threat to the Amazon and other ecosystems, affecting forest dynamics, carbon and nutrient cycling, and freshwater and coastal ecosystems (*60*, *61*). As predicted by climate models (*62*, *63*) and well documented by climatic records (*11*), precipitation patterns are becoming more variable in time and space, with more frequent and severe floods (*64*) and more persistent and widespread droughts (*39*). Climate change is rapidly desiccating the southern and eastern portions of the Amazon rainforest, contributing to higher frequency and severity of wildfires and contraction of the southern forest margin. Concomitant sea level rise is projected to inundate the biodiverse floodplain and coastal mangroves and estuaries, converting them to nearshore marine habitats and threatening coastal livelihoods (*65*).

How fast is the Amazon changing?

We compiled age and area estimates for 55 different anthropogenic and natural processes affecting terrestrial and aquatic ecosystems in South America and globally, including 11 anthropogenic and 21 natural processes in the former and 13 and 11 processes in the latter (Table 1). Ensemble rates were assessed by the exponent value of power-function regressions applied to each of these four categories.

We found that rates of anthropogenic processes affecting Amazonian ecosystems are up to hundreds to thousands of times faster than they are for natural climatic and geological phenomena (Fig. 1). These anthropogenic changes have reached the scale of millions of square kilometers within just decades to centuries, as compared with millions to tens of millions of years for evolutionary, climatic, and geological processes. Destruction of Amazonian environments is far outpacing species', ecological interactions', and ecosystems' capacity to respond adaptively (*32*, *66*). The rate at which modern human activities is driving extinctions in the Neotropics is between 1000 and 10,000 times higher than the natural or "background" rate as estimated from the fossil record (*17*, *67*).

These anthropogenic changes to Amazonian environments are coupled to processes worldwide, racing ahead many times faster than those of natural counterbalancing processes in the Earth system (*68*). Among the most important ongoing imbalances are accelerating rates of climate change (*69*), sea level rise (*70*), terrestrial vegetation turnover (*32*), river delta avulsion (*71*), tropical deforestation (*72*, *73*), extinction (*74*), and soil erosion and waterway sedimentation (*75*–*77*). Whereas the residence time of carbon through the atmosphere, hydrosphere, and lithosphere is on the order of millennia to millions of years, modern human extraction and burning of fossil fuels occurs at time frames of decades to centuries (*78*). Global climate changes during the most recent deglaciation (for example, the Pleistocene-Holocene transition) occurred on the time frame of centuries to millennia as compared with ongoing anthropogenic changes that are observed at a decadal scale (*79*).

Given the key role of the Amazon in the Earth system, the causes and consequences of Amazonian and global system degradation are strongly linked (*1*), and the pace of anthropogenic changes exceeds that of many natural processes at regional to global scales (Fig. 1). For example, average annual global deforestation over the past decade has exceeded afforestation by about 100,000 km^2, causing a net loss of forest of about 1.4% every year (*80*). Global soil erosion exceeded soil formation by 35.9 billion tons (Gt) in 2012, representing a 2.5% increase over the erosion estimate from 2001 (*81*). Rates of vegetation change equal or exceed the deglacial rates globally, indicating that the scale of human effects on terrestrial ecosystems now exceeds the massive vegetation transformations during the most recent major global climate change event (*32*). In the Amazon, changes in the precipitation patterns, because of deforestation or withdrawal, are having a strong impact on the frequency and magnitude of intermittency of rivers and streams specially in the southeastern part of the Amazon. Last, although accurate data on groundwater withdrawals are difficult to collect, estimates indicate that depletion far exceeds recharging in most parts of the world, with net losses of up to 20% per year in some highly populated and aridifying regions of North America and Asia (*82*).

Global consequences of Amazon degradation

From a climate perspective, widespread Amazon degradation would be an irreversible global catastrophe. Amazonian forests and soils contain about 180 ± 30 Gt of carbon (GtC); approximately half of this carbon is stocked in the form of vegetation biomass, and the other half remains as soil carbon stocks (*9*). By comparison, this Amazonian carbon volume is equivalent to about 26% of the 690 ± 80 GtC released into the atmosphere by all human activities since the Industrial Revolution (1750 to 2020), achieved primarily by burning fossil fuels and land-use changes (*83*). Anthropogenic carbon emissions during this time period raised atmospheric carbon dioxide (CO_2) from 277 to 415 parts per million (ppm) and increased the average global temperature to 1.2°C above preindustrial levels. Releasing all the Amazonian carbon into the atmosphere would initially increase the airborne CO_2 concentration by an additional 85 ppm, representing another concerning ~0.5°C increase (*83*).

Under the 2015 Paris Climate Accords, to keep atmosphere warming below 2°C global civilization cannot emit more than 465 Gt more carbon, and the Amazon alone contains about 32 to 44% of that carbon total. Yet Amazonian fires from 2010 to 2018 released about 0.5 to 1.5 GtC per year into the atmosphere, whereas forest growth during this time period removed only about 0.5 GtC per year (*84*). The approximately 4.5 to 9.0 GtC left in the atmosphere is similar to total carbon emissions of Japan during this interval, which ranked fifth among nations for carbon pollution (*85*). To better compare the volume of Amazon carbon impact on global climate, we note that Amazonian afforestation in the centuries after the Iberian conquest (around 1500 to 1700) captured about 7.4 GtC (3.5 ppm CO_2 equivalent) from the atmosphere, perhaps contributing to the global cooling episode known as the Little Ice Age (*86*).

The adverse consequences of global anthropogenic carbon emissions extend beyond the Amazon to the whole Earth system. Without sufficient abatement, melting polar ice sheets will contribute more than 13 m (~43 feet) to global sea level rise by 2500, with complete loss of the Earth's ice sheets projected within the next 400 to 700 years (*87*). Ongoing melting of the Western Antarctic is projected to fragment the Thwaites Eastern Ice Shelf within the next five years, raising sea levels by more than 0.6 m and destabilizing neighboring glaciers (*88*, *89*). In an ice-free world, global sea levels would reach ~65 m (~213 feet) above the present level, as high as they were in the supergreenhouse world of the Eocene about 56 million years ago (*90*). Such melting would raise the global sea level 93 to 162 mm per year averaged over the next few centuries, starting slow (averaging 3.1 mm per year in the past 30 years) and accelerating toward the final collapse of the ice sheets. By comparison, sea levels rose about 60 m during the early and mid-Holocene (11,700 to 7000 years ago), at an average rate of about 12.9 mm per year (*91*). Thus, the potential anthropogenic rate of sea level rise in the next few years and decades is more than seven times faster than the maximum

Table 1. Anthropogenic and natural processes affecting terrestrial and aquatic ecosystems. Data specific to the Amazon is indicated with an asterisk. LIP, large igneous provinces; E-O, Eocene-Oligocene.

Category	Process	Age (million years)	Area (km^2)	References	Notes
Anthropogenic global	Land equipped for irrigation: 1700–2020	320	3,442,500	(136, 137, 158)	
	Wetland loss: 1700–2009	309	7,220,000	(159)	
	Freshwater withdrawals: 1800–2000	200	3,443,500	(160, 161)	
	Land equipped for irrigation since 1900	120	2,863,500	(136, 137, 158)	
	Land equipped for irrigation since 1950	70	2,383,500	(136, 137, 158)	
	Urban land expansion: 1970–2000	30	58,000	(162)	
	Land equipped for irrigation since 2000	20	703,500	(136, 137, 158)	
	Urban land expansion: 2010–2030	20	1,527,000	(162)	Most likely forecast
	Habitat loss from agricultural expansion: 2020–2050	20	3,350,000	(69)	
	Global forest cover loss: 2000–2012	12	1,500,000	(163)	Forests with >50% tree cover
	Global deforestation: 2012	1	74,532	(163)	Forests with >50% tree cover
Anthropogenic South America	Marine incursions to 80 M: by 2700	680	2,125,900	(164)	Area estimated from maps using ImageJ
	Rangeland desertified South America: 1960–2008	48	1,943,000	(165)	Area estimated from claim of 30% loss
	Amazon deforestation* 1975–2018	43	788,353	(20)	
	Petroleum concessions*: 1970–2008	38	688,000	(166)	Western Amazon (n = 188 concessions)
	Soybean expansion South America: 2000-2019	20	2,870,000	(52)	
	Soybean expansion Amazon*: 2000–2019	20	420,000	(52)	
	Anthropogenic forest loss: 2000–2017	18	540,000	(26)	
	Amazon fires*: 2003–2015	13	800,000	(167)	
	Amazon fires*: 2019	1	156,000	(168)	
	Amazon deforestation peak*: 2004	1	27,772	(72)	
Natural global	LIP: Siberian Traps	252,000,000	7,000,000	(169)	
	LIP: Ontong Java Plateau	120,000,000	1,500,000	(151)	
	Megariver captures stream orders 8 to 10	100,000,000	5,642,282	(34)	
	LIP: Deccan Traps	66,000,000	500,000	(170)	
	Megariver captures stream orders 6 to 8	10,000,000	253,195	(171)	
	Megariver captures stream orders 4 to 6	1,000,000	11,362	(171)	
	1 km bolide impacts	50,000	5,000	(152)	1 km diameter crater
	10 m bolide	500	2,150	(152)	Tunguska event, area deforested
	2.5 m bolide	50	1,875	(152)	Area deforested
Natural South America	Origins modern rainforest floras and faunas Western Gondwana	125,000,000	51,447,500	(4)	Western Gondwana is South America, Africa, and Arabia
	Megathermal forests across South America	125,000,000	17,840,000	(4)	
	Final separation South America and Africa	100,000,000	51,447,500	(4)	
	Diversification of modern rainforest floras and faunas	64,000,000	17,840,000	(4)	
	E-O global cooling, contraction of rainforests to tropical latitudes	34,000,000	14,000,000	(4)	
	Separation Amazon and Atlantic biotas, seasonally dry diagonal	34,000,000	7,000,000	(4)	
	Marine regression, expansion lowland basins	34,000,000	3,000,000	(4)	
	GAARlandia	33,000,000	4,000,000	(4)	
	Megariver captures in sub-Andean foreland	32,000,000	1,000,000	(4)	
	Pebas megawetland system	22,000,000	1,000,000	(4)	
	Expansion of C4 grasses and mammalian grazers	17,000,000	2,690,000	(4)	South American savannas
	Separation cis- and trans-Andean lowland biotas	12,000,000	2,000,000	(4)	Trans-Andean lowlands
	Desertification at continental periphery	10,000,000	1,708,000	(4)	Patagonia, Atacama, Sechura, Goajira, and Caatinga
	Great Amazonian Biotic Interchange (GAzBI)*	10,000,000	1,600,000	(152)	
	Rise of Fitzcarrald arch*	4,000,000	400,000	(172)	
	Ice ages cycles: forest-savanna*	100,000	500,000	(173)	
	Irion cycles: várzeas*	100,000	460,000	(174)	
	Irion cycles: igapos*	100,000	320,000	(174)	
	Megafauna extinctions—changes woody-savanna cover	10,000	290,000	(174)	
	Ice ages cycles: shorelines	10,000	200,000	(164)	

recorded rate after the most recent global deglaciation.

The rapid pace of human activities is readily seen in Stommel diagrams that plot the characteristic temporal and spatial scales of disparate human economic, geological, climatological, and biological processes (Fig. 2). In this context, it is useful to compare the modern anthropogenic biodiversity and climate crises with the Paleocene-Eocene Thermal Maximum (PETM) event, a global but relatively brief hyperthermal episode that occurred about 55.5 million to 54.5 million years ago. During the PETM, atmospheric CO_2 rose to the highest levels of the Cenozoic Era, and the global average temperature spiked about 5° to 8°C to a temperature about 9° to 14°C warmer than today, driving large changes to the geographic ranges and adaptive traits of many terrestrial and marine organisms (*92*). By contrast, current rates of change in CO_2 and global average temperature are hundreds of times faster than were during the PETM (*93*, *94*). Such unprecedentedly high rates of environmental change constitute the most important challenges to adaptation and persistence of plant and animal species in Amazonian ecosystems and to global civilization (*95*).

Transformative pathways for sustainable development

The current state and future fate of the Amazon are inextricably bound to that of the entire Neotropical region, the global biosphere as a whole, and the future of civilization worldwide (*45*, *48*, *96*). Preserving Amazonian biodiversity and ecosystem services will require fundamental changes to legal, economic, and energy systems at both regional and global scales. Policy actions must be implemented to reverse climate change and reduce economic incentives in the international trade system that support export-driven economic development (*97*). These changes to international legal and economic systems must deliberately be built into the next phase of the Anthropocene, when civilization transitions from carbon-based to renewable energy technologies and a bioeconomy of healthy standing forest and flowing rivers with sustainable governance (*98*, *99*).

A new legal framework

Successful economic development in many parts of the world has historically rested on a robust legal framework that incentivizes prosocial—and disincentivizes antisocial—behaviors and activities (*100*–*102*). Recent advances in environmental ethics and international justice provide robust legal standing for natural entities such as landscape features (rivers and forests) and nonhuman species (*103*, *104*). For example, in a landmark ruling, the Constitutional Court of Ecuador applied the constitutional provision on the "Rights of Nature" to safeguard cloud forests from mining concessions (*4*, *105*). This legal precedent was grounded in decades of scholarship (*106*, *107*), and similar laws have been codified in other countries (*98*, *108*). "Earth system law" provides a complementary approach for addressing gaps in governance that arise from improper deregulation and dispersed regulatory architecture across institutions and geographic regions (*25*, *109*). These legal tools can be designed to impose criminal penalties of heavy fines and imprisonment to criminalize activities that wantonly and substantially damage or destroy Amazonian ecosystems or that harm the health and well-being of Amazonian species (*110*, *111*). The importance of legal mechanisms in landscape preservation is well demonstrated by the success of the PPCDAm in reducing deforestation in Brazil from 2004 to 2015 and by decisions made at the federal level not to prosecute illegal activities that dramatically accelerated deforestation from 2016 to 2022 (*112*).

A new Amazonian bioeconomy

The sustainable use of biodiversity resources is an important path for developing Amazonian economies to become integrated into the international economy under advantageous conditions (*99*). More than 40 million people inhabit the Amazon region, with more than 65% living in urban areas, all of whom are affected by climate change. IPLCs play a critical role in shaping, protecting, and restoring ecosystems, biodiversity, and cultural diversity in the Amazon (*113*, *114*). A successful bioeconomy extends beyond extractive and export-based economic activities (such as lumber, mining, soy, and cattle) by prioritizing and monetizing biodiversity and ecosystem services and promoting broad development goals in education, health, sanitation, and employment. Improving the quality of life of the Amazonian population—in urban, peri-urban, and rural areas—is one of the principles of a bioeconomy based on standing forests and flowing rivers.

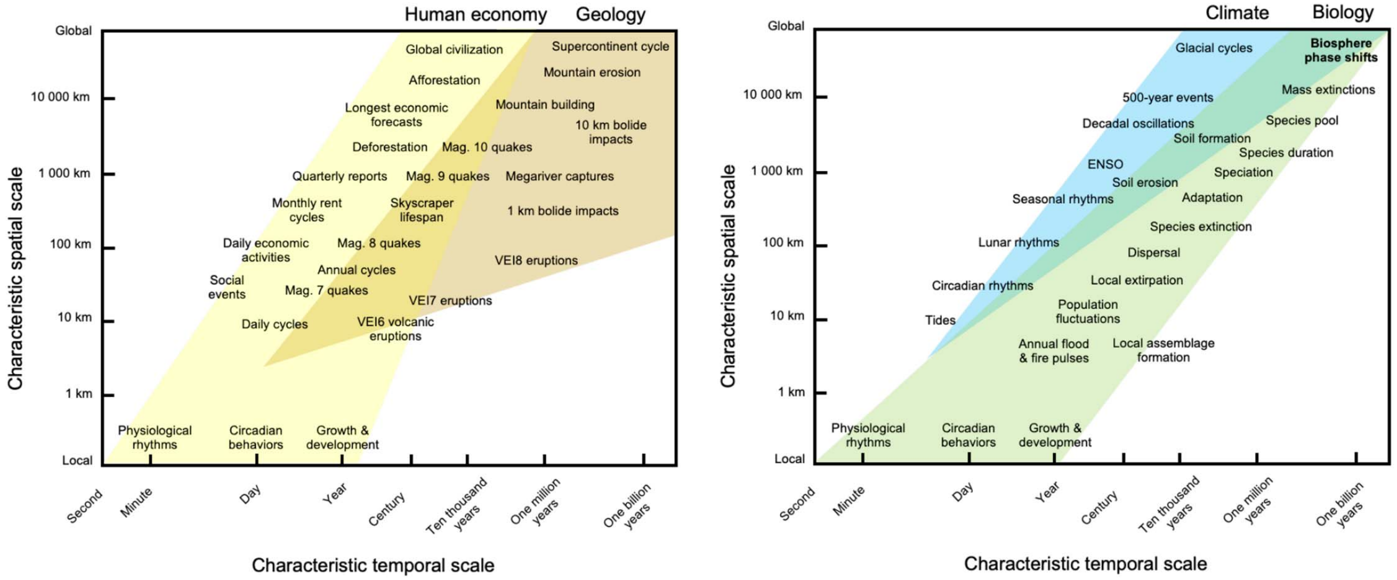

Fig. 2. Stommel diagrams estimating the temporal and spatial scales for 52 natural processes across four domains. (**Left**) Human economy (*73*, *76*, *77*, *138*–*142*) and geology (*143*–*152*). (**Right**) Climate (*81*, *153*, *154*) and biology (*155*–*157*). Axes are plotted by using logarithmic scales, with log seconds on the horizontal axis and log kilometers on the vertical axis. Biosphere phase shifts (top right) include long-wave climate (greenhouse-icehouse) cycles and distinct events such as the Neoproterozoic formation of an oxidizing atmosphere, Cambrian explosion of animal body plans, Devonian colonization of the continents and formation of terrestrial biotas, and the Anthropocene climate and biodiversity crises. Human economic activities affect larger spatial scales more rapidly than do most other natural processes.

Desired outcomes of a new Amazonian bioeconomy optimize carbon sequestration, biodiversity recovery, and human livelihoods (*115*, *116*). Sustainable bioeconomic development projects are most effective when they integrate modern scientific and commercial resources of urban communities with the traditional knowledge and skills accumulated by Indigenous and local farming communities over many generations (*48*). Lasting sustainability means prolonged coexistence of natural and human economic and social systems, and Amazonian development projects must therefore meet the immediate and long-term needs of the Amazonian population. Paramount among these needs are high-quality communication and transportation services to improve the commercialization of products, as well as institutional investments and international collaborations that support education, science, and technology institutions located within the Amazon. The installation of any new large-scale infrastructure projects (such as mega-dams or transportation arteries exceeding 500 km) must be avoided and replaced with low-impact alternatives (*117*). Mining initiatives that threaten Indigenous lands, the health of all Amazonian inhabitants, and biodiversity should also be avoided.

Resilient planning and management of Amazonian bioresources must necessarily prioritize the social and political actions that preserve species, habitat diversity, and functional redundancy; manage connectivity and feedback that stabilize longer-term processes over decades; promote reciprocal cultural and educational exchanges; and enhance integrated and decentralized (versus hierarchical and centralized) governance (*117*–*119*). Rates of deforestation in the Amazon since 2000 have closely responded to policy changes enacted at the national level that affect these kinds of social and political actions (*117*, *119*).

By contrast, market mechanisms based on international commodity pricing have entirely failed to assess the real economic and social values of Amazonian landscape and ecosystem resources (*99*, *120*). Further, prospects are dim for using market forces in landscape conservation efforts in the near future (*51*). Public policies to correct these market failures are available, modeled from strategies successfully used in other regions of the world where standing forests and flowing rivers have been allowed to persist for multiple decades, even under the context of intensive economic development (*121*, *122*). These policies successfully price the full market value of ecosystem services, provide incentives for activities that support forest and river preservation, and impose penalties for predatory and negligent actions (*123*).

The "Grand Energy Transition"

Preserving Amazonian biodiversity and ecosystem services requires modifying economic incentives in the international trade system that drive export-driven development (*97*). Such a Grand Energy Transition is already well underway (*124*); the average cost per unit energy for renewable energies has fallen below that of fossil fuels in aggregate for the first time in human history (*125*). Yet the barriers to complete this transition remain high, including the high costs of infrastructure installation and resistance by powerful stakeholders of the carbon economy (*126*). One of the biggest challenges is the high volume of fossil carbon still sequestered within the lithosphere; about 60% of oil and fossil methane gas and 90% of coal must be left in the ground to limit global warming to 1.5°C (*127*).

Yet time is running short. Emerging technologies, social innovations, and broader shifts in cultural practices are being implemented to support a resilient biosphere and help maintain a healthy Amazon (*95*, *128*). These shifts can be accelerated with economic and legal actions that support a post-carbon global economy that includes alternative energies, CO_2 capture and sequestration, and possibly geoengineering. New socioeconomic innovations must prioritize circular economic supply and waste networks and nurture green values and land ethics. New political and ecological innovations require coordination among leaders from the local, regional, and national levels. Widespread public support for greener development has already had qualitative impacts in many settings, and public awareness must be increased in Amazonian countries to influence elections and political decisions concerning environmental protection (*129*).

Policy actions and priorities

Long-term (decades to centuries) conservation critically relies on economic and legal support to Amazonian universities, research institutions, and scientific collections. These academic institutions are singularly situated to document Amazonian systems at multiple structural, geographic, and temporal scales and to characterize poorly known organisms (such as plants, fungi, invertebrates, and microbes), which are the "ecosystem engineers" that regulate biogeochemical cycles in Amazonian soils and surface and ground waters. These institutions also provide the skilled labor force required to monitor Amazonian environments through time and to train the next generation of Amazonian scientists.

Yet action is also required at broader scales. The global community must work closely and swiftly with national governments whose sovereignty includes Amazonian territory to enact economic, legal, and scientific actions that limit global warming to 1.5°C above preindustrial levels (*130*) and disincentivize activities for commodity export, especially soy, beef, timber, mineral, and hydrocarbon extraction (*131*). These actions are abstracted from the SPA Assessment Report (*1*, *132*) and other recent global environmental assessments (*133*, *134*). These actions recognize the knowledge and rights of IPLCs, who play a critical role in shaping, protecting, and restoring ecosystems and biodiversity in the Amazon and other tropical regions (*25*, *131*, *132*).

The most effective conservation actions enhance legal protections and punish illegal activities for areas under public, private, community, and Indigenous management, and reward companies, agencies, and communities committed to sustainable economic practices (*132*, *135*–*137*). These actions prioritize partnerships with IPLCs, areas with distinctive and threatened species, ecosystems, culturally important landforms, and the highest anthropogenic threat—those with the most rapidly expanding human footprint. International financial institutions (such as IDB and BRI) must immediately suspend funding for IIRSA mega-infrastructure projects (such as roads, bridges, railways, dams, ports, and mines) in Amazonia, pending thorough, independent, and regional-scale environmental assessments (*135*). Annual commodity supply chain reports of imports by country will enhance accountability. Success critically relies on robust, long-term partnerships among Amazonian people in the business, scientific, and IPLC communities. These partnerships provide sustained administrative, financial, and legal resources to IPLCs to secure land tenure rights; monitor, protect, and restore Amazonian ecosystems and biodiversity; and exchange biodiversity and conservation information between academic and local knowledge bases.

As we approach an irreversible tipping point for Amazonia, the global community must act now. Policies to prevent the worst outcomes have been successfully identified, but implementation is a matter of leadership and political will. To fail the Amazon is to fail the biosphere, and we fail to act at our own peril.

REFERENCES AND NOTES

1. Science Panel for the Amazon (SPA), *Amazon Assessment Report 2021* (United Nations Sustainable Development Solutions Network, 2021).
2. I. Amigo, When will the Amazon hit a tipping point? *Nature* **578**, 505–507 (2020). doi: 10.1038/d41586-020-00508-4; pmid: 32099130
3. M. H. Costa *et al*., in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
4. J. M. Guayasamin *et al*., in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
5. E. Berenguer *et al*., in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
6. A. Antonelli *et al*., Amazonia is the primary source of Neotropical biodiversity. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 6034–6039 (2018). doi: 10.1073/pnas.1713819115; pmid: 29760058
7. A. S. Meseguer, P. O. Antoine, A. Fouquet, F. Delsuc, F. L. Condamine, The role of the Neotropics as a source of world tetrapod biodiversity. *Glob. Ecol. Biogeogr.* **29**, 1565–1578 (2020). doi: 10.1111/geb.13141

8. P. H. Raven *et al*., The distribution of biodiversity richness in the tropics. *Sci. Adv.* **6**, eabc6228 (2020). doi: 10.1126/sciadv.abc6228; pmid: 32917691
9. Y. Malhi *et al*., in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
10. M. Jung *et al*., Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nat. Ecol. Evol.* **5**, 1499–1509 (2021). doi: 10.1038/s41559-021-01528-7; pmid: 34429536
11. M. H. Costa, L. Borma, P. M. Brando, J. A. Marengo, S. R. Saleska, L. v. Gatti, in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
12. X. Xu, G. Jia, X. Zhang, W. J. Riley, Y. Xue, Climate regime shift and forest loss amplify fire in Amazonian forests. *Glob. Chang. Biol.* **26**, 5874–5885 (2020). doi: 10.1111/gcb.15279; pmid: 32662146
13. W. Steffen *et al*., Trajectories of the Earth System in the Anthropocene. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 8252–8259 (2018). doi: 10.1073/pnas.1810141115; pmid: 30082409
14. R. B. Larson, *Just Add Water: Solving the World's Problems Using its Most Precious Resource* (Oxford Univ. Press, 2020); https://academic.oup.com/book/33629.
15. J. Marotzke, D. Semmann, M. Milinski, The economic interaction between climate change mitigation, climate migration and poverty. *Nat. Clim. Chang.* **10**, 518–525 (2020). doi: 10.1038/s41558-020-0783-3
16. D. J. Kaczan, J. Orgill-Meyer, The impact of climate change on migration: A synthesis of recent empirical insights. *Clim. Change* **158**, 281–300 (2019). doi: 10.1007/s10584-019-02560-0
17. V. Radchuk *et al*., Adaptive responses of animals to climate change are most likely insufficient. *Nat. Commun.* **10**, 3109 (2019). doi: 10.1038/s41467-019-10924-4; pmid: 31337752
18. C. A. Nunes *et al*., Linking land-use and land-cover transitions to their ecological impact in the Amazon. *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2202310119 (2022). doi: 10.1073/pnas.2202310119; pmid: 35759674
19. C. A. Boulton, T. M. Lenton, N. Boers, Pronounced loss of Amazon rainforest resilience since the early 2000s. *Nat. Clim. Chang.* **12**, 271–278 (2022). doi: 10.1038/s41558-022-01287-8
20. D. C. da Cruz, J. M. R. Benayas, G. C. Ferreira, S. R. Santos, G. Schwartz, An overview of forest loss and restoration in the Brazilian Amazon. *New For.* **52**, 1–16 (2021). doi: 10.1007/s11056-020-09777-3
21. MapBiomas Amazonia, Collection 2.0 of annual maps of land cover, land use and land use changes between 1985 to 2018 in the Pan-Amazon (2020); https://amazonia.mapbiomas.org.
22. W. Hubau *et al*., Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* **579**, 80–87 (2020). doi: 10.1038/s41586-020-2035-0; pmid: 32132693
23. M. J. P. Sullivan *et al*., Long-term thermal sensitivity of Earth's tropical forests. *Science* **368**, 869–874 (2020). doi: 10.1126/science.aaw7578; pmid: 32439789
24. L. v. Gatti *et al*., in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
25. T. Kukla *et al*., The resilience of Amazon tree cover to past and present drying. *Global Planet. Change* **202**, 103520 (2021). doi: 10.1016/j.gloplacha.2021.103520
26. Y. Qin *et al*., Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. *Nat. Clim. Chang.* **11**, 442–448 (2021). doi: 10.1038/s41558-021-01026-5
27. J. Barichivich *et al*., Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation. *Sci. Adv.* **4**, eaat8785 (2018). doi: 10.1126/sciadv.aat8785; pmid: 30255149
28. D. J. BertassoliJr *et al*., Spatiotemporal variations of riverine discharge within the Amazon basin during the late Holocene coincide with extratropical temperature anomalies. *Geophys. Res. Lett.* **46**, 9013–9022 (2019). doi: 10.1029/2019GL082936
29. I. S. A. A. Bezerra *et al*., Incision and aggradation phases of the Amazon River in central-eastern Amazonia during the late Neogene and Quaternary. *Geomorphology* **399**, 108073 (2022). doi: 10.1016/j.geomorph.2021.108073
30. H. Sato *et al*., Dry corridors opened by fire and low CO_2 in Amazonian rainforest during the Last Glacial Maximum. *Nat. Geosci.* **14**, 578–585 (2021). doi: 10.1038/s41561-021-00777-2
31. M. B. Bush *et al*., Widespread reforestation before European influence on Amazonia. *Science* **372**, 484–487 (2021). doi: 10.1126/science.abf3870; pmid: 33926948
32. O. Mottl *et al*., Global acceleration in rates of vegetation change over the past 18,000 years. *Science* **372**, 860–864 (2021). doi: 10.1126/science.abg1685; pmid: 34016781
33. S. Payette, in *Ecosystem Collapse and Climate Change*, J. G. Canadell, R. B. Jackson, Eds. (Springer, 2021), vol. 241, pp. 101–129; https://link.springer.com/chapter/10.1007/978-3-030-71330-0_5.
34. J. S. Albert, V. A. Tagliacollo, F. Dagosta, Diversification of Neotropical Freshwater Fishes. *Annu. Rev. Ecol. Evol. Syst.* **51**, 27–53 (2020). doi: 10.1146/annurev-ecolsys-011620-031032
35. N. Wunderling, J. F. Donges, J. Kurths, R. Winkelmann, Interacting tipping elements increase risk of climate domino effects under global warming. *Earth Syst. Dyn.* **12**, 601–619 (2021). doi: 10.5194/esd-12-601-2021
36. A. Cardil *et al*., Recent deforestation drove the spike in Amazonian fires. *Environ. Res. Lett.* **15**, 121003 (2020). doi: 10.1088/1748-9326/abcac7
37. J. C. O'Connor *et al*., Forests buffer against variations in precipitation. *Glob. Chang. Biol.* **27**, 4686–4696 (2021). doi: 10.1111/gcb.15763; pmid: 34319636
38. F. Hofhansl *et al*., Climatic and edaphic controls over tropical forest diversity and vegetation carbon storage. *Sci. Rep.* **10**, 5066 (2020). doi: 10.1038/s41598-020-61868-5; pmid: 32193471
39. A. Staal *et al*., Hysteresis of tropical forests in the 21st century. *Nat. Commun.* **11**, 4978 (2020). doi: 10.1038/s41467-020-18728-7; pmid: 33020475
40. G. S. Cooper, S. Willcock, J. A. Dearing, Regime shifts occur disproportionately faster in larger ecosystems. *Nat. Commun.* **11**, 1175 (2020). doi: 10.1038/s41467-020-15029-x; pmid: 32157098
41. B. M. Flores, M. Holmgren, White-sand savannas expand at the core of the Amazon after forest wildfires. *Ecosystems* **24**, 1624–1637 (2021). doi: 10.1007/s10021-021-00607-x
42. M. Goulding *et al*., Ecosystem-based management of Amazon fisheries and wetlands. *Fish Fish.* **20**, 138–158 (2019). doi: 10.1111/faf.12328
43. A. L. B. Fares, F. A. S. Nonato, T. S. Michelan, New records of the invasive macrophyte, *Urochloa arrecta* extend its range to eastern Brazilian Amazon altered freshwater ecosystems. *Acta Amazon.* **50**, 133–137 (2020). doi: 10.1590/1809-4392201903831
44. A. Rosell-Melé *et al*., Oil pollution in soils and sediments from the Northern Peruvian Amazon. *Sci. Total Environ.* **610-611**, 1010–1019 (2018). doi: 10.1016/j.scitotenv.2017.07.208; pmid: 28847095
45. Y. le Polain de Waroux *et al*., The restructuring of South American soy and beef production and trade under changing environmental regulations. *World Dev.* **121**, 188–202 (2019). doi: 10.1016/j.worlddev.2017.05.034
46. L. Ferrante, P. M. Fearnside, Countries should boycott Brazil over export-driven deforestation. *Nature* **601**, 318–318 (2022). doi: 10.1038/d41586-022-00094-7; pmid: 35042995
47. E. L. Bullock, C. E. Woodcock, C. SouzaJr.., P. Olofsson, Satellite-based estimates reveal widespread forest degradation in the Amazon. *Glob. Chang. Biol.* **26**, 2956–2969 (2020). doi: 10.1111/gcb.15029; pmid: 32022338
48. S. Hecht *et al*., in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
49. A. Franco-Solís, C. Montanía, Dynamics of deforestation worldwide: A structural decomposition analysis of agricultural land use in South America. *Land Use Policy* **109**, 105619 (2021). doi: 10.1016/j.landusepol.2021.105619
50. X. He, G. M. DePaula, W. Zhang, in *2021 Agricultural & Applied Economics Association Annual Meeting* (Agricultural & Applied Economics Association, 2021); https://ageconsearch.umn.edu/record/312818.
51. G. M. DePaula, L. Justino, in *2020 Annual Meeting* (Agricultural and Applied Economics Association, Kansas City, Missouri, 2020); https://ageconsearch.umn.edu/record/304482.
52. X. P. Song *et al*., Massive soybean expansion in South America since 2000 and implications for conservation. *Nat. Sustain.* **2021**, 784–792 (2021). doi: 10.1038/s41893-021-00729-z; pmid: 34377840
53. R. Rajão *et al*., The rotten apples of Brazil's agribusiness. *Science* **369**, 246–248 (2020). doi: 10.1126/science.aba6646; pmid: 32675358
54. R. T. Walker *et al*., Avoiding Amazonian catastrophes: Prospects for conservation in the 21st century. *One Earth* **1**, 202–215 (2019). doi: 10.1016/j.oneear.2019.09.009
55. B. A. Roy *et al*., New mining concessions could severely decrease biodiversity and ecosystem services in Ecuador. *Trop. Conserv. Sci.* 10.1177/1940082918780427 (2018). doi: 10.1177/1940082918780427
56. R. Andrade, in *The Political Economy of Hydropower in Southwest China and Beyond*, H.-S. S. Rousseau, Ed., International Political Economy Series (Palgrave Macmillan, 2021), pp. 275–293; https://link.springer.com/chapter/10.1007/978-3-030-59361-2_14.
57. V. S. Daga *et al*., Water diversion in Brazil threatens biodiversity. *Ambio* **49**, 165–172 (2020). doi: 10.1007/s13280-019-01189-8; pmid: 31030418
58. D. M. Larrea-Alcázara, N. Cuvi, J. F. Valentim, L. Diaz, S. Vidal, G. Palacio, in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
59. R. Heilmayr, L. L. Rausch, J. Munger, H. K. Gibbs, Brazil's Amazon Soy Moratorium reduced deforestation. *Nat. Food* **1**, 801–810 (2020). doi: 10.1038/s43016-020-00194-5
60. K. F. de Moraes *et al*., Climate change and bird extinctions in the Amazon. *PLOS ONE* **15**, e0236103 (2020). doi: 10.1371/journal.pone.0236103; pmid: 32678834
61. G. A. Herrera-R *et al*., The combined effects of climate change and river fragmentation on the distribution of Andean Amazon fishes. *Glob. Chang. Biol.* **26**, 5509–5523 (2020). doi: 10.1111/gcb.15285; pmid: 32785968
62. P. G. Zaninelli, C. G. Menéndez, M. Falco, N. López-Franca, A. F. Carril, Future hydroclimatological changes in South America based on an ensemble of regional climate models. *Clim. Dyn.* **52**, 819–830 (2019). doi: 10.1007/s00382-018-4225-0
63. M. Iturbide *et al*., An update of IPCC climate reference regions for subcontinental analysis of climate model data: Definition and aggregated datasets. *Earth Syst. Sci. Data* **12**, 2959–2970 (2020). doi: 10.5194/essd-12-2959-2020
64. J. C. Espinoza, J. A. Marengo, J. Schongart, J. C. Jimenez, The new historical flood of 2021 in the Amazon River compared to major floods of the 21st century: Atmospheric features in the context of the intensification of floods. *Weather Clim. Extrem.* **35**, 100406 (2022). doi: 10.1016/j.wace.2021.100406
65. D. A. Edmonds, R. L. Caldwell, E. S. Brondizio, S. M. O. Siani, Coastal flooding will disproportionately impact people on river deltas. *Nat. Commun.* **11**, 4741 (2020). doi: 10.1038/s41467-020-18531-4; pmid: 32994404
66. M. Moraes R., *et al*., in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
67. V. Rull, A. C. Carnaval, *Neotropical Diversification: Patterns and Processes*, Fascinating Life Sciences (Springer International Publishing, 2020); http://link.springer.com/10.1007/978-3-030-31167-4.
68. S. Sanderson *et al*., The pace of modern life, revisited. *Mol. Ecol.* **31**, 1028–1043 (2022). doi: 10.1111/mec.16299; pmid: 34902193
69. D. R. Williams *et al*., Proactive conservation to prevent habitat losses to agricultural expansion. *Nat. Sustain.* **4**, 314–322 (2020). doi: 10.1038/s41893-020-00656-5
70. R. S. Nerem *et al*., Climate-change-driven accelerated sea-level rise detected in the altimeter era. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 2022–2025 (2018). doi: 10.1073/pnas.1717312115; pmid: 29440401
71. A. J. Chadwick, M. P. Lamb, V. Ganti, Accelerated river avulsion frequency on lowland deltas due to sea-level rise. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 17584–17590 (2020). doi: 10.1073/pnas.1912351117; pmid: 32661152
72. C. H. L. Silva Junior *et al*., The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade. *Nat. Ecol. Evol.* **5**, 144–145 (2021). doi: 10.1038/s41559-020-01368-x; pmid: 33349655
73. E. A. T. Matricardi *et al*., Long-term forest degradation surpasses deforestation in the Brazilian Amazon. *Science* **369**, 1378–1382 (2020). doi: 10.1126/science.abb3021; pmid: 32913104
74. M. Davis, S. Faurby, J. C. Svenning, Mammal diversity will take millions of years to recover from the current biodiversity crisis. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 11262–11267 (2018). doi: 10.1073/pnas.1804906115; pmid: 30322924
75. A. Esquivel-Muelbert *et al*., Compositional response of Amazon forests to climate change. *Glob. Chang. Biol.* **25**, 39–56 (2019). doi: 10.1111/gcb.14413; pmid: 30406962
76. A. Cendrero, L. M. Forte, J. Remondo, J. A. Cuesta-Albertos, Anthropocene geomorphic change. Climate or human activities? *Earths Futur.* **8**, e2019EF001305 (2020). doi: 10.1029/2019EF001305

77. G. H. E. Lense, J. C. Avanzi, T. C. Parreiras, R. L. Mincato, Effects of deforestation on water erosion rates in the Amazon region. *Agraria* **15**, 1–7 (2020). doi: 10.5039/agraria.v15i4a8500
78. C. W. Arnscheidt, D. H. Rothman, The balance of nature: A global marine perspective. *Ann. Rev. Mar. Sci.* **14**, 49–73 (2022). doi: 10.1146/annurev-marine-010318-095212; pmid: 34115541
79. V. Brovkin *et al*., Past abrupt changes, tipping points and cascading impacts in the Earth system. *Nat. Geosci.* **14**, 550–558 (2021). doi: 10.1038/s41561-021-00790-5
80. R. Hannah, R. Max, Forests and Deforestation—Our World in Data (2021); https://ourworldindata.org/forests-and-deforestation.
81. P. Borrelli *et al*., Land use and climate change impacts on global soil erosion by water (2015-2070). *Proc. Natl. Acad. Sci. U.S.A.* **117**, 21994–22001 (2020). doi: 10.1073/pnas.2001403117; pmid: 32839306
82. S. Jasechko, D. Perrone, Global groundwater wells at risk of running dry. *Science* **372**, 418–421 (2021). doi: 10.1126/science.abc2755; pmid: 33888642
83. P. Friedlingstein *et al*., Global Carbon Budget 2021. *Earth Syst. Sci. Data Discuss.* **2021**, 1–191 (2021).
84. C. Burton *et al*., South American fires and their impacts on ecosystems increase with continued emissions. *Clim. Resil. Sustain.* **1**, e8 (2022). doi: 10.1002/cli2.8
85. L. V. Gatti *et al*., Amazonia as a carbon source linked to deforestation and climate change. *Nature* **595**, 388–393 (2021). doi: 10.1038/s41586-021-03629-6; pmid: 34262208
86. R. Hamilton *et al*., Non-uniform tropical forest responses to the 'Columbian Exchange' in the Neotropics and Asia-Pacific. *Nat. Ecol. Evol.* **5**, 1174–1184 (2021). doi: 10.1038/s41559-021-01474-4; pmid: 34112995
87. G. L. Foster, D. L. Royer, D. J. Lunt, Future climate forcing potentially without precedent in the last 420 million years. *Nat. Commun.* **8**, 14845–14848 (2017). doi: 10.1038/ncomms14845; pmid: 28375201
88. P. Voosen, Ice shelf holding back keystone Antarctic glacier within years of failure. *Science* **374**, 1420–1421 (2021). doi: 10.1126/science.acz9833; pmid: 34914505
89. E. C. Pettit *et al*., in *AGU Fall Meeting* (AGU, 2021); https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/978762.
90. J. E. Tierney *et al*., Past climates inform our future. *Science* **370**, eaay3701 (2020). doi: 10.1126/science.aay3701; pmid: 33154110
91. S. Dangendorf *et al*., Persistent acceleration in global sea-level rise since the 1960s. *Nat. Clim. Chang.* **9**, 705–710 (2019). doi: 10.1038/s41558-019-0531-8
92. G. N. Inglis *et al*., Global mean surface temperature and climate sensitivity of the early Eocene Climatic Optimum (EECO), Paleocene-Eocene Thermal Maximum (PETM), and latest Paleocene. *Clim. Past* **16**, 1953–1968 (2020). doi: 10.5194/cp-16-1953-2020
93. L. L. Haynes, B. Hönisch, The seawater carbon inventory at the Paleocene-Eocene Thermal Maximum. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 24088–24095 (2020). doi: 10.1073/pnas.2003197117; pmid: 32929018
94. R. Guoyu *et al*., Characteristics, drivers and feedbacks of paleo-climatic variations and the implications for modern climate change research. *J. Quat. Sci.* **41**, 824–841 (2021).
95. C. Folke *et al*., Our future in the Anthropocene biosphere. *Ambio* **50**, 834–869 (2021). doi: 10.1007/s13280-021-01544-8; pmid: 33715097
96. D. Leclère *et al*., Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551–556 (2020). doi: 10.1038/s41586-020-2705-y; pmid: 32908312
97. T. A. Gardner *et al*., Transparency and sustainability in global commodity supply chains. *World Dev.* **121**, 163–177 (2019). doi: 10.1016/j.worlddev.2018.05.025; pmid: 31481824
98. G. Chapron, Y. Epstein, J. V. López-Bao, A rights revolution for nature. *Science* **363**, 1392–1393 (2019). doi: 10.1126/science.aav5601; pmid: 30872530
99. R. Abramovay *et al*., in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
100. C. Kremen, A. M. Merenlender, Landscapes that work for biodiversity and people. *Science* **362**, eaau6020 (2018). doi: 10.1126/science.aau6020; pmid: 30337381
101. N. E. Nedzel, *The Rule of Law, Economic Development, and Corporate Governance* (Edward Elgar Publishing, 2020).
102. A. Di Sacco *et al*., Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. *Glob. Chang. Biol.* **27**, 1328–1348 (2021). doi: 10.1111/gcb.15498; pmid: 33494123
103. D. Wilkinson, in *Locality and Identity: Environmental Issues in Law and Society* (Taylor and Francis, 2019), pp. 17–50; https://www.taylorfrancis.com/chapters/edit/10.4324/9780429449925-2/using-environmental-ethics-create-ecological-law-david-wilkinson.
104. B. E. Rollin, in *Problems of International Justice* (Taylor and Francis, 2019), pp. 124–1437; https://www.taylorfrancis.com/chapters/edit/10.4324/9780429303111-8/environmental-ethics-international-justice-bernard-rollin.
105. J. M. Guayasamin *et al*., Biodiversity conservation: local and global consequences of the application of 'rights of nature' by Ecuador. *Neotrop. Biodivers.* **7**, 541–545 (2021).
106. C. D. Stone, *Should Trees Have Standing? Law, Morality, and the Environment | Environment & Society Portal* (Oxford Univ. Press, ed. 3, 2010); https://www.environmentandsociety.org/mml/should-trees-have-standing-law-morality-and-environment.
107. D. R. Boyd, *Rights of Nature: A Legal Revolution That Could Save the World* (ECW Press, 2017).
108. E. L. O'Donnell, J. Talbot-Jones, Creating legal rights for rivers: Lessons from Australia, New Zealand, and India. *Ecol. Soc.* **23**, art7 (2018). doi: 10.5751/ES-09854-230107
109. X. Feng *et al*., How deregulation, drought and increasing fire impact Amazonian biodiversity. *Nature* **597**, 516–521 (2021). doi: 10.1038/s41586-021-03876-7; pmid: 34471291
110. P. Higgins, D. Short, N. South, Protecting the planet: A proposal for a law of ecocide. *Crime Law Soc. Change* **59**, 251–266 (2013). doi: 10.1007/s10611-013-9413-6
111. M. Lynch, Regressive prosecutors: Law and order politics and practices in Trump's DOJ. *Hastings J. Crime Punish* **1**, 195 (2020).
112. T. A. P. West, P. M. Fearnside, Brazil's conservation reform and the reduction of deforestation in Amazonia. *Land Use Policy* **100**, 105072 (2021). doi: 10.1016/j.landusepol.2020.105072
113. S. Díaz *et al*., Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* **366**, eaax3100 (2019). doi: 10.1126/science.aax3100; pmid: 31831642
114. E. S. Brondízio *et al*., Locally based, regionally manifested, and globally relevant: Indigenous and local knowledge, values, and practices for nature. *Annu. Rev. Environ. Resour.* **46**, 481–509 (2021). doi: 10.1146/annurev-environ-012220-012127
115. D. E. Bunker *et al*., Species loss and aboveground carbon storage in a tropical forest. *Science* **310**, 1029–1031 (2005). doi: 10.1126/science.1117682; pmid: 16239439
116. C. E. Wheeler *et al*., Carbon sequestration and biodiversity following 18 years of active tropical forest restoration. *For. Ecol. Manage.* **373**, 44–55 (2016). doi: 10.1016/j.foreco.2016.04.025
117. B. Soares-Filho, R. Rajão, Traditional conservation strategies still the best option. *Nat. Sustain.* **1**, 608–610 (2018). doi: 10.1038/s41893-018-0179-9
118. R. Agudelo *et al*., Land use planning in the Amazon basin: Challenges from resilience thinking. *Ecol. Soc.* **25**, 18 (2020).
119. INPE — Coordenação-Geral de Observação da Terra, "PRODES 2020: Monitoramento do Desmatamento da Floresta Amazônica Brasileira por Satélite" (2020); http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes.
120. N. Stern, J. Stiglitz, C. Taylor, The economics of immense risk, urgent action and radical change: Towards new approaches to the economics of climate change. *J. Econ. Methodol.* **29**, 181–216 (2022). doi: 10.1080/1350178X.2022.2040740
121. A. A. Min-Venditti, G. W. Moore, F. Fleischman, What policies improve forest cover? A systematic review of research from Mesoamerica. *Glob. Environ. Change* **47**, 21–27 (2017). doi: 10.1016/j.gloenvcha.2017.08.010
122. R. Hajjar, J. A. Oldekop, Research frontiers in community forest management. *Curr. Opin. Environ. Sustain.* **32**, 119–125 (2018). doi: 10.1016/j.cosust.2018.06.003
123. R. Brouwer, R. Pinto, A. Dugstad, S. Navrud, The economic value of the Brazilian Amazon rainforest ecosystem services: A meta-analysis of the Brazilian literature. *PLOS ONE* **17**, e0268425 (2022). doi: 10.1371/journal.pone.0268425; pmid: 35588116
124. M. Paldam, *The Grand Pattern of Development and the Transition of Institutions* (Cambridge Univ. Press, 2021).
125. IRENA, "World Energy Transitions Outlook: 1.5°C Pathway" (Abu Dhabi, 2021); https://irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook.
126. C. Wilson *et al*., Granular technologies to accelerate decarbonization. *Science* **368**, 36–39 (2020). doi: 10.1126/science.aaz8060; pmid: 32241941
127. D. Welsby, J. Price, S. Pye, P. Ekins, Unextractable fossil fuels in a 1.5 °C world. *Nature* **597**, 230–234 (2021). doi: 10.1038/s41586-021-03821-8; pmid: 34497394
128. J. Rockström, O. Edenhofer, J. Gaertner, F. DeClerck, Planet-proofing the global food system. *Nat. Food* **1**, 3–5 (2020). doi: 10.1038/s43016-019-0010-4
129. A. A. Zuniga-Teran *et al*., Challenges of mainstreaming green infrastructure in built environment professions. *J. Environ. Plann. Manage.* **63**, 710–732 (2019). doi: 10.1080/09640568.2019.1605890
130. C. Levis *et al*., Help restore Brazil's governance of globally important ecosystem services. *Nat. Ecol. Evol.* **4**, 172–173 (2020). doi: 10.1038/s41559-019-1093-x; pmid: 32015426
131. S. Athayde *et al*., in *Amazon Assessment Report 2021*, C. Nobre *et al*., Eds. (United Nations Sustainable Development Solutions Network, 2021).
132. IPBES, (2019), *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES secretariat, 2019); https://www.ipbes.net/global-assessment.
133. M. H. Ruckelshaus *et al*., The IPBES Global Assessment: Pathways to Action. *Trends Ecol. Evol.* **35**, 407–414 (2020). doi: 10.1016/j.tree.2020.01.009; pmid: 32294422
134. P. R. Shukla *et al.*, "Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems" (IPCC, 2019).
135. K. O. Winemiller *et al*., Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* **351**, 128–129 (2016). doi: 10.1126/science.aac7082; pmid: 26744397
136. B. R. Scanlon, I. Jolly, M. Sophocleous, L. Zhang, Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water Resour. Res.* **43**, 3437 (2007). doi: 10.1029/2006WR005486
137. E. C. Ellis, K. K. Goldewijk, S. Siebert, D. Lightman, N. Ramankutty, Anthropogenic transformation of the biomes, 1700 to 2000. *Glob. Ecol. Biogeogr.* **19**, 589–606 (2010). doi: 10.1111/j.1466-8238.2010.00540.x
138. J. F. Bastin *et al*., The global tree restoration potential. *Science* **365**, 76–79 (2019). doi: 10.1126/science.aax0848; pmid: 31273120
139. D. C. da Cruz, J. M. R. Benayas, G. C. Ferreira, S. R. Santos, G. Schwartz, An overview of forest loss and restoration in the Brazilian Amazon. *New For.* **52**, 1–16 (2021). doi: 10.1007/s11056-020-09777-3
140. N. Saintilan *et al*., Thresholds of mangrove survival under rapid sea level rise. *Science* **368**, 1118–1121 (2020). doi: 10.1126/science.aba2656; pmid: 32499441
141. C. D. Storlazzi *et al*., Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Sci. Adv.* **4**, eaap9741 (2018). doi: 10.1126/sciadv.aap9741; pmid: 29707635
142. T. E. Törnqvist, K. L. Jankowski, Y.-X. Li, J. L. González, Tipping points of Mississippi Delta marshes due to accelerated sea-level rise. *Sci. Adv.* **6**, eaaz5512 (2020). doi: 10.1126/sciadv.aaz5512; pmid: 32494741
143. J. S. Albert, J. M. Craig, V. A. Tagliacollo, P. Petry, in *Mountains, Climate, and Biodiversity*, C. Hoorn, A. Perrigo, A. Antonelli, Eds. (John Wiley, ed. 1, 2018), pp. 273–294.
144. L. W. Alvarez, Mass extinctions caused by large bolide impacts. *Phys. Today* **40**, 24–33 (1987). doi: 10.1063/1.881078; pmid: 11542219
145. B. Gutenberg, C. F. Richter, *Seismicity of the Earth and Associated Phenomena* (Princeton Univ. Press, ed. 2, 1954).
146. C. G. A. Harrison, Rates of continental erosion and mountain building. *Geol. Rundsch.* **83**, 431–447 (1994). doi: 10.1007/BF00210556
147. N. E. Matthews, J. A. Vazquez, A. T. Calvert, Age of the Lava Creek supereruption and magma chamber assembly at Yellowstone based on 40Ar/39Ar and U-Pb dating of sanidine and zircon crystals. *Geochem. Geophys. Geosyst.* **16**, 2508–2528 (2015). doi: 10.1002/2015GC005881

148. P. Papale, W. Marzocchi, Volcanic threats to global society. *Science* **363**, 1275–1276 (2019). doi: 10.1126/science.aaw7201; pmid: 30898915
149. Y. Sawai, Y. Namegaya, Y. Okamura, K. Satake, M. Shishikura, Challenges of anticipating the 2011 Tohoku earthquake and tsunami using coastal geology. *Geophys. Res. Lett.* **39**, L21309 (2012). doi: 10.1029/2012GL053692
150. C. Wang, R. N. Mitchell, J. B. Murphy, P. Peng, C. J. Spencer, The role of megacontinents in the supercontinent cycle. *Geology* **49**, 402–406 (2021). doi: 10.1130/G47988.1
151. C. R. Neal, J. J. Mahoney, L. W. Kroenke, R. A. Duncan, M. G. Petterson, The Ontong Java Plateau. *Geophys. Monogr.* **100**, 183–216 (1997).
152. P. A. Bland, N. A. Artemieva, The rate of small impacts on Earth. *Meteorit. Planet. Sci.* **41**, 607–631 (2006). doi: 10.1111/j.1945-5100.2006.tb00485.x
153. W. C. Clark, Scales of climate impacts. *Clim. Change* **7**, 5–27 (1985). doi: 10.1007/BF00139438
154. M. Nearing, F. F. Pruski, M. R. O'Neal, Expected climate change impacts on soil erosion rates: A review. *J. Soil Water Conserv.* **59**, 43–50 (2004).
155. M. E. Clapham, P. R. Renne, Flood basalts and mass extinctions. *Annu. Rev. Earth Planet. Sci.* **47**, 275–303 (2019). doi: 10.1146/annurev-earth-053018-060136
156. P. D. Gingerich, Rates of evolution. *Annu. Rev. Ecol. Evol. Syst.* **40**, 657–675 (2009). doi: 10.1146/annurev.ecolsys.39.110707.173457
157. C. A. Suarez, M. Edmonds, A. P. Jones, Earth catastrophes and their impact on the carbon cycle. *Elements* **15**, 301–306 (2019). doi: 10.2138/gselements.15.5.301
158. S. Siebert *et al.*, A global data set of the extent of irrigated land from 1900 to 2005. *Hydrol. Earth Syst. Sci.* **19**, 1521–1545 (2015). doi: 10.5194/hess-19-1521-2015
159. S. Hu, Z. Niu, Y. Chen, L. Li, H. Zhang, Global wetlands: Potential distribution, wetland loss, and status. *Sci. Total Environ.* **586**, 319–327 (2017). doi: 10.1016/j.scitotenv.2017.02.001; pmid: 28190574
160. J. D. Milliman, K. L. Farnsworth, *River Discharge to the Coastal Ocean: A Global Synthesis* (Cambridge Univ. Press, 2011).
161. M. T. H. van Vliet *et al.*, Global river discharge and water temperature under climate change. *Glob. Environ. Change* **23**, 450–464 (2013). doi: 10.1016/j.gloenvcha.2012.11.002
162. K. C. Seto, M. Fragkias, B. Güneralp, M. K. Reilly, A meta-analysis of global urban land expansion. *PLOS ONE* **6**, e23777 (2011). doi: 10.1371/journal.pone.0023777; pmid: 21876770
163. M. C. Hansen *et al.*, High-resolution global maps of 21st-century forest cover change. *Science* **342**, 850–853 (2013). doi: 10.1126/science.1244693; pmid: 24233722
164. P. Val *et al.*, in *Amazon Assessment Report 2021*, C. Nobre *et al.*, Eds. (United Nations Sustainable Development Solutions Network, 2021).
165. L. Yahdjian, O. E. Sala, Climate change impacts on South American rangelands. *Rangelands* **30**, 34–39 (2008). doi: 10.2111/1551-501X(2008)30[34:CCIOSA]2.0.CO;2
166. M. Finer, C. N. Jenkins, S. L. Pimm, B. Keane, C. Ross, Oil and gas projects in the Western Amazon: Threats to wilderness, biodiversity, and indigenous peoples. *PLOS ONE* **3**, e2932 (2008). doi: 10.1371/journal.pone.0002932; pmid: 18716679
167. L. E. O. C. Aragão *et al.*, 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nat. Commun.* **9**, 536–12 (2018). doi: 10.1038/s41467-017-02771-y; pmid: 29440640
168. M. V. F. Silveira *et al.*, Drivers of fire anomalies in the Brazilian Amazon: Lessons learned from the 2019 fire crisis. *Land (Basel)* **9**, 516 (2020). doi: 10.3390/land9120516
169. A. Ivanov *et al.*, Siberian Traps large igneous province: Evidence for two flood basalt pulses around the Permo-Triassic boundary and in the Middle Triassic, and contemporaneous granitic magmatism. *Earth Sci. Rev.* **122**, 58–76 (2013). doi: 10.1016/j.earscirev.2013.04.001
170. R. N. Singh, K. R. Gupta, Workshop yields new insight into volcanism at Deccan Traps, India. *Eos* **75**, 356–356 (1994). doi: 10.1029/94EO01005
171. J. S. Albert, P. Val, C. Hoorn, The changing course of the Amazon River in the Neogene: Center stage for Neotropical diversification. *Neotrop. Ichthyol.* **16**, e180033 (2018). doi: 10.1590/1982-0224-20180033
172. N. Espurt *et al.*, Flat subduction dynamics and deformation of the South American plate: Insights from analog modeling. *Tectonics* **27**, TC3011 (2008). doi: 10.1029/2007TC002175
173. A. Rocha *et al.*, Pleistocene climatic oscillations associated with landscape heterogeneity of the South American dry diagonal explains the phylogeographic structure of the narrow-billed woodcreeper (*Lepidocolaptes angustirostris*, Dendrocolaptidae). *J. Avian Biol.* **51**, jav.02537 (2020). doi: 10.1111/jav.02537
174. F. Wittmann, W. J. Junk, in *The Wetland Book*, Finlayson C., Milton G., Prentice R., Davidson N., Eds. (Springer, 2016), pp. 1–20; https://link.springer.com/referenceworkentry/10.1007/978-94-007-6173-5_83-2.

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