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Loss of native forest changes the biophysical dynamics of the water cycle: a brief review

Abstract

This is a brief review of advances in understanding the forest-water relationship, particularly how the loss of native forests affects biophysical aspects of the water cycle. Initially, we address the participation of forests in the water cycle, especially in intracontinental systems, and how changes in land use and land cover can lead to water insecurity. Next, we present a synthesis of the advanced studies on the influence of evapotranspiration on the availability of water vapour to the atmosphere, and how diverse this process is in tropical ecosystems, which makes the possibility on inferences on an intercontinental and global scale complex. We also compiled information on the influence of the presence of native forests on atmospheric circulation and on the formation of condensation nuclei. Finally, we discuss some implications of forest fragmentation and what some studies point out, as well as considerations about the need to include biological aspects in the design and implementation of scientific models and institutional arrangements at local, regional, and transcontinental scales for understanding and maintenance of a resilient water cycle.

Keywords: forest loss, water cycle, native vegetation, evapotranspiration, moisture atmospheric, condensation

Volume 6 Issue 2 - 2022

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Received: March 20, 2022 | **Published:** April 11, 2022

Introduction

The availability of water determines where life can occur, and on the other hand, life forms affect the availability of water in both quantity and quality. The growth of the human population and, consequently, the demand for natural resources is affecting the Earth's surface.[1] According to Sheil[2] more than a third of ice-free continental surfaces are being used for activities such as agriculture, grazing and urbanization. Hansen et al.[3] point to the loss of 1.5 billion km² of tree cover in just over a decade (2000-2012). At the same time, assessments indicate significant increases in the number of people without access to water and those exposed to flooding.[4] For those who face these situations, the question is to know enough to understand how land cover influences water availability and, from then on, develop forecasting tools and actions that guarantee access to this resource.

About 0.25% of the atmospheric mass is made up of water vapor, which is equivalent to 2.5 cm of liquid on the entire surface of the Earth; of this amount, less than one hundredth corresponds to water in other states, droplets and ice.[2] The behavior of this atmospheric water, however, governs the availability of water on the continents. Terrestrial life, including human life, depends on and affects this availability. Understanding these linkages and vulnerabilities is indispensable in preventing extreme events resulting from changes in land cover.

Vegetation and climate are closely related, and changes in one of the links, reflect changes in the other. Although the understanding of these relationships is still far from what we can imagine, some issues are already very clear. First, it is known that approximately half of the solar energy incident on the Earth is converted in the process of evaporating water, cooling the Earth's surface.[5] Second, water vapor is dominant in our planet's greenhouse gas.[6] Third, the distribution of clouds and snow has a great influence on planetary albedo (the portion of incident light reflected back into space) and energy balance.[7]

It is also clear that water is the most limiting factor for the uptake of carbon by terrestrial ecosystems. Therefore, uncertainties about water imply uncertainties regarding the fixation of biomass and carbon.[8,9] In addition, there is no doubt about the importance of freshwater for biodiversity, supporting over 126,000 plant and animal species, distributed over 0.8% of the Earth's surface (many of them vulnerable), and the link between terrestrial biodiversity and atmospheric moisture.[10]

The research aimed to review the understanding of the forest-water relationship, focusing on how the loss of native forests influences the biophysical aspects of the water cycle, focusing on the challenges and advances in understanding this relationship between forest and water.

Material and methods

Publications containing datasets were searched using the ISI Web of Science database and Google Scholar with keywords comprising: 'water cycle', 'forest hydrology', 'evapotranspiration', 'atmospheric moisture flows', 'forest loss'. A candidate list of papers was checked for evidence of datasets or analyses that fitted our criteria – published no more than 10 years ago, thereby being coincident with the most recent climate changes. Additional papers were added based on expert knowledge and considering recent reviews.

This present review focused on water cycle from ecological and biophysical point of view, its relevance for climate change research and its implications and applications in conservation. Thus, we strive to attain broad but concise thematic, selecting key topics with relevant contributions to the conservation and management of natural systems, rather than perform an exhaustive review.

The participation of forests in the water cycle

Life on the continent depends on water that precipitates from the atmosphere, regardless of its form (rain, snow, hail, etc.), and demand continues to grow, despite uneven and often limited availability. According to Ripple et al.[11] since the beginning of the 1990s, there has been a significant reduction in the availability of fresh water per capita on the planet, in the order of more than 25%, which represents a reduction of more than 2,000 m³ per person. The proportion of the population experiencing water scarcity for more than 30 days year^{-1} is around two-thirds, and more than half a billion people live (or survive) with water scarcity throughout the year.[12] In addition to scarcity, the occurrence of extreme events (droughts and floods) with disastrous results has also grown in the last century, killing more than 18 million people by 2013.[13]

While much of the atmospheric water vapor originates in the oceans, much is also recycled on the continent. According to Schneider et al.[14] 61% of the annual precipitation on the planet derives from continental environments, with the remaining 39% coming from the oceans. Most of the precipitation incident on the interior of the continents derives from the humidity produced by the continental ecosystems themselves. More than half of continental atmospheric moisture result of plant evapotranspiration, although there is no consensus on the exact fraction.[15] Data analyzed by Sterling et al.[16] estimated a reduction of up to 6% in global atmospheric humidity, due to changes in soil cover, which, added to the increasing demand for water, negatively and directly impact the water cycle.

Precipitation rates depend on variation in moisture production by continental ecosystems.[17] The Amazon Basin *e.g.* is among the main sources of water vapor for areas located downwind.[18] Considering the great distances that moisture travels in the atmosphere before precipitating (500-5,000 km), large-scale land cover changes can crucially influence this part of the hydrological cycle.[19] Wang-Erlandsson et al.[20] evaluated this relationship and concluded that even in important watersheds such as the Amazon Basin, precipitation was more influenced by changes in land use that occurred outside the basin.

For Sheil[2] despite the increasing sophistication of climate simulation models, there are still many problems with these models, increasing the uncertainties of predictions regarding the effects of changes in the hydrological cycle. This constitutes, according to Marotzke et al.[21] a major challenge to determine the future availability of water. These models do not perceived variations in the speed and patterns of wind circulation, temperature, moisture and vegetation cover between different regions of the planet. This makes predictions at very large scales flawed.[22] The absence of characterization of biological processes in these models results in the discrepancies and uncertainties often observed, as they omit and/or misrepresent key processes and mechanisms that are directly linked to the stages of the hydrological cycle.[2]

Evapotranspiration as a significant source of moisture atmospheric

Atmospheric moisture can derive from several sources and processes: evaporation from open water, soil, precipitation interception, and evapotranspiration. As seen earlier, much of the precipitation over the continent is recycled from the continental ecosystems themselves and, according to Sheil[2] more than half of this derives from plant transpiration. All higher plants control the timing and intensity of water vapor release. Leaves and other plant parts are typically waxy and relatively impermeable, with most gas exchange and water loss occurring through stomatal pores. The stomata simultaneously control the entry of carbon dioxide into the leaf and the emission of water vapor by transpiration, regulating the temperature of the leaves.[23]

These adjustable pores evolved around 400 Ma, and since then have influenced the planet's water cycle.[24] Control of these pores determines the gas exchange, including water vapor and carbon dioxide, between the intercellular space of plants and the external atmosphere. The behavior of the stomatal pore aims to optimize carbon fixation, being able to adjust to environmental conditions (such as water availability). However, according to Matthews et al.[23] the understanding of these relationships is still under construction. In addition, trees capture nutrients by absorbing water from the soil, thus, the increase in transpiration rates may be a response to the low availability of nutrients in the environment.[25]

The dynamics of transpiration is quite complex. The stomata of tropical trees generally close after a few hours of intense photosynthesis, due to the temporary depletion of water availability. However, this behavior varies between species and according to environmental conditions.[26] Azcón-Bieto and Talón[27] state that there are processes that somehow coordinate stomatal opening and closing between the leaves of a plant, and even within the leaves, which can lead to varied patterns of moisture release. In addition, many types of plants, in different biomes, continue to lose water to a certain degree, leaving their stomata open at night, in a transpiration process that would be related to competition for nutrients.[2] That is why it is so challenging to develop a model that integrates all these processes and relationships.[23]

Water that evaporates from wet surfaces, including that intercepted and held in vegetation, is also a major source of atmospheric moisture. The amount of water vapor emitted by forests generally exceeds that of other plant formations and even evaporation from open water. A good example is the Amazon Basin, which evaporates 1.37 m of water year^{-1}.[28] The large leaf area and the roots capable of accessing moisture even when the most superficial layers of the soil are dry maintain high transpiration rates. Furthermore, some trees have the ability to capture moisture from mists or dew and then (re)evaporate, in a process often driven by epiphytic vegetation.[29]

Forest soils are deeper, more porous and more permeable than other soils, increasing infiltration and moisture storage and reducing surface runoff. Despite the constant association made by hydrologists between the increase in water availability and the decrease in tree cover, the short-term flow gain is opposed to the long-term loss in precipitation. Therefore, fragmentation or forest loss in an area can increase local runoff, but can reduce regional precipitation by a greater amount.[30] Furthermore, Thompson et al.[31] and Filoso et al.[32] emphasize that comparing open lands with dense forests neglects non-linear relationships such as infiltration, soil desiccation, precipitation and scale effects, providing an incomplete picture.

According to Malmer et al.[33] despite the growing number of studies, we know less about the influence of forest restoration and expansion on water than is assumed. Although local water production in young forest declines, this flow changes and may increase as vegetation matures.[32] But this trend escapes short-term studies. Advances in studies have increasingly demonstrated that changes in forest cover, such as fragmentation and deforestation, influence local and regional climate.[34] Reduction and/or loss of forest cover generally correlates with declining rainfall (rain and mists), although these correlations and causal relationships are difficult to prove, given the impossibility of replication and the multiple potential influences.[2]

The effects of forest on condensation and atmospheric circulation

Water vapor condenses when the air is sufficiently saturated. The saturation limit depends, according to Després et al.[35] temperature, pressure and available surfaces. Condensation nuclei, regions where particles have the ability to promote condensation, depend on two main factors: surface chemistry (hygroscopicity) and particle size, since larger particles tend to gather more water.[35] While larger particles such as pollen grains and fungal spores can promote droplet formation without increasing in size, smaller particles need to grow before playing this role.[36]

It is important to emphasize that in addition to dust, smoke, and marine salts, many biological materials, such as bacteria, virus, pollen, spores and organic debris, also constitute the particulate portion of the atmosphere, in a proportion comparable to mineral particles; and these values may be higher in forested regions.[37] Changes in the abundance, characteristics or dynamics of these aerosols can impact the hydrologic cycle, but these relationships are not linear.[38] Amato et al.[39] detected genetic material from more than 28,000 species of bacteria and 2,600 eukaryotic species, mainly fungi, in water samples collected from clouds at the Dôme Mountain Meteorological Station (France), much of this metabolically active material.

As Sheil[2] argues, surface chemistry and the size of atmospheric particles can be altered by the decomposition products of VOCs, volatile organic compounds, in the atmosphere. About 75% of these VOCs are relatively reactive and last less than a day in the atmosphere (like isoprene), involving varied chemical pathways.[2] According to Ehn et al.[40] chemical changes imply the loss of volatility of these compounds, which adhere to the surfaces of the particles, accumulating and allowing even the smallest particles to reach sizes that allow the formation of droplets.

Most VOCs are of biological origin and forests are the main sources.[41] According to Gu et al.[42] the main constituent seems to be isoprene, produced mainly in tropical regions, where plants are stressed by heat, with significant production by trees, with considerable variations in the Amazon region. Isoprene shows an ability to increase cloud cover during periods of heat stress, decreasing temperature and stimulating precipitation.[2] Fragmentation and loss of vegetation cover can modify the emissions of these compounds. Bateman et al.[43] also clarify that the effects of atmospheric pollution, resulting from anthropogenic activities, can mask the influence of the loss of forest areas on rainfall. The smoke from fires or industrial processes reduces the aggregation promoted by particles derived from the isoprene released over forests, and studies dealing with the water cycle need to address these.

Wright et al.[44] showed that forest transpiration plays another significant role, which is to provide moisture for monsoon rains in the transition zone between wet and dry areas in southern Amazonia. As proposed by Sheil[2] regions that generate high evaporation rates develop zones of lower pressure, which suck in air from neighboring regions. This air converges, rises and cools and the moisture condenses, causing rainfall that can overcome local evaporation. Thus, regions with larger leaf area would attract winds from regions with smaller leaf area. This relationship implies that large forested areas actively attract moisture from other regions, in a process called the "biotic pump".[2]

According to Makarieva et al.[45] and Sheil[2] the biotic pump explains, for example, the maintenance of high rainfall in the interior of the continental Amazon, while in areas without forest, the decline in rainfall in the more interior regions is accentuated with increasing distance in in relation to coastal areas. This effect of attracting rainfall to continental interiors requires biologically functional forests.[45] Thus, the fragmentation of native forest and replacement by other types of cover such as crops; interrupt the ecosystem processes that guarantee the functionality of these areas.

Implications of forest fragmentation for the cycle of water

Evergreen forests maintain relatively high humidity throughout the year, even in dry periods. In the Amazon, this capacity plays a key role in determining rainfall in the southern transition region.[44] Transpiration in the dry season allows for some rainfall to occur, and the retention of this moisture facilitates the return of the rainy season, avoiding abrupt change, as occurs in drier regions.[2] The reduction in forest cover, which is increasingly fragmented, may change this dynamic and reduce transpiration rates and, consequently, lead to an even greater decrease in rainfall in the dry season.

The impact of deforestation on local atmospheric pressure and therefore on the likelihood of subsequent rain exists, as Makarieva et al.[46] points out. From the analysis of pressure and precipitation data from meteorological stations of the INMET, Nacional Institute of Meteorology of Brazil, located inside and outside the Amazon rainforest, these researchers verified that rainy days in the forested area of the Amazon are preceded by a period of greater pressure, consistent with the accumulation of water vapor. In the more peripheral and deforested regions, the results show a pressure drop before the rains, suggesting that these places do not sustain enough evaporation to cause rain locally, depending on the movement of air masses originating in other areas.[46]

If rainfall in the interior of the continent depends on large contiguous forested areas, the fragmentation caused by deforestation can potentially change the interior conditions of the continent (from humid to dry), with catastrophic implications as is already the case with the loss of vegetation in the Atlantic Forest, where desiccation has resulted in a decline in rainfall, an increase in droughts and, consequently, an increase in the number of fires.[47]

According to McVicar et al.[48] if regional patterns in the relative abundance of water vapor generate and stabilize winds, then reduced vegetation cover and increased atmospheric carbon dioxide reduce humidity, leading to a reduction in precipitation and related winds. A number of historical data already indicate a long-term decline in the intensity of tropical winds.[48]

The approach of biological processes in the analysis of precipitation patterns can help the understanding of the dynamics that determine these phenomena.[49] In addition to the genetic methods that are being used to identify the microorganisms that make up aerosols, as we have seen, the use of geoprocessing techniques and satellite images already allow the diagnosis and monitoring of environmental and climatic patterns on a global scale. However, studies at local scales are not amenable to interpretation from large-scale atmospheric behavior.[49]

Final considerations

The lives and livelihoods of billions of people depend on access to water, and it is necessary to safeguard the processes on which that access depends. Therefore, it is necessary to understand how the hydrological cycle works and what it depends on. The complexity and number of factors involved make it difficult to fully understand, weakening some predictions and models.

What we known is that changes in land cover impact atmospheric humidity, temperature, aerosols and air mass movements, influencing the hydrological cycle at various spatial and temporal scales; whereas tropical forests play a significant role; and that the loss of forest cover and, consequently, the associated stomatal activity, reduces evaporation and increases the availability of atmospheric carbon dioxide. In addition to the influence exerted by the forest cover area, intrinsic properties of each forest, such as leaf phenology and emission of volatile gases, also influence climatic conditions. The complexity of these aspects and their effects generalizes difficult.

In comparison with planted forests, for example, native forests maintain a mild understory temperature during the day, generating a local atmospheric inversion at night, and keeping the stratum moist, influencing the release of water vapor. The species diversity of native forests also reduces vulnerability to external changes and disturbances, stabilizing climate responses. In other words, there is no linearity in forest-water relationships.

Large-scale forest loss or fragmentation reduces atmospheric humidity, cloud formation, rainfall; and increases the possibility of more intense droughts. Anthropogenic activities are the main drivers of these changes, also causing the rapid release of large amounts of carbon dioxide. In this sense, the restoration of Vegetation cover is essential for stabilizing the water cycle. However, the challenges go beyond the biophysical aspects. The design and implementation of institutional arrangements at the local, regional and transcontinental scales plays a key role in understanding and, more significantly, in actions to maintain a resilient hydrological cycle.

Acknowledgments

The authors thank the Postgraduate Program in Botany at the State University of Feira de Santana (PPGBOT/UEFS), the Professional Master's Program in Management and Regulation of Water Resources at the University of the State of Amazonas (PROFAGUA/UEA), and the Coordination for the Improvement of Higher Education Personnel (CAPES).

Conflicts of interest

The author declares there is no conflict of interest.

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