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PERSPECTIVE

Managing water services in tropical regions: From land cover proxies to hydrologic fluxes

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Abstract Watershed investment programs frequently use land cover as a proxy for water-based ecosystem services, an approach based on assumed relationships between land cover and hydrologic outcomes. Water flows are rarely quantified, and unanticipated results are common, suggesting land cover alone is not a reliable proxy for water services. We argue that managing key hydrologic fluxes at the site of intervention is more effective than promoting particular land-cover types. Moving beyond land cover proxies to a focus on hydrologic fluxes requires that programs (1) identify the specific water service of interest and associated hydrologic flux; (2) account for structural and ecological characteristics of the relevant land cover; and, (3) determine key mediators of the target hydrologic flux. Using examples from the tropics, we illustrate how this conceptual framework can clarify interventions with a higher probability of delivering desired water services than with land cover as a proxy.

Keywords Hydrology · Land use · Payments for watershed services · Tropical ecosystems · Watershed management

INTRODUCTION

Watershed investment programs are premised on the assumption that managing land use and land cover in water source areas will protect or enhance downstream water services, such as the provision of clean drinking water, enhanced dry-season flow for transport or irrigation, and flood mitigation (Brauman et al. 2007). These programs occur in a variety of forms, including bilateral agreements, water funds, trading and offsets, and in-stream buybacks (Bennett et al. 2013), but all seek to capitalize on the natural ecohydrologic functions of watershed landscapes by conserving or creating "green" infrastructure.

To this end, they engage upstream landowners, residents, or managers and then promote the adoption of selected land-use activities, such as ecosystem conservation and protection, agricultural best practices, reforestation, and restoration of degraded lands (Engel et al. 2008; Porras et al. 2013). Common land covers associated with these activities include forest, alpine grassland, tree plantations, and agroforest. The size of land parcels enrolled in programs is frequently small. For example, in Mexico's payment for watershed services program (i.e., where downstream residents compensate upstream suppliers for delivering water services), the current land area requirement is 100–200 hectares per individual service provider or 200–3000 hectares per community (Sims et al. 2014). Because they offer the prospect of a flexible and economically efficient avenue for securing water resources, the number of watershed investment programs continues to grow (Goldman-Benner et al. 2012).

However, questions are beginning to arise about the extent to which these programs effectively deliver water and other targeted ecosystem services (Porras et al. 2013). To date, watershed investment programs have relied predominantly on land cover (e.g., forest area) as a proxy for water service provision (Quintero et al. 2009). Programs typically forego measurement and monitoring of water flows and instead rely on presumed relationships between

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land cover and water service outcomes. Monitoring, when it occurs, is generally used to ensure compliance with required actions (e.g., maintenance of forest cover), rather than to assess whether land management has resulted in measurable changes to water resources.

Here, we explore some of the challenges and opportunities that exist with watershed investment programs in tropical landscapes. Of primary importance, projects in tropical regions are widespread and expanding (Bennett et al. 2013). For example, from 2001 to 2011, >3.4 million hectares of land across Latin America were managed for water benefits through water services projects (Balvanera et al. 2012; Bennett et al. 2013). In 2014, The Nature Conservancy announced a US$ 27M investment in a Latin American Water Funds Partnership with the stated objective of managing ~3 million hectares of watershed lands (The Nature Conservancy 2014). Despite these investments, empirical data on water flows within and across the broad suite of tropical land-cover types targeted for investments are surprisingly limited (Wohl et al. 2012; Ponette-González et al. 2014). As a result, land cover proxies for water service provision are often based on observations from temperate ecosystems or, as noted by Calder (2004), on 'conventional wisdom' that may prove inappropriate for tropical systems. Although we focus on tropical watersheds, the insights we draw here are applicable to regions elsewhere with growing interest in water services programs and limited data and/or monitoring capacity.

Challenges and opportunities

We consider three major challenges with the design and evaluation of watershed investment programs in tropical regions. First, water managers often face financial and logistical constraints to adequate hydrologic monitoring (Jeanes et al. 2006). For example, in mountainous areas, lack of roads and other infrastructure may preclude access to suitable sampling sites or certain types of data collection (e.g., distance from laboratory facilities limits analysis of water chemistry; Gunston 1998). Second, when and where hydrologic monitoring is conducted, it is not usually linked explicitly to land-use or land-cover modification (Farley et al. 2011). Third, the opportunity to measure water flows often arises simultaneously with the opportunity for intervention. As a result, the paucity of baseline data prevents assessing the absolute impact of an intervention.

In light of these challenges, we advocate that proposed land-use or land-cover actions could be evaluated for how they will affect key hydrologic fluxes at the site of intervention and that those impacts should be interpreted for how they will affect desired water services. In this context, we define local hydrologic fluxes as the inputs, outputs, and flows of water and its constituents through the site of intervention (Weathers et al. 2012). The local fluxes most likely to be directly influenced by watershed investment programs, which we designate as key fluxes—and are the focus of this analysis—are canopy interception, evapotranspiration, infiltration, and erosion (Box 1).

Measuring local fluxes is often straightforward and can be done inexpensively and effectively (Gunston 1998). For example, rainfall and throughfall (water that drips from plant canopies to the soil below) can be measured using low-cost tools such as buckets. The effectiveness of contour ditches for mitigating erosion and detaining sediment on soil hardpans can be evaluated using sediment pins (LaFevor 2014). At the onset of a project, such methods can be applied at sites with and without interventions and resulting measurements compared over time. Thus, the benefit of a watershed investment project can be directly evaluated as the additional flow or improved water quality it provides in comparison with the flow or quality that would have occurred in the absence of the project, a concept known as additionality (Porras et al. 2013). Although novel statistical and model-driven methods to detect vegetation effects on water flow are being developed (e.g., van der Velde et al. 2013), data constraints coupled with local land-cover transitions make these methods untenable at present for many projects (Guswa et al. 2014).

Beyond the site of intervention, hydrologic flow paths and interactions also will influence the extent to which activities in project areas translate into downstream water services. For example, if nitrate pollution in drinking water is caused by nitrate released from legacy stores in the subsurface, or leaking septic tanks close to wells, and subsequently carried downstream, then managing nitrate inputs upstream will not alleviate the problem (Destouni et al. 2010; Åkesson et al. 2014). However, focusing on key local fluxes affected by an intervention program ensures that, at the very least, broad-scale effectiveness of the program can be assessed.

From land cover proxies to hydrologic fluxes: Framework for effective water management

Reliance on land cover as a proxy for water service provision in data-poor tropical regions is widespread and problematic. The major disadvantage of this approach is that land cover, at the broadest descriptive level, cannot accurately represent hydrologic function if the land cover does not capture the structural and ecological characteristics that affect hydrologic fluxes (Eigenbrod et al. 2010). A straightforward alternative is to directly manage the hydrologic fluxes in project regions that serve as controls on downstream water services of interest.

This shift in focus from land cover proxies to key local hydrologic fluxes requires that watershed investment programs (1) identify the specific water service of interest and

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associated hydrologic flux; (2) account for structural and ecological characteristics of the current and alternate land cover; and (3) determine key mediators of the target hydrologic flux when designing watershed investments (Fig. 1). Below, we demonstrate how this conceptual framework can be used to identify interventions with a higher probability of delivering desired water services than with land cover as a proxy.

Match the specific water service with the associated hydrologic flux

"Water services" is a broad term that explicitly links hydrologic attributes such as water quantity and quality to human uses of water. For example, watershed investment programs may seek to increase dry-season water flows for transportation (e.g., Panama Canal Watershed) or decrease water flows to protect against flood damages (e.g., Napa River Flood Protection Project, California) (Brauman et al. 2007). Therefore, it is imperative to identify the specific water service of interest at the onset of the project (Higgins and Zimmerling 2013; Fig. 1).

Water management programs are more likely to achieve their aims while reducing undesirable side effects if, once identified, the water service is matched with key local hydrologic fluxes relevant for management (Fig. 2, Box 1). The recent expansion of tree plantations on tropical alpine grasslands (*páramos*) illustrates how this step can clarify the land management options likely to be most effective in water services projects. Tropical tree plantations are promoted as a means to obtain wood products, store carbon, and generally to improve watershed conditions (Farley 2007; Harden et al. 2013; Fig. 3). In addition, tree plantation establishment on grasslands may increase interception and water uptake and stabilize soils, effectively reducing soil erosion (van Dijk and Keenan 2007; Fig. 4). If sediment originating as erosion in *páramos* is a source of unwanted drinking water contamination, then expanding plantations may lead to improvements in water quality for downstream water facilities.

However, in drier climates, the lower throughfall and increased evapotranspiration characteristic of planted forests compared to grasslands can reduce annual surface runoff by 13–44 %, decreasing the amount of water delivery downstream (Krishnaswamy et al. 2013; Ponette-González et al. 2014; Fig. 4). Thus, where increasing or maintaining dry-season water flow is also a service of interest, adjusting cultivation or grazing practices to reduce soil erosion may be more effective than establishing plantation forests. For example, construction and maintenance of agricultural terraces on degraded hillslopes (LaFevor 2014) and reduction in livestock densities (Mwendera and Saleem 1997) are

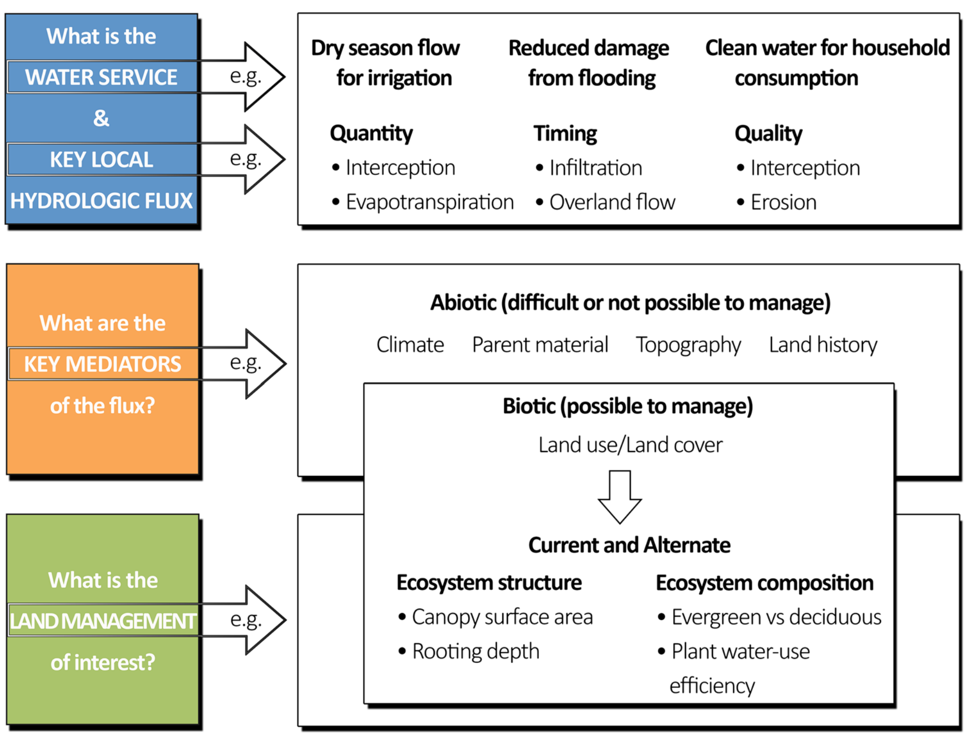

Fig. 1 Questions designed to assist in the design and assessment of watershed investment programs. Water managers are interested in a diverse array of water services. Several key local hydrologic fluxes, biotic and abiotic controls on those fluxes, and land management options have the potential to affect water service delivery. Here, we provide specific examples to illustrate how our conceptual framework can be applied to determine effective land management actions or interventions in water source areas

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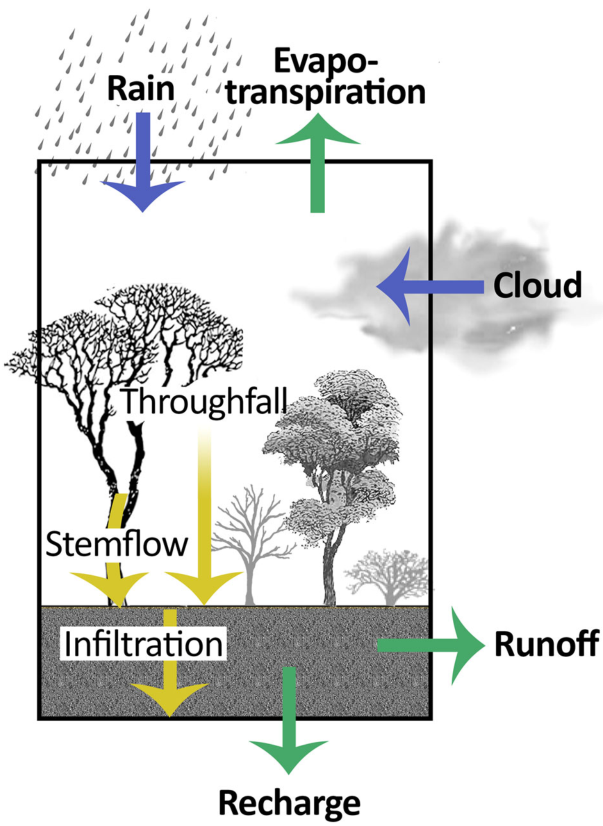

Fig. 2 Key local hydrologic fluxes that mediate the effect of land use and land cover on water quantity and quality: inputs to the ecosystem in the form of rain and cloud (*blue arrows*); water flows through the ecosystem as throughfall, stemflow, and infiltration (*green arrows*); and outputs from the ecosystem as evapotranspiration, runoff, and groundwater recharge (*yellow arrows*). Detailed groundwater dynamics are not included as these are not local fluxes most likely to be influenced directly by watershed services programs

Box 1 Hydrologic fluxes in tropical landscapes

The viability of watershed services programs depends on their ability to improve the quantity, reliability, or quality of water delivered from watersheds. Water quantity is affected by the balance between water inputs to ecosystems and outputs. At regional scales (i.e., million km^2), large-scale land-use change can alter precipitation inputs to ecosystems. However, these regional tele-connections are beyond the spatiotemporal scale of most watershed investment projects, which generally focus on altering water flows within a watershed. At the scale of parcels to small watersheds, land management actions and interventions promoted by tropical watershed investment programs are most likely to influence key local hydrologic fluxes. Groundwater dynamics, while critical for many services, cannot be managed directly by upstream landowners in tropical watershed investment programs, and thus we do not address them here.

Land-use and cover mediate water inputs and outputs through effects on key local hydrologic fluxes, such as interception, evapotranspiration, and infiltration. Water that lands on plant, rock, or ice surfaces and evaporates or sublimates does not enter the pool of water that could move downstream; direct interception of cloudwater by vegetation can increase water input to soil. Land cover also regulates water output through evapotranspiration. Water that moves from the subsurface through plants to the atmosphere via transpiration is no longer available to move downstream. In addition, vegetation may shade snow or ground, reducing evaporation.

Land cover also affects hydrologic transport. For example, by reducing rainsplash and increasing soil organic matter inputs and soil porosity, vegetation may increase the rate at which water moves into the subsurface via infiltration. Once in the subsurface, water can be transpired, move laterally to surface water bodies, or move to deeper groundwater reserves. Water stored in the near subsurface is available to deep-rooted vegetation and can be transpired, so enhancing infiltration may entail a reduction in the total volume of water available downstream.

Water quality is also affected by water movement through the biosphere. As water is deposited to a vegetated canopy, ions contained within can be taken up by, leached, or washed from plant surfaces, altering the chemistry of water deposited to soil via throughfall. As plants transpire, they take up nutrients from the soil, and as water moves downward through the soil, ions can be retained in soil or move in soil solution. Vegetation can also prevent erosion by stabilizing soils and streambanks. Whether chemical additions are a larger flux than removal will depend on climate, parent material, land cover, topography, and time (for references, see Likens 2010).

management options that have been shown to decrease soil erosion rates in tropical highlands while conserving water.

Account for the structural and ecological characteristics of the relevant land cover

Identifying land-cover characteristics, such as canopy leaf area and vegetation rooting depth, which influence key local hydrologic fluxes is crucial to predict the impact of different management practices on water resources (Fig. 1). If the relevant biophysical characteristics are not accounted for, then proposed land management actions may be ineffective. For example, a common approach of water service programs in Latin America is to increase the overall percentage of forest cover (Goldman-Benner et al. 2012). This simplistic strategy is based on the persistent yet incorrect assumption that a tree-dominated land cover will provide similar hydrologic services regardless of its structural or ecological properties (Putz and Redford 2010).

Yet, forested ecosystems differ considerably in vegetation structure and species composition, and thus, in their effects on hydrologic fluxes (Fig. 4). Throughfall, for example, appears to be particularly sensitive to differences in canopy characteristics even within the general land-cover category of 'forest', with distinctive patterns for montane forest, agroforest, and tree plantation (Ponette-González et al. 2014). A survey of 34 high-elevation tropical sites (see Electronic Supplementary Material) suggests a significant, albeit weak, relationship between throughfall and leaf area

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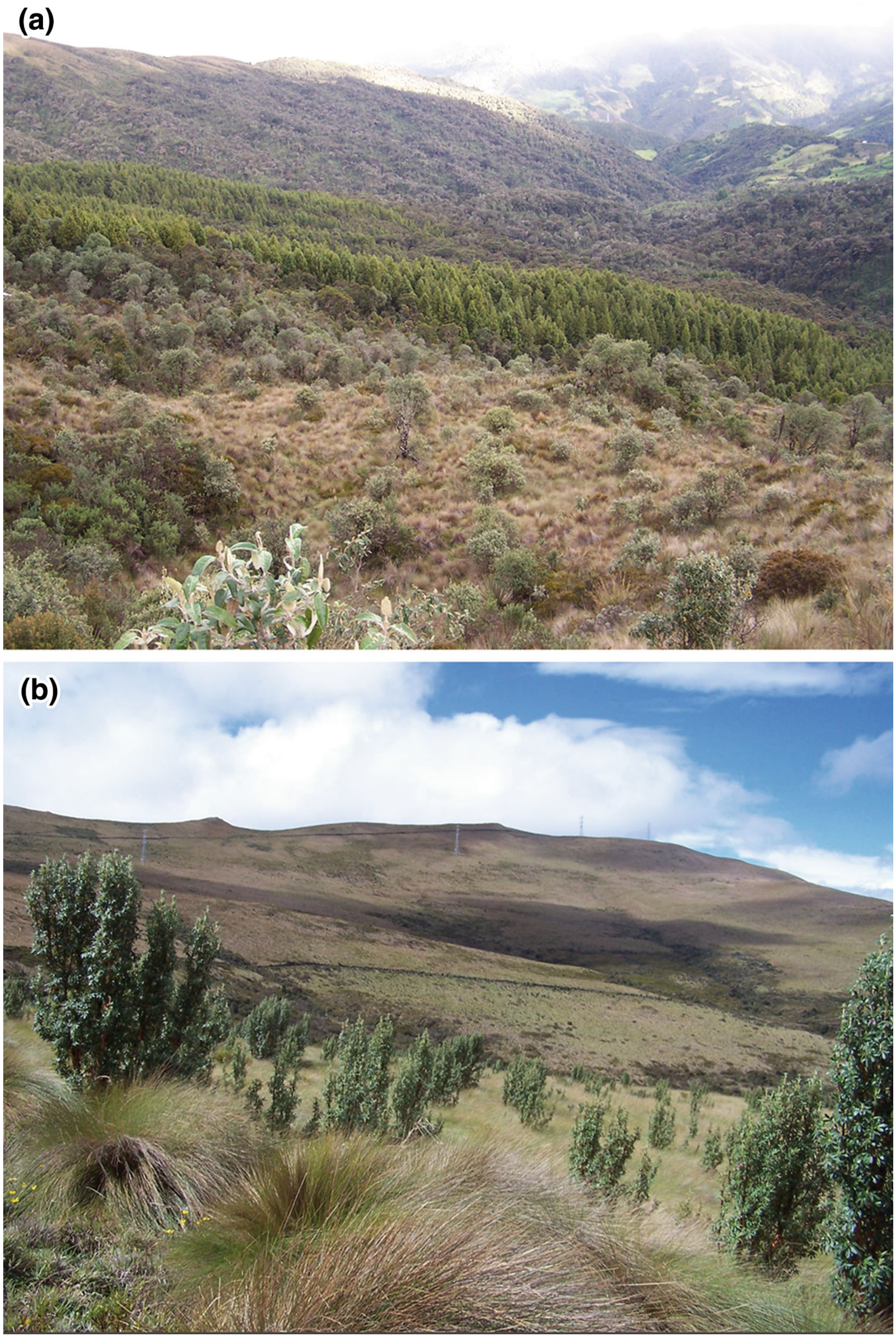

Fig. 3 Tree plantations established on tropical alpine grasslands in the Ecuadorian Andes. Common species used in tropical plantations include **a** *Pinus patula* and, more recently, **b** *Polylepis racemosa* (photographs courtesy of K.A. Farley)

index (LAI) (Fig. 5). Species composition may also alter water availability for downstream users because plant species differ in their water use characteristics (Kagawa et al. 2009). Hence, not all forests will result in similar hydrologic capture or loss, and in turn watershed hydrologic services.

Although there may be substantial uncertainty regarding the hydrologic function of different vegetation types in tropical systems, identifying the service and flux of interest makes it possible to ascertain and refine which elements of an ecosystem are best managed and monitored. In Mexico,

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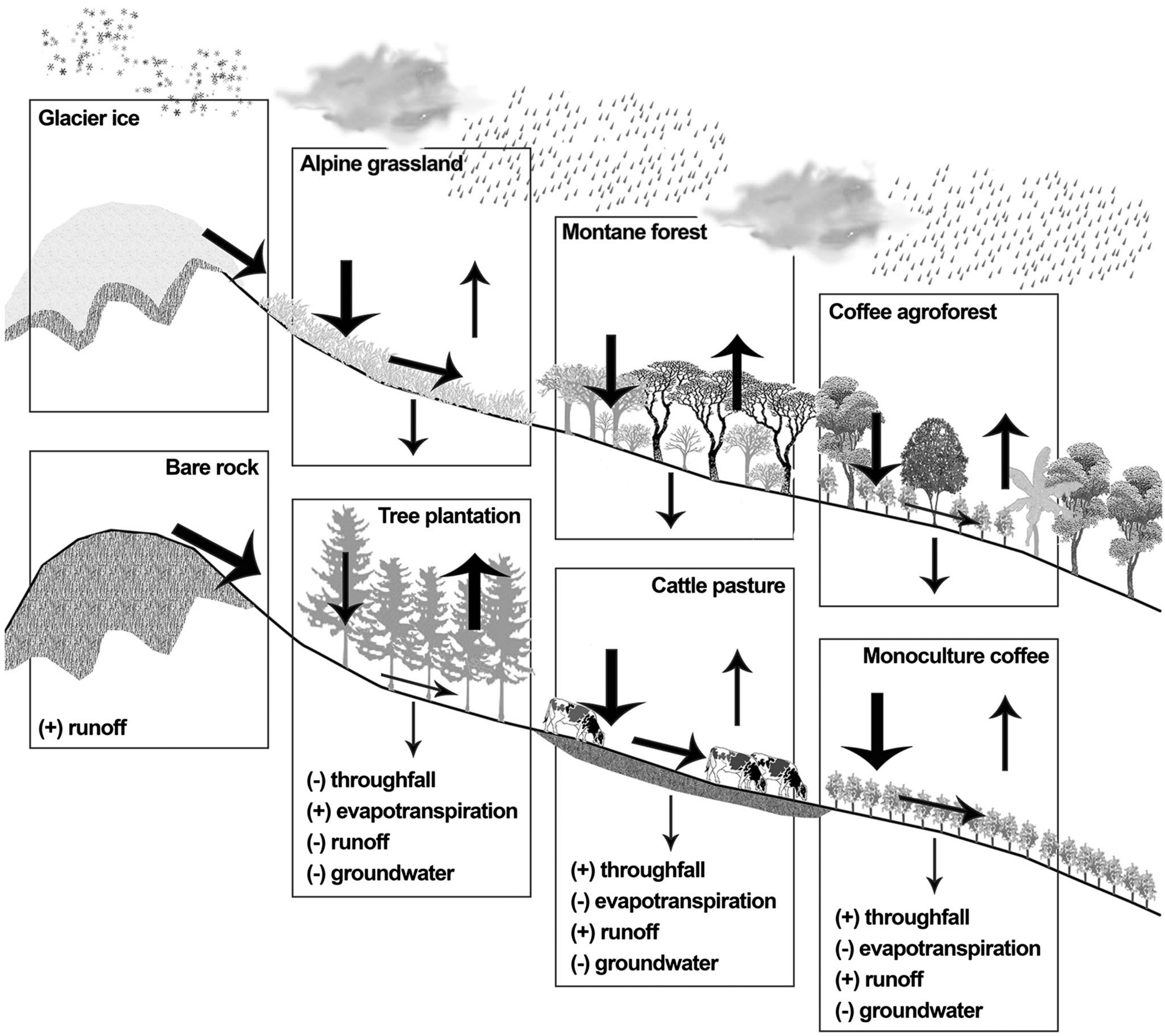

Fig. 4 *Top* An idealized tropical montane landscape showing water fluxes in glacial, alpine grassland, montane forest, and coffee agroforest ecosystems. *Bottom* Potential changes in water fluxes with glacier retreat, tree plantation establishment on alpine grassland, forest conversion for cattle grazing, and coffee intensification

landowners participating in the watershed investment program receive ~US$40 ha $year^{-1}$ to conserve montane cloud forest because program designers assumed that dry-season cloudwater interception represents an important contribution to streamflow (Muñoz-Piña et al. 2008). Payments are contingent on the extent of forest cover and not on forest condition, even though cloud deposition varies with canopy leaf area (Brauman et al. 2010; Ponette-González et al. 2010). Managed agroforests or young forests with low leaf areas may have insufficient surface area to capture and deliver cloudwater (>100 % throughfall) to downstream water users (Fig. 5). Where leaf area is high (e.g., many plantation forests), intercepted water may remain in the canopy and translate into little water input to the soil (Nadkarni and Sumera 2004). A program that specified thresholds of canopy leaf area would likely better serve downstream beneficiaries of water investments.

Determine key mediators of the target hydrologic flux

Climate, parent material, land cover, topography, and time ("state factors" sensu Jenny 1941) serve as broad-scale controls on water and water-mediated fluxes within

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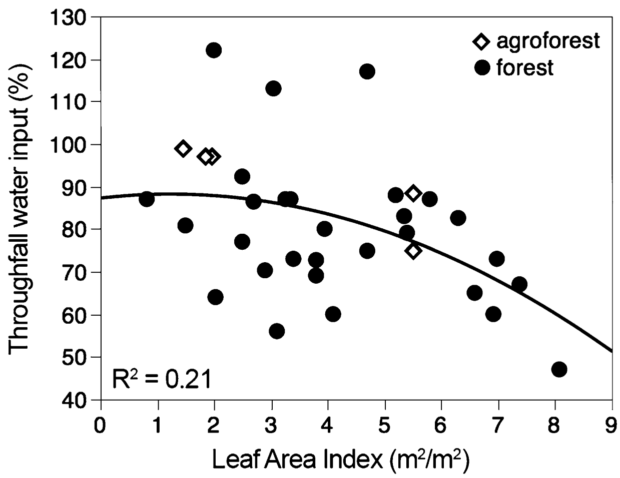

Fig. 5 Relationship of leaf area index to throughfall water input ($TF\% = 97.38 - (3.46*LAI) - 0.612*(LAI - 4.07)^2$, $p < 0.0258$) for forest and agroforest in the high-elevation Latin American tropics. See also Electronic Supplementary Material

ecosystems. Only land use and cover can be modified and managed within the time frame of watershed investment projects, although the other state factors interact with land cover to control hydrologic fluxes. As a result, similar land uses or land covers may have diverse effects on water services across space and time (Ponette-González et al. 2010). The location and topography (e.g., elevation, aspect) of a target area, as well as its position relative to other land covers, influence the extent to which interventions will be effective (Polasky et al. 2008).

Understanding the role of state factors is therefore critical to identify appropriate sites for intervention as well as management options for watershed investment programs. For example, many conservation-oriented water projects are based on the assumption that forests "produce water" or increase runoff (Calder 2004), yet an established principle in forest hydrology is that water yield from forest, at both plot and watershed scales, tends to be lower than that from non-forest ecosystems (Bosch and Hewlett 1982; Brown et al. 2005). This apparent contradiction stems from the paucity of attention to hydrologic fluxes in context. In the montane tropics of Latin America, evapotranspiration from forests can be 12–30 % higher than that from grasslands (Ponette-González et al. 2014; Fig. 4). Under seasonal precipitation regimes and when climatic conditions favor high rates of evapotranspiration, tree planting is likely to decrease water yield (Zhang et al. 2001). However, at cloudy and humid tropical montane sites where water is not limiting and wind speeds are low, evapotranspiration may be lower from forest than from grassland (Brauman et al. 2012). Considering these abiotic controls on hydrologic fluxes will improve watershed investment project outcomes.

Implementing programs for water services

Watershed investment projects have considerable potential to improve water resources. However, there is evidence that beneficiaries will not continue to pay for water services unless these investments can be shown to generate and sustain intended benefits (Jack et al. 2008; Porras et al. 2013). Directly measuring a change in water service delivery through long-term paired watershed studies, evaluation of changing watershed response over time, or comparison among many similar watersheds (van der Velde et al. 2013; Carlson et al. 2014) is ideal. When time, budget, or logistics preclude these, targeting key local hydrologic fluxes provides an alternative approach.

Landscapes are linked hydrologically through atmospheric pathways, thus precipitation and its chemistry often are altered by human activities, including land-use and land-cover changes that occur far from the focal watershed (Weathers and Ponette-González 2011). Changes in vegetation, especially when irrigation is introduced, can affect regional precipitation regimes by altering evaporative flux (Destouni et al. 2013). Many tropical watershed investment programs affect relatively small land areas, so while they are unlikely to alter regional land–atmosphere feedbacks, they may be influenced by them. In Costa Rica, for example, complete deforestation of lowland and premontane regions (<1000–1400 m.a.s.l.) was hypothesized to generate an upward 50–100 m shift in cloudbank elevation (Ray et al. 2006). Such an effect would impart considerable influence on any project designed to increase cloudwater interception at lower elevations.

Watershed investment projects should also be designed with climatic change in mind, as shifting climate is projected to stress ecosystems and associated ecohydrologic functions (Staudt et al. 2013). For example, glacier retreat may increase runoff in the short-term, but in the long-term, may reduce dry-season flow (Bury et al. 2013), potentially increasing the need for land management to increase groundwater recharge. Monitoring programs associated with watershed investment projects must account for changing climate by thoroughly evaluating assumptions about expected hydrologic response under business-as-usual conditions (Milly et al. 2008).

Investments in watershed service programs have expanded rapidly in recent decades. Targeting key local hydrologic fluxes for measurement and monitoring can contribute to improvements in project design, particularly because they allow projects to account for diverse exogenous forces, from varying geographies to climate change. Focusing on local hydrologic fluxes has strong potential to improve water services delivery.

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