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SOUTH AMERICAN HYDROLOGY

Forests and water in South America

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Abstract

South America is experiencing rapid change in forest cover, of both native and planted forest. Forest cover loss is primarily attributable to fire, logging, and conversion of native forest to agriculture, pasture, and forest plantations, and types of change vary within and among the many diverse types of forests in South America. Major changes in forest cover and growing policy concerns underscore an urgent need for research on sustainable forest management and water ecosystem services in South America. Differences in land ownership and management objectives create trade-offs between wood production and water ecosystem services from forests. Work is needed to quantify how forest change and management affect ecosystem services, such as wood production versus water provision. Current scientific understanding of forest management effects on water ecosystem services in South America has important limitations, including a scarcity of long-term records and few long-term integrated watershed studies. Industry, government, universities, and local communities should collaborate on integrated applied studies of forests and water. Data archiving and publically available data are required. The creation of national networks and a multi-country South America network to identify and implement common water research protocols, share results, and explore their implications would promote common and well-supported policies. Hydrologists working in South America are well placed to tackle the challenges and opportunities for collaborative research that will maintain the intrinsic values and water ecosystem services provided by South America's forests.

KEYWORDS

deforestation, ecosystem service trade-offs, forest plantations, paired watersheds, water yield

1 | INTRODUCTION

Forests provide multiple ecosystem services related to water, including provisioning water, regulating water flows, supporting aquatic ecosystem function, and providing recreation and amenity values (Millennium Ecosystem Assessment, 2005). In addition to these instrumental values, people also value forests and water intrinsically (Bengston, 1994; Meyer, 1997). Uncertainty about how changes in forest cover affect hydrologic processes has fueled conflict over the social and environmental consequences of forest policy in South America (Reyes & Nelson, 2014; Schirmer, 2013). International conventions on biodiversity and climate change as well as forest certification programs, among other factors, provide new incentives for scientists, environmentalists, government, industry, native peoples, and communities to work together to examine trade-offs among water and wood

Correction added on 31 January 2017, after first online publication: Under the ‘Acknowledgement’ section, the author has added ‘CONICYT/FONDAP/15110009 Grant’.

production and other forest management objectives. In South America, as highlighted in this special issue, researchers examine hydrologic processes in forests from nested perspectives of (1) ecohydrology (vegetation–water interactions), (2) forest hydrology (various forest types), and (3) hydrology of managed forests. The many studies on forests and water in the northern hemisphere are of limited relevance to South America, where native forests are diverse and industrial forest plantations are managed on very short rotations, typically using fast-growing non-native species, over large areas. Hydrologists working in South America are well placed to lead research to support sustainable forest management and water ecosystem services.

South America is experiencing a rapid change in forest cover, of both native and planted forest. Six South American countries were among the top 20, and eight were in the top 30, of 180 countries on earth in terms of total forest cover loss from 2000 to 2012 (Hansen et al., 2013; Table 1). From 2000 to 2012, forest cover loss exceeded forest cover gain by an order of magnitude in all South American countries except Chile and Uruguay (Figure 1a). Loss of forest cover exceeded 10% in Argentina, Paraguay, and Uruguay and 5% in Brazil and Chile (Hansen et al., 2013; Figure 1b). Forest cover loss is primarily attributable to fire, logging, and conversion of native forest to agriculture, pasture, and forest plantations, driven by population growth, industrial wood and food production, and poverty (Aide et al., 2013; Allen & Barnes, 1985; Lara et al., 2008; Reyes & Nelson, 2014).

Land cover transitions vary in South America (Figure 2; Meyfroidt et al., 2010). Agriculture and pasture have replaced native forest in Brazil, Bolivia, Colombia, Ecuador, and Peru. Secondary forest and shrublands have replaced native forest in Chile (Miranda, Altamirano, Cayulea, Lara, & Gonzalez, 2016). Forest plantations have replaced agriculture, pasture, native forest, and secondary native forest in Chile (Echeverria et al., 2006; Miranda, Altamirano, Cayuela, Pincheira, & Lara, 2015; Miranda et al., 2016; Nahuelhual, Carmona, Lara, Echeverría, & González, 2012; Zamorano-Elgueta, Benayas, Cayuela, Hantson, & Armenteras, 2015) and native grassland and pasture in Argentina and Uruguay (Farley, Jobbágy, & Jackson, 2005). Secondary forest has replaced agricultural land in Colombia (Sanchez-Cuervo, Aide, Clark, & Etter, 2012).

The expansion of plantation forestry for wood export (e.g., Carle, Vuorinen, & Del Lungo, 2002; Sedjo, 1999) led to gains of >35% of forest cover in Uruguay, 8% in Chile, 3% in Argentina, and 2% in Brazil from 2000 to 2012 (Table 1; Hansen et al., 2013). In Chile and Uruguay, forest cover gain exceeded loss as forest plantation area expanded from 2000 to 2012 (Table 1; Figure 1b,c). In Chile, forest plantations have expanded rapidly in the Maule, Araucania, and Los Rios regions (35° to 40°s) since the mid-1970s (Miranda et al., 2016). In Uruguay, the area of forest plantations of *Eucalyptus* and *Pinus* spp. increased 30-fold from 1988 to 2013 (Uruguay Forest Industry, 2014).

Multiple incentives have been developed to improve ecosystem services associated with forests. For instance, international agencies are promoting integrated watershed management as a framework to sustain water ecosystem services from forests (Burgeon, Hofer, van Lierop, & Wabbes, 2015). Forest sustainability was central to Agenda 21 of the 1992 United Nations Conference on Environment and Development. The Montreal Process Working Group, launched in 1994, developed criteria and indicators for forest conservation and management. In 2003, member countries including Argentina, Chile, and Uruguay published their first Country Forest reports (Montreal Process, 2015). International forest certification standards also recognize potential adverse hydrological effects of forest plantation management. The Forest Stewardship Council international standard (Forest Stewardship Council, 2015) requires forest management organizations to "assess and record the presence and status of … critical ecosystem services … including protection of water catchments and control of erosion of vulnerable soils and slopes," and to "develop effective strategies that maintain and/or enhance [ecosystem services and] … demonstrate that periodic monitoring is carried out." However, the environmental benefits from forest certification programs are a matter of debate (e.g., Heilmayr & Lambin, 2016; Moog, Spicer, & Böhm, 2015).

In summary, major changes in forest cover and growing policy concerns underscore an urgent need for research on sustainable forest management and water ecosystem services in South America. The remainder of this commentary briefly reviews the science, presents an approach for examining trade-offs between water and wood production, and makes recommendations for future research on forests and water in South America.

2 | STATE OF THE SCIENCE OF FORESTS AND WATER IN SOUTH AMERICA

In addition to the Amazonian rainforest, South America has many diverse forest types, including moist and dry, natural and managed forests, with a wide range of associated hydrologic research. Much scientific effort has been focused on the capacity for South American tropical rainforests, including the Amazon basin and its surroundings, to generate and recycle as much as 50% of precipitation, maintaining climate and ecosystem integrity and functioning. Yet these extensive rainforests also depend on external factors, notably large-scale, long-term moisture transfer via atmospheric circulation and climate cycles, suggesting that deforestation and land use and cover changes may perturb climate systems and forests throughout the South American continent (Makarieva & Gorshkov, 2007; Marengo, 2006; Marengo & Espinoza, 2015; Mulligan, Rubiano, Burke, & Van Soesbergen, 2013; Nobre, Oyama, & Oliveira, 2014; Salati & Vose, 1984; Swann, Longo, Knox, Lee, & Moorcroft, 2015; Victoria, Martinelli, Mortatti, & Richey, 1991; Werth & Avissar, 2002).

Many studies have explored the hydrological response to forest cover change, which strongly depends on the initial state of the ecosystem (Figure 2). Conversion of native forest to crops or pasture increases peak runoff and sediment delivery (e.g., Germer et al., 2009), while forest plantation establishment on agricultural lands reduces peak flows and sediment delivery locally (Molina, Vanacker, Balthazar, Mora, & Govers, 2012). Intensively managed monospecific stands (i.e., forest plantations) are associated with reduced streamflow, especially during the dry season (Almeida, Soares, Landsberg, & Rezende, 2007; Calder, 2007; Farley et al., 2005; Iroumé, Mayen, & Huber, 2006; Iroumé & Palacios, 2013; Jackson et al., 2005; Lara et al., 2009; Little, Lara, McPhee, & Urrutia, 2009; Llerena, Hermoza, & Llerena, 2007; Silveira & Alonso, 2009; Scott, 2005). Evapotranspiration in plantations varies with climate, season, forest type, and affected

TABLE 1 South American forest cover loss and gain summary statistics (km^2) by country, 2000 to 2012, ranked by total loss out of 180 countries, for forests with various canopy densities (25%, 50%, and 75% tree cover)

Country	Total loss (km^2)	Total gain (km^2)	Total loss/total land area (excluding water) (%)	>25% tree cover loss/year 2000 >25% tree cover (%)	>50% tree cover loss/year 2000 >50% tree cover (%)	>75% tree cover loss/year 2000 >75% tree cover (%)	Total gain/year 2000 >50% tree cover (%)	>50% loss + total gain/2000 >50% tree cover (%)	Previous column less double counting pixels with both loss and gain (%)	Rank of total loss for all countries
Brazil	360,277	75,866	4.3	6.4	6.4	6.1	1.6	8.0	7.5	2
Argentina	46,958	6,430	1.7	10.4	11.8	12.2	2.8	14.6	13.9	10
Paraguay	37,958	510	9.6	14.7	17.2	16.4	0.4	17.6	17.6	11
Bolivia	29,867	1,736	2.8	4.5	4.9	5	0.3	5.2	5.1	12
Columbia	25,193	5,516	2.2	3.0	3.1	3.1	0.7	3.8	3.7	14
Peru	15,288	1,910	1.2	1.9	2.0	2.0	0.2	2.2	2.1	20
Venezuela	12,958	1,910	1.4	2.1	2.1	1.8	0.4	2.5	2.4	25
Chile	11,879	14,611	1.6	6.0	6.5	8.0	8.2	14.7	12.2	30
Ecuador	5,246	1,027	2.1	2.7	2.8	3.0	0.6	3.4	3.3	44
Uruguay	2,027	4,985	1.2	11.5	13.9	19.3	35.9	49.8	45.2	69
Guyana	915	114	0.4	0.5	0.5	0.5	0.1	0.5	0.5	90
Suriname	724	70	0.5	0.5	0.5	0.5	0.1	0.6	0.5	98
French Guiana	441	42	0.5	0.5	0.5	0.5	0.1	0.6	0.6	106

Forest cover includes both native forests and forest plantations. Source: Hansen et al., 2013, Supplemental material, table S3

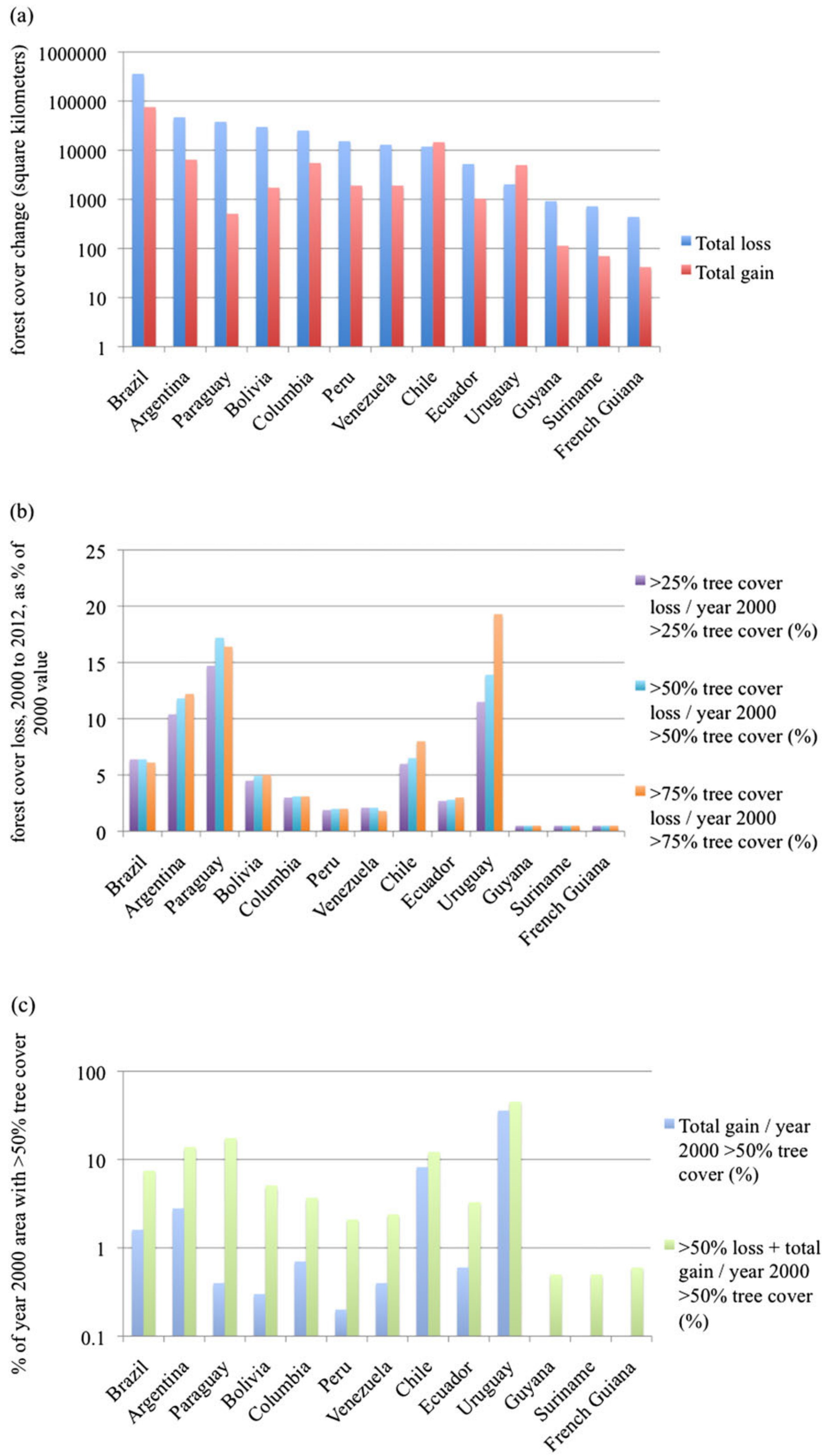

FIGURE 1 South American forest cover loss and gain summary statistics by country, 2000 to 2012, ranked by total loss. (a) Total forest loss and total forest gain (km^2), (b) loss of forest with tree cover >25%, >50%, and >75% as percent of forest area in 2000, (c) total gain as a percent of year 2000 forest area with tree cover >50%. Forest cover includes both native forests and forest plantations. (Source: Hansen et al., 2013, Supplemental material, table S3)

portion of the hydrograph (floods, low flows, groundwater; Almeida & Soares, 2003; Calder, 2007; Hervé-Fernández et al., 2016; Lima, 2011; Lima et al., 2012b). Evapotranspiration may exceed 90% of precipitation in plantations of *Eucalpytus* and *Pinus* spp., reducing water yield and depleting groundwater (Almeida, Smethurst, Sigins, Cavalcante, & Borges, 2016; Huber, Iroumé, & Bathurst, 2008; Jobbágy and Jackson 2004; Jobbágy et al., 2013; Silveira, Gamazo, Alonso, & Martinez, 2016; van Dijk & Keenan, 2007). Plantation forestry may not be cost-effective when the value of evapotranspired water is taken into account (Chisholm, 2010; Núñez, Nahuelhual, & Oyarzún, 2006). At the large river basin or landscape scale, over the long term, the amount of native forest cover strongly influences hydrologic processes (Ferraz, Lima, & Rodrigues, 2013), and net conversion of native forest to plantations is associated with declining water ecosystem services (Aguirre et al., 2014; Balthazar, Vanacker, Molina, & Lambin, 2015; Little et al., 2009).

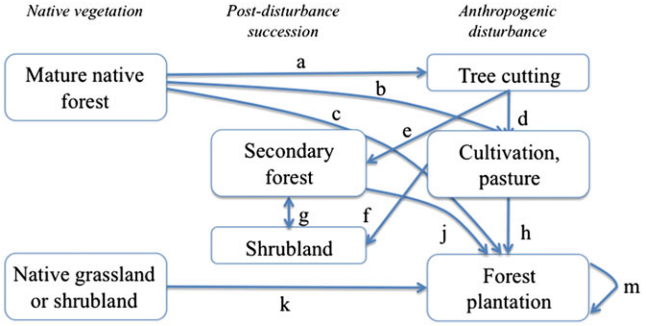

FIGURE 2 Multiple pathways of land conversion affect forests in South America, and all of these pathways affect hydrology. Native forest may be affected by tree cutting (a), cleared for cultivation or pasture (b), or converted into forest plantations (c). Forests affected by tree cutting may become areas of cultivation or pasture (d) or secondary forest (e). Areas of cultivation or pasture may be abandoned and undergo succession to shrubland or secondary forest (f,g). Forest plantations may be created in areas of cultivation or pasture (h), secondary forest (j), native forest (c), or native grassland or shrubland (k). Forest plantations also undergo harvest and replanting (m). Forest hydrology studies can examine effects of any of these changes, which are gradual rather than discrete, producing a wide variety of possible outcomes

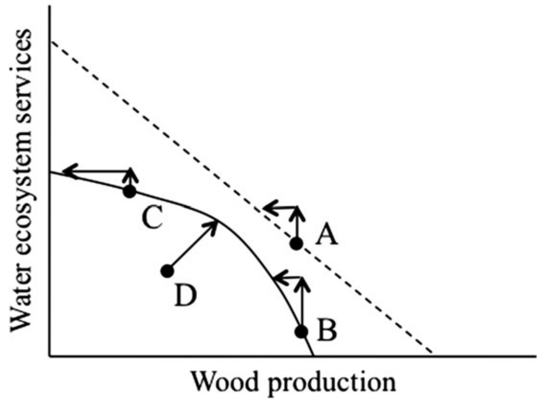

FIGURE 3 Hypothetical trade-off curve between wood production and water ecosystem services from forests, including provision (e.g., water yield), regulation (e.g., timing, seasonal variability, maintenance of base flows, and reduction of flood occurrence); and supporting (e.g., aquatic habitat, stream temperature [shading], retention of sediment, and nutrients) services. If the trade-off curve is linear (dashed line), then reductions in wood production produce equal gains in water ecosystem services at all levels of wood production and water ecosystem services (point A). However, if the trade-off curve is nonlinear and convex relative to the origin (solid curved line), the relative gains and losses depend on the level of wood production. At high levels of wood production, relatively large gains in water ecosystem services may be achieved with relatively small reductions in wood production (point B), but at low levels of wood production, only relatively small gains in water ecosystem services can be achieved even with large reductions in wood production (point C). However, existing forest management may be inefficient relative to both wood and water ecosystem services, such that improvements in sustainable wood production may also increase water ecosystem services (point D)

3 | FOREST LAND OWNERSHIP AND TRADE-OFFS BETWEEN WATER AND WOOD PRODUCTION

Forest land ownership affects how forests are managed, which in turn affects water yield, timing, and quality from forests. In South America, despite differences among the countries, forest plantations tend to occur on private land, whereas in many cases native forests are predominantly on public land. The forest industry and its wood suppliers manage forest plantations primarily for wood production. In contrast, native forests on private land are managed for timber and firewood, often using non-sustainable practices under precarious land tenure arrangements or illegal operations, accounting for much of the forest loss and degradation observed in South America (Karsenty, Drigo, Piketty, & Singer, 2008; Keller et al., 2007; Llerena, Hermoza, Yalle, Flores, & Salinas, 2016). At the same time, individuals, conservation organizations, indigenous peoples, the forest industry, and government agencies have created public and private protected forest areas, which are dedicated to various ecosystem services including water provision and regulation (Serenari, Peterson, Wallace, & Stowhas, 2016). Differences in land ownership and management objectives create trade-offs between wood production and water ecosystem services from forests at scales ranging from small (<1 km^2) to mid-size (100 km^2) to large (>10,000 km^2) watersheds and to whole regions.

Work is needed to quantify trade-offs between competing goods and ecosystem services, such as wood production versus water provision, in South America (e.g., Onaindia, de Manuel, Madariaga, & Rodríguez-Loinaz, 2013). A framework based on trade-offs among ecosystem services can help formulate hydrology research questions (Figure 3). For example, the establishment of riparian buffer zones in plantation forests may lead to significant increases in water ecosystem services such as nutrient or sediment retention with relatively small losses in wood production, relative to monospecific forest plantations (Figure 3, point B; e.g., Lima et al., 2012a; Little, Cuevas, Lara, Pino, & Schoenholtz, 2014; Smethurst, Almeida, & Loos, 2015). In contrast, other forest management practices may reduce wood production but provide relatively small improvements in water ecosystem services. For example, compared to more intensive harvest, selective logging may greatly reduce wood production without increasing water yield or quality (e.g., Perez, Carmona, Farina, & Armesto, 2009) (Figure 3, point C). Some forest management practices may currently produce the highest possible levels of both wood and water (Figure 3, points A–C). However, in many cases, changes in forest management (e.g., species, planting density, rotation length, and thinning) may jointly enhance wood production and water ecosystem services (Figure 3, point D; Lara et al., 2009). This framework could be applied to consider trade-offs among biomass production, biodiversity, and water, at multiple scales.

4 | RECOMMENDATIONS FOR FUTURE RESEARCH

Although much progress has been made, current scientific understanding of forest management effects on water ecosystem services in South America has important limitations, as shown by this special issue. Progress includes increased work on the basic hydrology and ecohydrology of native forests, studies of hydrologic response to climate change and variability in forests, and applied studies of forest plantation management effects on hydrologic processes. However, research is limited by the scarcity of long-term records of climate and streamflow, especially in headwater mountain ecosystems with native forests; the lack of whole-watershed studies integrating vegetation, climate, streamflow, sediment, temperature, and biogeochemistry; and relatively few paired watershed experiments that compare managed, planted forest to managed or unmanaged native vegetation (forest, grassland).

Long-term, paired watershed studies, which have a before-after, control-impact design, provide appropriate spatial and temporal scales for integrated study of forest effects on water and may be complemented by before-after or space-for-time studies and modeling. Although some paired watershed studies exist in South America (e.g., Almeida et al., 2016; Ferraz et al., 2013; Germer et al., 2009; Iroumé et al., 2006; Jobbágy et al., 2013; Little et al., 2014; Ochoa-Tocachi et al., 2016), studies are needed to compare forest plantations with native forests in various management and disturbance regimes and to contrast with studies from other continents (e.g., Brown, Zhang, McMahon, Western, & Vertessy, 2005; Creed et al., 2014; Jones et al., 2012; Jones & Post, 2004; Scott, 2005; van Dijk & Keenan, 2007). Long-term data on precipitation, temperature, soil moisture, streamflow, and groundwater (e.g., Figure 4) allow researchers to test hypotheses about change in water yield and storage over time in watersheds with contrasting forest cover and management practices. For example, runoff ratios (Q/P) plotted as a function of time can show how forest growth, climate change, and disturbance affect streamflow (Figure 5). Streamflow from a watershed that has experienced some kind of vegetation modification can be compared to streamflow from

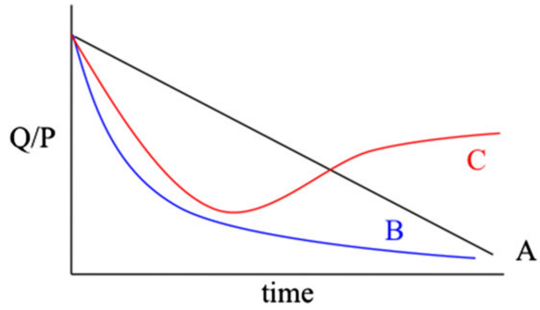

FIGURE 5 Work is needed to quantify trajectories of change in water yield (Q) relative to precipitation (P) over time (or age of forest stand, or time since last major forest disturbance). Native forest succession or forest plantation establishment on pasture, shrub, or barren land may result in a linear decline in water yield over time (curve A) or a rapid decline in early years, which tends to stabilize in later years (curve B). On the other hand, forest plantation establishment may result in declines in water yield followed by increases as plantations age, or when they are harvested (curve C). Many other curves are possible. The Q/P response through time depends on many variables including (1) tree growth and evapotranspiration rates (as affected by native versus exotic, needleleaf or broadleaf, deciduous or evergreen species); (2) disturbance type (e.g., by fire, volcanism, and windthrow), severity, and time since last disturbance; (3) stand management (i.e., thinning, rotation length, native forest riparian buffer width, and harvesting systems such as clearcut or shelterwood); and (4) trends and variability in climate (precipitation and temperature)

a reference watershed to test hypotheses about how forest management affects trajectories of streamflow response over time (Figure 6). Example questions include the following:

1. How do water yield, storage, timing, and quality compare over time in watersheds with (a) plantations, versus native forests, grasslands, shrublands, or agricultural land or (b) undisturbed native forests, compared to native forests affected by harvest, fire, grazing, or natural disturbances such as volcanism?
2. How do these effects scale from small watersheds to large river basins?
3. How do effects vary by season, type of climate, or with climate change?
4. What are the best watershed management options to meet objectives of different stakeholders and policy makers?

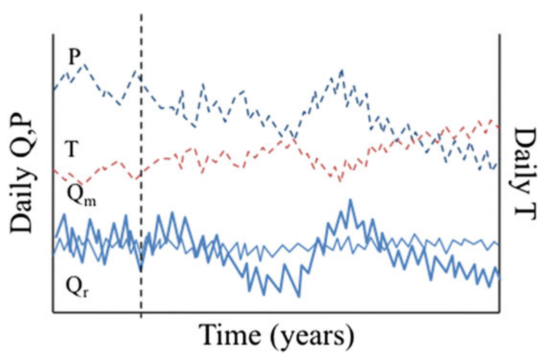

FIGURE 4 Long-term data are needed for quantifying trade-offs between water ecosystem services and sustainable wood production: long-term precipitation (P, blue dashed line), temperature (T, red dashed line), discharge (Q) from a modified watershed (Q_m, thick blue solid line), and a reference watershed (Q_r, thin blue solid line). Vertical dashed black line represents a perturbation, such as forest clearance or plantation establishment. Daily or finer-scale data collected over multiple years permit analysis of how water yield, timing, and water quality respond over time to perturbations such as forest succession after natural disturbance (fire, volcanic eruption); conversion of native forests to industrial exotic plantations, agriculture or pasture; forest plantation growth under varied management; and climate change and variability

Given the very rapid rate of transformation of South American forests, hydrologists and ecologists working in this region have an important role to play in research on forests and water. Hydrologic research is needed to formulate forest policy to sustain terrestrial and aquatic ecosystems and provide and regulate water for agriculture, municipal use, and industry. Work is needed to continue and extend long-term watershed-scale studies, to create and analyze long-term records, to elucidate hydrologic flow paths using isotopic tracers, to apply and validate hydrological models, and to incorporate human values and perceptions of forests and water. Data archiving and publically available data are required. Integrated applied research should be undertaken on lands managed by private landowners (including rural communities and the forest industry), on protected

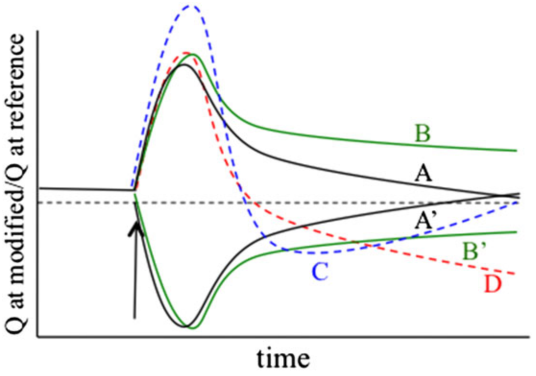

FIGURE 6 Research is needed to quantify trajectories of water yield over time from modified versus reference watersheds, after the system has been perturbed by forest harvest, forest planting, abandonment of agriculture or grazing, or a natural disturbance such as wildfire or volcanic eruption. Prior to the modification (black arrow), the relationship between the modified and reference watershed is quasi-constant. After the modification, water yield in the modified watershed may increase or decrease initially relative to the reference watershed and then recover to prior levels (solid curves A, A′), or remain elevated or reduced (solid curves B, B′). More complex responses are possible, such as an initial increase followed by a reduction and return to prior levels (dashed curve C) or an increase followed by a persistent reduction (dashed curve D)

lands (both public and private), and in experimental forests managed by universities and other entities. The creation of national networks and a multi-country South America network to identify and implement common water research protocols, share results, and explore their implications would add value to all participant countries and would promote common and well-supported policies.

In these efforts, interdisciplinary teams can describe the response of forest structure and composition to disturbance and climate variability and develop consensus on appropriate protocols and indicators of the water balance and water partitioning. Hydrologists should partner with foresters to experiment with forest management practices including tree species, rotation lengths, and planting densities in order to optimize trade-offs between wood production and water ecosystem services from forest plantations (e.g., Almeida et al., 2016; Bremer & Farley, 2010; Brockerhoff, Jactel, Parrotta, & Ferraz, 2013; Ferraz et al., 2013; Hartley, 2002; Lima, 2011; Lima et al., 2012a; Lima et al., 2012b; Little et al., 2014; Pawson et al., 2013; Thompson et al., 2014). Hydrologists and forest engineers should collaborate to quantify effects of forest practices and roads on erosion, flood occurrence, and water quality (e.g., sediment load, turbidity, and eutrophication). Social scientists should be involved to promote participatory processes from local communities to jointly improve wood production and water ecosystem services (e.g., Donoso et al., 2014).

Hydrologists working in South America are well placed to tackle the challenges and opportunities for collaborative research with ecologists, foresters, forest engineers, and social scientists to develop models for sustainable forest management, conservation, and restoration that will maintain the intrinsic values and water ecosystem services provided by South America's forests.

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