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The Andes–Amazon–Atlantic pathway: A foundational hydroclimate system for social–ecological system sustainability

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The Amazon River Basin's extraordinary social–ecological system is sustained by various water phases, fluxes, and stores that are interconnected across the tropical Andes mountains, Amazon lowlands, and Atlantic Ocean. This "Andes–Amazon–Atlantic" (AAA) pathway is a complex hydroclimatic system linked by the regional water cycle through atmospheric circulation and continental hydrology. Here, we aim to articulate the AAA hydroclimate pathway as a foundational system for research, management, conservation, and governance of aquatic systems of the Amazon Basin. We identify and describe the AAA pathway as an interdependent, multidirectional, and multiscale hydroclimate system. We then present an assessment of recent (1981 to 2020) changes in the AAA pathway, primarily reflecting an acceleration in the rates of hydrologic fluxes (i.e., water cycle intensification). We discuss how the changing AAA pathway orchestrates and impacts social–ecological systems. We conclude with four recommendations for the sustainability of the AAA pathway in ongoing research, management, conservation, and governance.

Amazon Basin | freshwater | conservation | aquatic | South America

Along with being the world's largest river basin, the Amazon is widely recognized for its major influence on global climate, its extraordinary biodiversity, and its rich sociocultural diversity. These features of the Amazon Basin are linked, sustained, and shaped by the many forms, fluxes, and stores of water that are interconnected across the high-elevation tropical Andes mountains, Amazon lowlands, and Atlantic Ocean. This "Andes–Amazon–Atlantic" (AAA) hydroclimate pathway (Fig. 1) is linked by the regional water cycle through continental hydrology, moving water from the Andes to Amazon to Atlantic, and through large-scale atmospheric circulation, moving moisture from the Atlantic to Amazon to Andes (1).

The tropical Atlantic Ocean is the main source of moisture input to the Amazon Basin (2, 3) via evaporation and condensation processes, which are accelerated by warmer sea surface temperatures (SST) (4, 5). This atmospheric moisture forms "aerial rivers," which are essentially low-level winds of high humidity that move along preferential pathways (6). Driven by trade winds, aerial rivers flow westward from the Atlantic Ocean over the Amazon lowlands and toward the Andes Mountains, releasing precipitation. Along the way, aerial rivers are also recharged with moisture from forest evapotranspiration, a process also known as "moisture recycling" (7, 8). Once the aerial rivers hit the physical barrier of the Andes mountains, they turn southward and eventually go beyond the Amazon basin into central Brazil and the La Plata basin (9, 10).

Due to the abundance of rainfall along the eastern flank of the Andes (11), rivers draining from Andean countries (Japurá-Caquetá, Iça-Putumayo, Napo, Marañón, Ucayali, and Madeira) have the largest runoff per unit area of the Amazon Basin (12, 13). Rivers of Andean origin are also a major source of streamflow and sediments to the Amazon mainstem and Atlantic Ocean, exporting ~90% of the Amazon Basin's total sediment (14–16), and are classified as "whitewater" rivers (17, 18). Seasonal flood pulse patterns drive whitewater rivers from the Andes mountains to the Amazon lowlands, where waters expand laterally into floodplains and flow longitudinally downstream, ultimately making their way to the Atlantic Ocean (19). The Amazon lowlands also host large interfluvial wetlands with shallow waters which are mainly flooded by local rainfall and runoff (20).

Here, we aim to articulate the AAA hydroclimate pathway as a foundational system for research, management, conservation, and governance of Amazonian aquatic systems. In this perspective paper, we use evidence from the published literature, mostly of the past decade, to identify and describe the AAA pathway as an interdependent,

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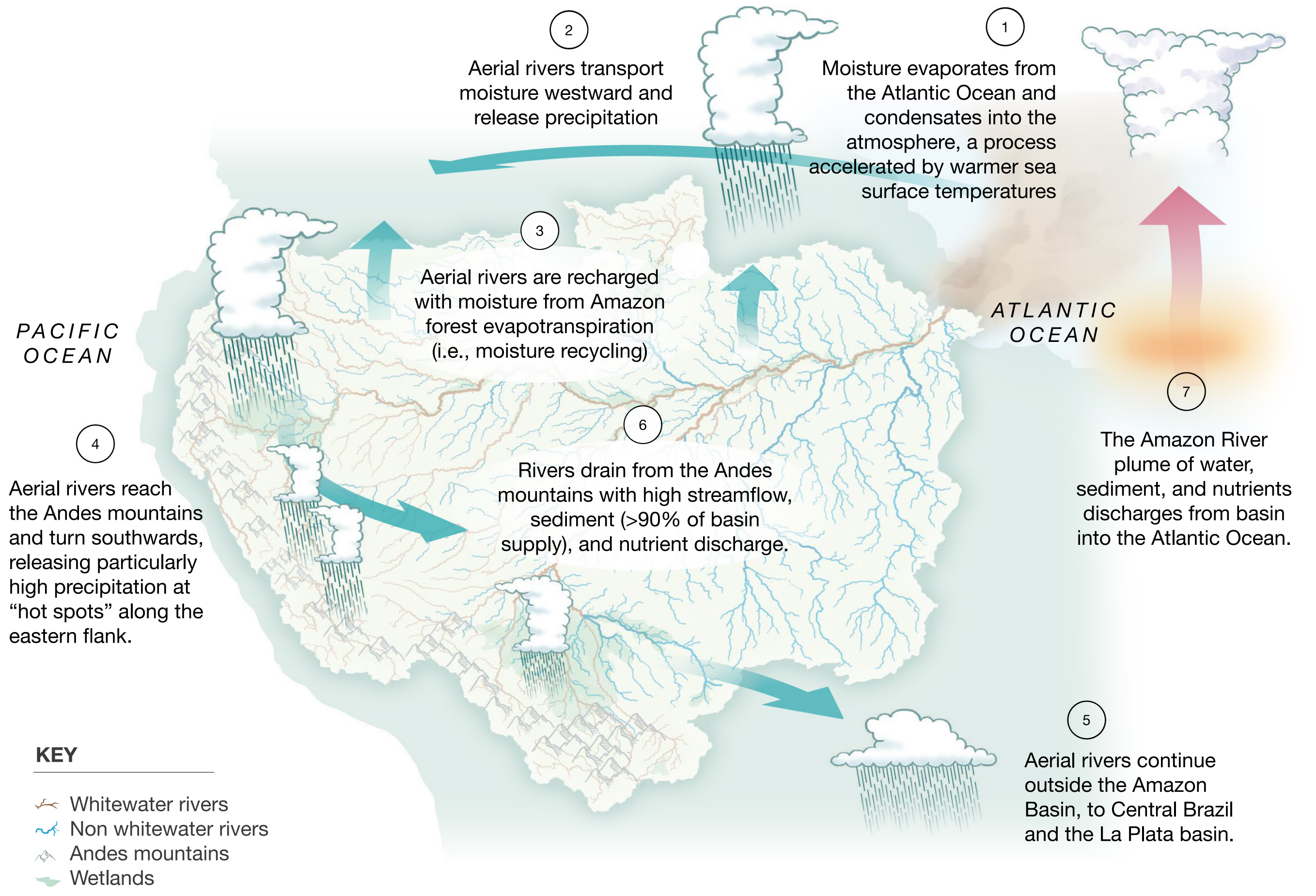

Fig. 1. Key processes along the AAA hydroclimate pathway, reflecting how the regional water cycle is linked through continental hydrology, moving water from the Andes to Amazon to Atlantic, and through large-scale atmospheric circulation, moving moisture from the Atlantic to Amazon to Andes. These processes along the AAA pathway underpin social–ecological systems within and beyond the Amazon basin boundaries.

multidirectional, and multiscale hydroclimate system. We then assess recent changes in the AAA pathway, primarily reflecting an acceleration in the rates of hydrologic fluxes (i.e., water cycle intensification). We discuss how the changing AAA pathway affects social–ecological systems that are closely tied to seasonal hydrologic patterns. We conclude with four recommendations for the sustainability of the AAA pathway in ongoing research, management, conservation, and governance.

Amazon terrestrial ecosystems and Andes–Amazon riverine systems have long been emphasized in the scientific literature and in conservation practice for their importance (17, 21, 22). However, these systems are limited in spatial scale and social–ecological process dynamics, and not fully suited to addressing the increasing threats to Amazon social–ecological systems and other regions that the Amazon influences. Compared to these systems, the AAA pathway offers a broader geographic and hydroclimatic perspective which can promote more robust and resilient management policies and practices. Notably, the AAA system integrates the dynamics of both green water (precipitation that returns to the atmosphere as evapotranspiration) and blue water (precipitation that partitions into surface runoff or groundwater), which are critical to understand in balancing the water needs of human and natural ecosystems (23, 24). We aim to promote recognition of the AAA system across government, private, and academic sectors.

The AAA Pathway as a Globally Important Interdependent Hydroclimatic System

The AAA pathway has a marked role in the global hydroclimate system due to its unique location in the tropics, enclosure by the Andes mountains, and massive fluvial and atmospheric water fluxes (25–27). Regional and global atmospheric circulation, along with continental hydrology, drive the AAA pathway’s interdependent, multidirectional, and multiscale water cycle dynamics. For instance, the annual cycle of solar radiation controls the seasonalities of temperature and modulates rainfall patterns that alternate between the northern and southern hemispheres, with the Amazon Basin being located in both (1). The AAA pathway also plays a key role in modulating broader hydroclimate systems, particularly the Hadley and Walker circulations (1).

The Amazon River is Earth’s largest single source of continental freshwater discharge to the ocean (6,600 km^3/y; ~20% globally, ~50% of Atlantic Ocean) and a major source of the Atlantic Ocean’s sediment (40%) and nutrient fluxes (28). In the estuary, Amazon fluxes are characterized by strong influence of tide at seasonal and interannual time scales (29). The Amazon River plume extends several thousands of kilometers into the Atlantic Ocean, and its composition makes it vital to ocean nutrient balance and carbon dioxide sequestration (30). Due to the plume’s low salinity, it dictates water stratification and ocean surface heat fluxes over a large area off South America's northeastern coastline (31–33) and is an important biogeographic filter for marine biodiversity in the Atlantic Ocean (34). Additionally, the plume supplies to the Atlantic most of the sediment that deposits along the 1,500 km-long coastline of the Guianas (30).

An enormous amount of water is exported from the Amazon Basin to the atmosphere via aerial rivers and moisture recycling (~6,400 km^3/y) (Fig. 1) (13). This amount of water is roughly equivalent to the volume of water discharged by the Amazon River to the Atlantic Ocean annually, which is consistent with the Amazon runoff ratio estimated at 0.5 (35). Aerial rivers (originating from the Atlantic) and moisture recycling processes (facilitated by Amazon forests) dictate rainfall patterns within and beyond basin boundaries, and are particularly important for the tropical Andes and Western Amazon and during dry periods. The Western Amazon encompasses the rainiest region of the basin, with "precipitation hot spots" of >6,000 mm/y in the eastern Andean foothills (36, 37). At times, up to 50% of this Western Amazon rainfall can come from moisture that has been recycled by Amazon forests (38), and that moisture can be recycled five to six times before it reaches the Andes (22). For comparison at a basin scale, the Amazon basin's average precipitation is ~2,200 mm/y and the average proportion of rainfall originating from moisture recycled within the basin has been estimated as ~32% (7).

Beyond the Amazon basin, regions that depend on moisture recycled from the Amazon include the La Plata basin (~24% of precipitation from Amazon) (39), Pantanal wetlands (up to ~20%), and the western flanks of the Andes Mountains (up to ~50%) (7, 38–40). Moisture recycled from the Amazon directly supports water resources for some of the most populated cities in South America (São Paulo, Buenos Aires, ~24% of precipitation from the Amazon; Bogotá, ~10%; Lima, ~20 to 30%; ~70 million people combined) (7, 8, 27, 39).

Reviewing Recent Changes in the AAA Pathway

Hydroclimate variability in the Amazon is natural, to an extent, due to inherent variability in the Atlantic and Pacific SST, including the El Niño Southern Oscillation (14, 41, 42). During the 20th century, most of the extreme dry and wet hydroclimatic episodes in the Amazon have been attributed

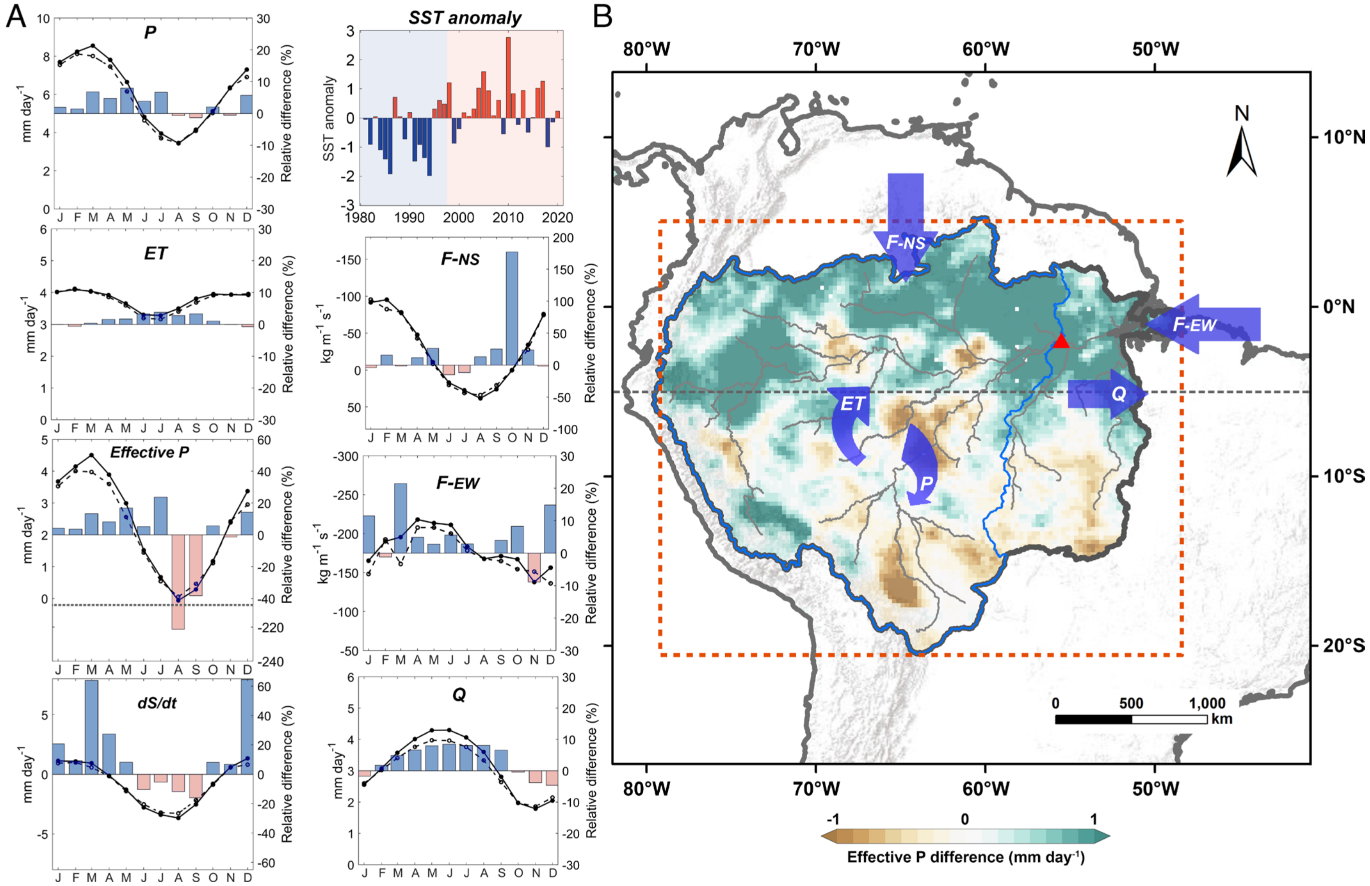

Fig. 2. Change in monthly climatology of the surface and atmospheric water balance components of the Amazon Basin (*A*) and simplified scheme of these variables over tropical South America (*B*): precipitation (P; represented by downward curved arrow in panel *B*), evapotranspiration (ET; upward curved arrow in *B*), effective precipitation (Effective P, defined as P minus ET), terrestrial water storage variation (dS/dt), zonal and meridional vertically integrated moisture fluxes (F-EW and F-NS, respectively; straight arrows entering the dashed polygon in *B*), and river discharge (Q; horizontal arrow in *B*) at Óbidos (red triangle). In panel *A*, all variables are basin-wide averages except Q. Dashed lines represent monthly averages during the baseline period (1981 to 1997) and the solid lines represent monthly averages during the intensification period (1998 to 2020). The blue and red bars show relative positive and negative differences, respectively, from the baseline period to the intensification period. F-EW and F-NS (1,000 to 300 hPa) are computed in the eastern and northern borders of the red dashed polygon in *B*. For reference, the 1981 to 2020 evolution of the annual SST anomalies in the tropical north Atlantic (5°N to 20°N; 40°W to 20°W) are shown (red and blue for positive and negative, respectively). In panel *B*, the map inside the basin shows the average difference in effective P from the baseline to intensification period for the March–May season (MAM). The dashed line at 5° S represents the approximate delineation between northern and southern Amazonia. See *SI Appendix* for all data sources.

to El Niño and La Niña events, respectively. El Niño produced extreme seasonal droughts such as in 1912, 1926, 1983, and 1997 to 1998, while La Niña events have been related to extreme floods, such as in 1989 and 1999 (43). However, since the end of the 1990s, extreme hydroclimatic events have not always been related to El Niño or La Niña alone and changes in the regional climate, global warming, and land use/land cover appear as key drivers of hydrological extremes in the Amazon (3, 42, 44–46).

Regarding changes in regional land use/land cover, a dominant impact is deforestation, particularly in southern and southeastern Amazonia (26, 28). As a consequence, hydroclimate patterns of the AAA pathway have been significantly changing in recent decades, most evidently since the end of the 1990s (47–49). These changes have mainly been interpreted as an intensification of the hydrologic cycle (i.e., increase in the rates of water fluxes) and extreme events (floods and droughts) along the Amazon mainstem (26, 43, 49). Since the beginning of the 21st-century extreme floods were reported in 2009, 2012, 2013, 2014, 2015, 2017, 2019, and 2021 (46), while extreme droughts were recorded in 2005, 2010, 2015 to 2016 (44, 50), and recently in 2023 (51). Notably, in the 2023 drought, the river water level in Manaus reached the lowest level in 121 y (52).

Hydroclimatic changes propagate along the AAA pathway among the closely interacting systems of the regional water cycle, atmospheric circulation, terrestrial land surface, and land-atmosphere exchange. Fig. 2 illustrates this propagation of changes, outlining recent patterns in variables of the water cycle: precipitation (P) from CHIRPS, evapotranspiration (ET) from GLEAM, effective P (defined as P minus ET), terrestrial water storage change (dS/dt) from GRACE, and river discharge (Q) from the Brazilian National Water Agency (*SI Appendix*). These variables are spatially averaged over the entire basin except for Q which is from Óbidos, a gauging station that reflects the hydroclimatic variability of ~80% of the Amazon basin (~4,677,000 km^2; ~700 km upstream from river mouth; Fig. 2). We also included variables related to large-scale climate and atmospheric circulation: SST anomalies (SST-A; i.e., difference between observed annual average SST and long-term average SST in the tropical north Atlantic over 5°N to 20°N and 40°W to 20°W) and atmospheric moisture fluxes in the east–west and north–south directions (F-EW and F-NS, respectively; i.e., zonal and meridional vertically integrated fluxes) (see *SI Appendix* for all data sources).

We focused the analysis on monthly (Fig. 2) and seasonal (*SI Appendix*, Table S1) averages over the years 1981 to 2020, comparing what we refer to as the "baseline" period, 1981 to 1997, to the "intensification" period, 1998 to 2020. As a graphic example of spatial patterns in hydroclimatic changes, we also present the spatial difference in effective P between these two periods during MAM (Fig. 2). We chose MAM since this is the wet season for most of the northern basin, which is a period with relatively marked changes, as further described below. Differences in seasonal means of northern (mainly north of 5°S) and southern (mainly south of 5°S) Amazonia were also analyzed when possible (for data with sufficient spatial resolution), given the alternating seasonality in northern and southern Amazonia. That is, there is a marked wet season in austral summer (December to February) in the south and a longer wet season (mainly March to June) in the north (47) (*SI Appendix*, Table S1). In addition, we analyzed the difference in annual and seasonal land surface temperatures (T) between the baseline and intensification periods (Fig. 3).

Hydroclimate changes are evident from the overall basinwide increase in all analyzed variables from the baseline to intensification period (*SI Appendix*, Table S1). However, there is seasonal variability for basinwide average changes of P, ET, and effective P (Fig. 2). Increases in P by up to 8.0% occurred over the majority of months (December to June, October), which are mostly the wettest months for the entire basin. Slight decreases in P (down to –1.3%) occurred in August and September, which are two of the driest months overall, as well as November. As expected, these monthly

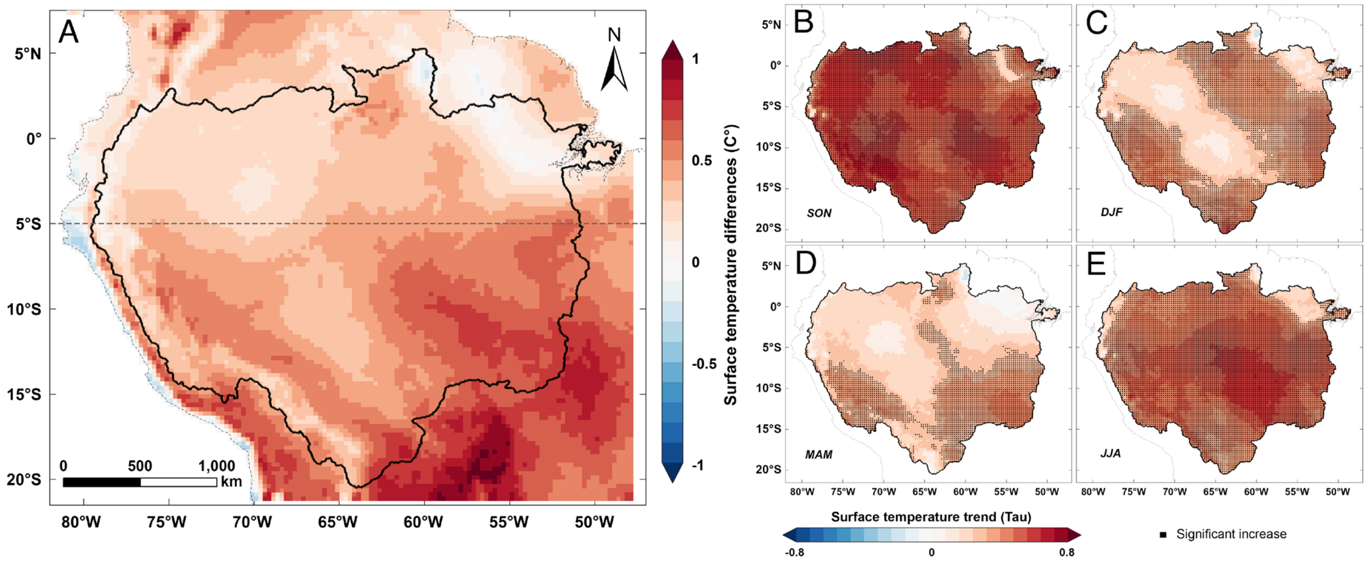

Fig. 3. Temperature trends across the Amazon basin. (*A*) Differences of the annual surface temperature from the baseline period (1981 to 1997) to intensification period (1998 to 2020), represented in blue (negative) to red (positive) colors. The dashed line at 5°S represents the approximate delineation between northern and southern Amazonia. (*B*–*E*) Seasonal trend (Tau coefficient) of monthly surface temperature for the entire analysis period (1981 to 2020). Black dots indicate significant increasing trends ($P < 0.05$). SON = September to November, DJF = December to February, MAM = March to May, JJA = June to August. See *SI Appendix* for all data sources.

changes in P patterns were largely consistent with the monthly changes in F-EW and F-NS, the moisture contribution from the Atlantic Ocean, which had peak increases in October, December, January, and March (up to 21%), and the largest decrease in June, July, and November (down to –8.9%). For ET, the moisture contribution from land, basinwide increases (up to 3.8%) also occurred over most months (March to October), although the timing was not entirely consistent with the changes in P patterns. This offset in P and ET patterns yielded considerable changes in overall effective P, which is a highly relevant variable in terms of water availability. Effective P increased up to 24% from December to July. It also decreased from July to September, where small effective *P* values (<1 mm/d) reflect that these are critical months of low water availability throughout the basin. We do not provide quantification of these changes in relative terms because the very low effective *P* values during this season give unrepresentative percentage values.

At local and regional scales, hydroclimatic changes vary spatiotemporally across the basin, which causes varying localized impacts on social–ecological systems. The periods of basinwide increases in P and effective P (December to June, Fig. 2) relate to increases in these variables in northern Amazonia during its extended wet season (DJF, MAM, JJA, *SI Appendix*, Table S1). Notably, the northern Amazon (north of 5°S) had a 10.1% average increase in P and 18.3% increase in effective P in MAM (wet season), with regions up to +33% P in MAM and +28% P in DJF (*SI Appendix*, Fig. S1). These trends are consistent with the increases in extreme flooding that have been documented in northern Amazonia, notably during the historic 2021 flood and other major floods (46, 53). Similarly, the periods of basinwide decreases in P and effective P (August, September, November, Fig. 2) relate to decreases in these variables in southern Amazonia (south of 5°S) during its dry-to-wet season transition (–0.5% and –4.0%, respectively) (SON, *SI Appendix*, Table S1). Rainfall diminution is most intense in regions of the Bolivian Amazon and southern Brazilian Amazon, with regions of –24% P in JJA and –17% P in MAM (*SI Appendix*, Fig. S1). These trends are consistent with the lengthening of the dry season (54–56) and the increasing drought frequency in southern Amazonia (1, 48, 57). Increases in basinwide ET during southern Amazonia's dry season (JJA) relate to increases in both northern (3.1%) and southern Amazonia (3.6%). Decreases in basinwide ET also relate to relative decreases in southern Amazonia during its wet season (DJF, –1.1%), particularly over regions characterized by large deforestation rates (58).

Along with drying trends, southern Amazonia is also strongly impacted by warming temperature conditions. From the baseline to intensification period, an annual average increase of 0.8 to 1.0 degrees Celsius has been observed in southern Amazonia (Fig. 3). This warming temperature trend has been most intense from June to November, which encompasses the southern Amazonia dry season and dry-to-wet season transition period, and thus overlaps with the season of reduced effective P. This period also aligns with the peak of the fire season in Amazonia (August to November) (59).

The combined changes in atmospheric moisture patterns (P, ET, F-EW) have had clear impacts on the terrestrial water components, Q and dS/dt, from the baseline to intensification period. At Óbidos, where the upstream water cycle impacts are aggregated, Q has increased up to 8.5% from February–September, which encompasses the local high-water period (Fig. 2 and *SI Appendix*, Table S1). This period also aligns with the wet and wet-to-dry season of northern Amazonia. By contrast, Q has decreased 4.7% from October to January, which spans the local low-water season. This period also aligns with the wet season of southern Amazonia, thus reflecting a decrease in Q from this region (14, 41). While dS/dt had large relative increases in March and December (up to 65%), these high percentages are due to these being months of low dS/dt (less than 1.4 mm/d). Nonetheless, increases in dS/dt occurred during the extended wet season in northern Amazonia (DJF, MAM) and decreases occurred during the extended dry season in southern Amazonia (JJA, SON). As dS/dt also represents the water accumulated in soil and groundwater, these changes have implications for water availability to ecosystems and fire activity.

The changes along the AAA pathway that we have described here are consistent with the evidence of hydroclimate intensification documented in the literature: the increase in P and flooding in northern Amazonia (46); and the reduction in P, lengthening of dry season, and diminution trend in Q in southern Amazonia (42, 48, 57, 60). Studies have related changes in the Amazon P patterns to the recent intensification of the Hadley and Walker circulations driven by warming of the tropical Atlantic Ocean and cooling of the tropical Pacific Ocean since the late 1990s (3, 5, 61, 62). An increase in atmospheric upward motion (i.e., upward flow of air masses) over northern Amazonia has been documented since the late 1990s, in connection with the upward branch of the Hadley and Walker circulations (46, 48, 61), producing changes in rainfall patterns even over the tropical Andes (63). This has driven the described increase in F-EW and P in northern Amazonia. In contrast, during the last decades, an increase in atmospheric subsidence (i.e., disturbance to upward flow of air) has been observed in southern Amazonia during the dry-to-wet transition season, in connection with the descending branch of the Hadley circulation (45, 48, 54, 55, 60, 61). This has driven the described decrease in P in southern Amazonia.

There are also perceived feedbacks among changing variables in the AAA pathway, such as the changes in interannual variability of P, ET, and Q into the ocean. It has been proposed that the primarily increased seasonal Q from the Amazon to Atlantic reduced the river plume salinity along its main export pathway by 3.5% per year (2002 to 2016). Then, based on a process-oriented model, it was suggested that the decreased plume salinity thickened the barrier layer between the ocean's shallow warmer surface waters and deep colder waters of higher salinity, thereby reducing mixing and contributing to the warming of the tropical Atlantic Ocean SST. Increased SST leads to increased ET and P over northern Amazonia (Fig. 1), and consequently increased seasonal Q to the Atlantic Ocean (26). This feedback mechanism, coupled with global warming, can lead to a future intensification of the Amazon hydrologic cycle similar to that which has been shown for 1981 to 2020.

Land use/land cover changes, especially the expansive deforestation in southern Amazonia, also have a significant influence on the AAA system and can exacerbate climate change impacts. Deforestation degrades moisture recycling processes, and several studies have shown that deforestation modifies the rainfall regime over southern Amazonia at different scales (27, 56, 58). For example, areas of Brazil deforested for over a decade have had reduced rainfall in dry seasons (64) and future deforestation scenarios in the Brazilian Amazon could reduce moisture in the atmosphere (65) and rainfall over the tropical Peruvian-Bolivian Andes by 20 to 30% (8). Furthermore, there is evidence of a reinforcing feedback between deforestation and droughts in the Amazon that becomes stronger with cumulative deforestation (66).

Water management practices have further impacts on the AAA system, and will likely continue to intensify with ongoing regional development. For example, hydropower dam operations in the Brazilian Amazon alter natural flow regimes (67). Thus, the continued expansion of hydropower in Brazil and in Western Amazon countries (68) may modify seasonal Q patterns across the Andes to Atlantic pathway. Irrigation, although currently limited in the Amazon, alters local ET patterns (58) and may have broader impacts if it expands. Increasing urbanization may also have manifold impacts due to increased urban water withdrawals and land cover changes.

Influence of the Changing AAA Pathway on Social–ecological Systems

Today, the Amazon biome (which extends beyond the hydrologic basin boundaries) has an estimated population of 47 million people (69). Of this total, approximately 2.2 million (4.6%) are Indigenous peoples belonging to at least 410 ethnic groups (70). A large part of the Amazon population increasingly resides in urban areas. Regardless of location, Amazon freshwaters underpin a unique social–ecological system that influences nearly all aspects of human life and livelihood in much of the basin. Freshwater species and ecosystems feature prominently in the cosmologies of numerous Indigenous groups in the Amazon, and the seasonal rise and fall of rivers—or river rhythmicity—aligns with social, economic, and cultural practices of riparian human communities (71). From an ecosystem services perspective, Amazonian people depend heavily on aquatic ecosystems for water, transportation, and food. Rivers are the main thoroughfare for movement of people and goods across the lowland Amazon (72), and many large cities–such as Iquitos, Perú, and Leticia, Colombia–are only reached by river or air. A key part of Amazon aquatic ecosystems are the 2,800 described species of freshwater fishes, which include hundreds of migratory fish species (73). Fish are the primary protein source for Amazonian people, who consume freshwater fishes at some of the highest rates globally (74–76), and migratory species are central to both subsistence and commercial fisheries (77).

The AAA pathway scales regional and global hydroclimate patterns to the Amazon's unique social–ecological systems. A principal example of this is seasonal flood pulses of water, sediments, and nutrients, which vary in timing and magnitude throughout the basin due to tropical rainfall patterns and runoff from high-relief areas of the Andes (20, 47). Natural flood pulses have historically been relatively predictable in their local timing and magnitude, and thus have orchestrated the activities of humans and aquatic and terrestrial species attuned to the rhythmicity of seasonal river flow changes (71, 78). These pulses along the AAA pathway seasonally inundate floodplain forests, supporting highly diverse ecological habitats (79–81) and high biological and fisheries productivity (82, 83). Many fish and other aquatic species migrate to floodplains in response to seasonal water levels, which is important for their life cycles and resource access, as well as resource distribution (82). Some floodplain plant species also show flowering, fruit ripening, and leaf fall and expansion in response to flood pulses (84).

For humans, flood pulse patterns are critical for livelihoods and income generating activities at local to regional scales (71, 85). For example, predictable fish behavior that aligns with flood pulse patterns can facilitate fish capture, often through fishing techniques and artisanal approaches developed over generations. However, flooding disperses fish, reducing capture per effort (86). Thus some human populations may shift to hunting during flood periods, given that terrestrial mammals concentrate on natural levees making them easier to spot (87). Flood periods also allow human floodplain communities to access the main rivers by boat, facilitating access to food, medicine, and markets (88).

One major impact of hydroclimate intensification is the shift of localized precipitation patterns and flood pulses in timing, duration, and magnitude across the basin, which disrupts the linked social–ecological activities such as fish migrations, fisheries, agriculture, and tree fruiting (89). For example, much of the cropland in southern Amazonia is devoted to the rainfed agricultural production of soy and maize that are planted and harvested in sequence each year. However, the lengthening of the dry season in southern Amazonia has negative consequences on second-crop (maize) yields (90). The impacts of increasing extreme hydroclimatic events are also manifold. Several studies have shown that extreme events can shift physicochemical and hydrobiological variables of estuaries, notably salinity, thereby impacting phytoplankton biomass (91, 92). Extreme floods that are increasing in northern Amazonia have negative implications for humans' health, safety, and food provision (93), such as by decreasing terrestrial mammal abundance available for hunting (87). During extreme dry periods, water recession typically starts earlier and disrupts fish migrations. There is also increased fish mortality due to hypoxia and extremely high river surface temperatures, which can lead to overfishing and conflicts (94).

Another social–ecological impact of hydroclimatic intensification is the linkage of drying conditions to forest resilience and fire risk. Since the early 2000s, the Amazon forest has been losing resilience, but faster in regions with less rainfall (95). Drying conditions in southern Amazonia could trigger local forest collapse, which could propagate to other parts of the basin (96). Droughts also increase forest flammability, fire incidence, and tree mortality, and suppress tree growth in Amazonia (45, 97–99). Furthermore, because floodplain forests have lower resilience to transitioning into a fire-dominated vegetation state compared to upland forests, floodplain fires have stronger and longer-lasting impacts on forest structure and soil fertility (100).

The various impacts of hydroclimatic changes on social–ecological systems are exacerbated by other anthropogenic impacts on aquatic systems. These include direct alterations to the AAA system such as river fragmentation, water pollution, and overexploitation of freshwater biota, which is more accessible via the river network relative to terrestrial fauna (101). These combined changes and cumulative impacts are occurring at faster speeds than social–ecological systems can adapt, threatening their resilience.

The AAA Pathway and Future Amazon Sustainability: Recommendations

We have heralded the importance of the AAA pathway and presented a novel synthesis of the increasing changes that affect it. There is a pressing need for integrated research, management, conservation, and governance approaches that properly address the complex challenges facing Amazonian social–ecological systems that depend on the AAA pathway. To this end, we offer four recommendations:

Expand Monitoring of All Components of the AAA System. The Amazon is generally a data-limited region, which leads to significant knowledge gaps and uncertainties about AAA pathway components, interconnections, and feedbacks. Data are also sparse in the Andes, where spatiotemporal hydroclimate patterns are highly complex, and in floodplains, where river gauges do not adequately capture hydrologic variability (89).

A valuable monitoring technology to leverage is satellite remote sensing, which has shown strong capacity for monitoring the Amazon hydrologic cycle, and continues to improve with the availability of higher spatial and temporal resolution datasets, retrieval algorithms, computing power, and artificial intelligence techniques (19). For example, the Surface Water and Ocean Topography (SWOT) satellite launched in December 2022 offers a promising opportunity to collect comprehensive water data. SWOT will provide unprecedented estimates of river discharge, such as the Amazon flood pulse, allowing a more complete observational understanding of water flux from the Andes to the Atlantic Ocean. This will also improve knowledge of flood pulse impacts on floodplain dynamics, where up to 20% of Amazon discharge circulates during flood period (102). By measuring variations in water storage in countless water bodies from small lakes in the Andes to floodplains in the Amazon lowlands, SWOT will help to better understand evaporative fluxes from the surface to the atmosphere, as well as human water withdrawals. Thus, SWOT brings unique potential to holistically observe the AAA systems' multidirectional water fluxes.

However, in situ hydroclimate observations must also be strategically expanded in their spatial and temporal frequency, in part to validate and enhance the benefits of satellite data. Observations are also important for hydroclimate modeling efforts, particularly high-resolution climate models for the Amazon-Andes transition valleys and for regional Earth system models coupling oceans, land surface, and atmosphere (8, 65, 103–106). Engaging local Amazonian communities in environmental monitoring can not only expand data collection but better equip communities with technical training and information for environmental decision-making and advocacy. This is clear from examples such as environmental and climatic monitoring initiatives conducted by the Federation of Indigenous Organizations of Rio Negro (107).

Coordination across Political Boundaries for Improved Data Collection and Management. Currently, hydroclimate data for the Amazon are often collected and managed by independent institutions (e.g., government agencies, academic research centers) and stored on a portal that is not readily accessible to other potential users. A network of shared, open-access regional observatories with user-friendly online platforms can be transformative for knowledge and management of Amazon aquatic ecosystems. Examples in the Amazon to build from include the observatory formed by communities of the Xingu River corridor (108); the hydrometeorological data observatories for the national water authorities of Brazil (109) and Peru (110); and the international SO-HyBam observatory for rivers and water resources (111). These observatories could also support the development and enforcement of transboundary management measures, such as basinwide implementation of environmental flow policies that capture comprehensive flow regime metrics (e.g., flood pulse timing, magnitude, duration, sediment dynamics) (112). For this, a major opportunity is the institutionalization of the Amazon Regional Observatory under the structure of the Amazon Cooperation Treaty Organization proposed as part of the Belem Declaration in August 2023 (113).

Strengthen Collaboration between Interdisciplinary Researchers, Water Managers, and Local Communities Facing Changes in the AAA Pathway. The focus of these efforts should include the different drivers of AAA pathway changes (e.g., climate change, land use/land cover change, infrastructure implementation), their interactions, and their relative and combined impacts on local, regional, and global social–ecological systems. This includes better understanding of the Amazon's blue and green water dynamics, interlinkages, and trajectories under climate and land use changes (23, 24, 114). These efforts can reduce AAA pathway uncertainties such as the magnitude of change in the water cycle due to the land-atmosphere feedback with deforestation and the consequences outside the Amazon Basin (8, 27, 115), including contribution to Amazon aerial rivers on major cities.

Amazonian communities, particularly Indigenous peoples and local traditional communities, are essential to engage in understanding and managing changes, as they hold experiential, long-term, and place-based knowledge about local aspects of hydroclimate cycles and interconnected social–ecological impacts (116, 117). They are also directly witnessing, experiencing, and adapting to hydroclimatic changes and their cascading impacts. This is exemplified in the Xingu Basin where local communities are adapting to a drier climate using forest management practices based on Indigenous knowledge (118). Improved understanding of current changes from diverse perspectives can improve discernment of plausible future scenarios for Andean–Amazon hydroclimate and social–ecological systems and support adaptation and mitigation measures.

Local staff in protected areas such as national parks and reserves can be pivotal in facilitating training and the implementation of these collaborations. Facilitation of these collaborations will rely on agencies that fund research, governance, and development work to prioritize approaches that integrate different disciplines and sectors of society. A central aspect of these collaborations should be the AAA pathway and its connection with local, regional, and global hydroclimate and social–ecological systems.

Zero-deforestation, Vegetation Restoration, and Climate Change Mitigation Policies in Amazonia. Finally, we call for immediate local- and regional-scale actions to mitigate and adapt to climate change impacts along the AAA pathway, which complement global-scale efforts to reduce greenhouse gas emissions and expand natural protected areas. Reinstating Amazon zero-deforestation policies and implementing widespread restoration will be critical for maintaining moisture recycling processes and carbon sequestration potential (22, 90, 119, 120). Vegetation restoration can be conducted strategically by considering the boundaries of "precipitation sheds," or the upwind areas that contribute evapotranspiration to given locations' precipitation, and selecting restoration sites based on those boundaries (i.e., "smart reforestation") (121, 122). Maintaining free-flowing rivers and their natural flow regime will help to absorb disturbances and buffer the surrounding land and ecosystem from climate change impacts (70, 123). Protecting and restoring functional floodplains will buffer impacts of extreme events and uniquely support biodiversity and livelihoods (89). Mitigation and adaptation actions such as these should be conducted in partnership with Amazonian communities that steward aquatic ecosystems.

Conclusion

We have presented the AAA hydroclimate pathway as a foundational system for research, management, conservation, and governance of Amazonian aquatic systems. Up to now, most research and conservation efforts have focused on the terrestrial rainforest biome, yet rainforest persistence hinges on the AAA pathway. Thus, there is an urgent need for a shift for research, conservation, and governance to keep the Amazon Basin wet and mitigate hydroclimatic change. The multidirectional nature of this system has critical implications for management of aquatic ecosystems as well as key risks to consider, such as deforestation impacts on the continental and global water cycle. The AAA pathway is also an important aspect of water management for rapidly urbanizing areas within and beyond the Amazon. The combined changes along the AAA pathway and their cumulative impacts are occurring at faster speeds than social–ecological systems can adapt, threatening their resilience. Our recommendations provide a roadmap for integrating the AAA pathway in social–ecological system sustainability.

Data, Materials, and Software Availability. All study data are included in the article and/or *SI Appendix*.

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