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SMALL WATER BODIES

Review Paper

Climate change and multiple stressors in small tropical streams

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Abstract Despite the importance of small tropical streams for maintaining freshwater biodiversity and providing essential ecosystem services to humans, relatively few studies have investigated multiple-stressor effects of climate and land-use change on these ecosystems, and how these effects may interact. To illustrate these knowledge gaps, we reviewed the current state of knowledge regarding the ecological impacts of climate change and catchment land use on small tropical streams. We consider the effects of predicted changes in streamflow dynamics and water temperatures on water chemistry, habitat structure, aquatic biota, and ecosystem processes. We highlight the pervasive individual effects of climate and land-use change on algal, macroinvertebrate, and fish communities, and in stream metabolism and decomposition processes. We also discuss potential responses of tropical streams in a multiple-stressor scenario, considering higher temperatures and shifts in hydrological dynamics. Finally, we identify six key knowledge gaps in the ecology of low-order tropical streams and indicate future research directions that may improve catchment management in the tropics to help alleviate climate-change impacts and biodiversity losses.

Keywords Tropical streams · Multiple stressors · Climate change · Agriculture

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Introduction

More than 50% of inland freshwater habitats globally were lost during the twentieth century, and most of those that remain are degraded due to changes in land cover and land use, the introduction of invasive species, hydrologic modification, overharvesting, pollution, and climate change (Millenium Ecosystem Assessment, 2005). Global climate change will affect not only multiple levels of biological organization but may also interact with other stressors to which freshwater ecosystems are also exposed (Woodward et al., 2010). Freshwater habitats hold a disproportionally high biodiversity relative to their area. For example, surface freshwater habitats represent only 0.01% of the world's water and 0.8% of Earth's surface, yet they contain about 9.5% of the animal species described on Earth (Dudgeon et al., 2006; Dudgeon, 2010).

Tropical streams represent one of the planet's most biodiverse freshwater ecosystems, but also one of the most threatened (Dudgeon et al., 2006; Wantzen et al., 2006; Boulton et al., 2008). These ecosystems are located in biodiversity hotspots (Myers, 1990; Mittermeier et al., 1998) and contain the world's highest richness and endemism of fishes, turtles, and amphibians (Abell et al., 2008). Draining many different types of soils and vegetation, tropical streams have many specific characteristics that imply much is to be learned about their ecology (Boyero et al., 2009). For example, tropical streams receive more solar radiation, have lower seasonal climatic variation, and higher water temperatures than temperate streams, and they are subjected to higher chemical weathering due to the year-round warm temperatures (Lewis Jr., 2008). Their geomorphology, landscape evolution, and geological history can also result in particularities, for example, in migratory barriers such as waterfalls that create predator-free environments and changes in the physical and chemical characteristics of water (Wantzen et al., 2006). Besides these natural factors, tropical streams are affected by multiple anthropogenic pressures, mostly due to changes in catchment or riparian land use, but increasingly also due to climate change (Boyero et al., 2009; Guecker et al., 2009). These anthropogenic pressures are more severe in tropical countries (Smith et al., 2010), increasing the likelihood of ecosystem degradation. Due to all these factors acting simultaneously when affecting aquatic communities, it is likely that interactions of physical and chemical variables and biological communities in tropical streams will cause responses in a different range to that observed in temperate streams.

In recent decades, global climate change has become a "hot topic" in the biological sciences due to the numerous effects this change is expected to have on ecosystems (Heller & Zavaleta, 2009). In running waters, many of the predicted changes to ecosystems are linked to changes in the hydrological cycle and water temperature (Dodds et al., 2015). Evidence suggests that in the tropics, these changes may be abrupt, with effects unprecedented in the last 5,200 years (Thompson et al., 2006). Tropical areas are predicted to experience markedly higher temperatures and considerable alterations in the timing and amount of rainfall (with increases in precipitation extremes), and these changes are expected to occur earlier than in other parts of the globe (O'Gorman, 2012; Mora et al., 2013; IPCC, 2014). Model projections anticipate that after 2050, every month will be an extreme climatic record in the tropics (Mora et al., 2013). These changes, in turn, will increase the risk of droughts, floods and landslides, and compounded stress on water resources (IPCC, 2014), with direct effects on the structure and functioning of tropical streams and rivers (Davies, 2010; Jiménez Cisneros et al., 2014). They also represent an important challenge for catchment management. Due to the relatively small natural climate variability in tropical regions that generates narrow climate bounds, a changing climate exceeding these bounds will likely be stressful for biological communities adapted to this narrow climate range (Mora et al., 2013), contributing to high extinction rates in the tropics (Ceballos et al., 2015). Considering the higher biodiversity and faster human population growth in the tropics, small tropical streams may be disproportionately at risk compared to temperate streams in the face of ongoing global change, resulting in negative and interactive effects on ecosystem structure and function, ecosystem services, water quality, biodiversity, and water availability.

Climate-change effects on streams have been studied mainly in temperate systems to date. In these ecosystems, a number of potential effects on biogeochemical cycles and biological communities have been observed (Durance & Ormerod, 2007; Buisson et al., 2008; Baron et al., 2009), although potential interactions between key climate-change drivers and other human-induced stressors such as those linked to agriculture remain largely unknown (Piggott et al., 2015a, b, c). By contrast, there has been little research into climate change effects on small tropical streams, and even less research on how predicted land-use changes will interact with climate change in these ecosystems. It is likely that the threats to the integrity of small tropical streams are different from temperate streams because tropical streams are subjected to a different range of temperatures and land-use dynamics and are situated within a region that is home to almost half of the global human population (Boyero et al., 2009; Harvey et al., 2014).

Small headwater streams are fragile ecosystems highly susceptible to anthropogenic impacts, reflecting their direct connections to the adjacent landscape that influence the supply, transport, and fate of water and solutes in a catchment (Alexander et al., 2007). Modifications in these areas also expose downstream receiving water bodies to the cumulative effects of upstream activities (Covich et al., 2006; Lorion & Kennedy, 2009). In tropical streams, anthropogenic landscape modifications can result in short and unpredictable flood pulses, which often “reset” the physical and biotic environment (Junk et al., 1989). Short and unpredictable flood pulses in tropical streams may occur more frequently under land use and climate change, shifting the functional dynamics of the ecosystem. Despite increasing concern about how climate and land-use change will affect freshwater ecosystems globally, few studies have focused on small tropical streams, highlighting the need for climate change and multiple-stressor research in these ecosystems (Ramirez et al., 2008).

In this paper, we conducted a qualitative review of global change and multiple-stressor-related studies in small streams (up to 3rd stream order) within the tropical zone (between 23°N and 23°S). We focused on small streams because they are one of the most widespread freshwater ecosystems and generally represent the majority of water bodies in a catchment (Benda et al., 2005). Some topics discussed hereafter remain largely unstudied in tropical systems. In these cases, we extrapolate likely scenarios based on well-established general biological and physical principles or theories.

Flow dynamics

Flow regimes play a major role in determining the structure and functioning of running water ecosystems (Richter et al., 1996; Poff et al., 1997, 2010; Bunn & Arthington, 2002). The flow dynamics of a stream are controlled mainly by the distribution and amount of rainfall, the catchment relief, and land-use characteristics in the catchment (DeFries & Eshleman, 2004; Foley et al., 2005; Stanfield & Jackson, 2011; Macedo et al., 2013). In the tropics, the massive and ongoing conversion of forests to other land uses such as agriculture and urbanization are altering flow regimes (Wu et al., 2007; Carlson et al., 2014) and changing stream characteristics (Table 1). Given the forecast for increasing tropical precipitation extremes due to climate change (O’Gorman, 2012; IPCC, 2014), further modifications of streamflow dynamics can be expected, with small tropical streams generally becoming flashier.

The tropical wet season, characterized in several regions by monsoonal rains, plays an important role in agriculture, hydroelectricity, industry, and providing the basic needs for the human population (Turner & Annamalai, 2012). During this period, considerable changes occur in small stream ecosystem dynamics, starting with flow patterns that, in turn, affect nutrient and carbon concentrations, sediment inputs, channel structure, and biological communities (Table 1). Thus, elevated stream flows limit benthic algal biomass accrual and affect benthic macroinvertebrate and fish communities directly via physical disturbance and indirectly via changes in resource availability, favoring species that are well adapted to fast-flowing, frequently disturbed lotic environments (Junk et al., 1989; Rosser & Pearson, 1995; Nolte et al., 1997; Pringle & Hamazaki, 1997; Townsend & Douglas, 2014; Carvalho & Tejerina-Garro, 2015). Wet-season-induced changes occur in both natural and anthropogenic environments, but more strongly in the latter. Because of anthropogenic land-use changes, lateral flow paths (surface and subsurface runoff) are more frequently active, eroding soil as well as nutrients and carbon previously stored in the soil and carrying them into streams (Dunne, 1979; Allan, 2004; Neill et al., 2006). Observational evidence suggests that land-use changes associated with agricultural intensification can also reduce the monsoonal rainfall in some parts of the tropics (Niyogi et al., 2010). Therefore, climate change effects during the wet season are likely to differ among small tropical streams depending on land-use intensity in the catchment and geographical location, because some regions may become drier whereas others may become wetter, with different consequences for the structure and dynamics of small tropical streams and shifts in aquatic biological communities.

During wet-season rainfall events (which are often intense in the tropics), high flows result in structural changes in the stream channel, its floodplain, and along its banks, and surface runoff (i.e., overland flow). This results in increased inputs of allochthonous organic matter from the riparian zone (including large woody debris) and sediment from the adjacent catchment or due to landslides (Table 1). The addition of large woody debris increases the organic carbon concentration in the water and causes obstructions in

Table 1 Stream responses to changes in rainfall and land-use intensity in the tropical zone

Effects	Physical and chemical responses	Biological responses	Location	Stream order	References
Increase in land-use intensity	Streamflow increase	Not evaluated	Mexico	1st and 2nd	Muñoz-Villers & McDonnell (2013)
			Africa	1st	Recha et al. (2012)
			Brazil	1st	Chaves et al. (2008) and Germer et al. (2009)
	Surface runoff	Not evaluated	Brazil	1st and 2nd	Guzha et al. (2015), Chaves et al. (2008) and Germer et al. (2009)
Rainfall increase	Wood and carbon export to streams	Not evaluated	Panama	2nd	Wohl & Ogden (2013)
			Brazil	1st	Johnson et al. (2006)
	High flow	Reduction in epilithic biomass, high taxon richness due to rare taxa	Australia	1st to 5th	Townsend & Douglas (2014)
	High flow	Steady algal biovolume in the presence of fishes, without fishes decreases in algal biovolume, richness, and diversity in fish exclusion treatments	Costa Rica	3rd to 4th	Pringle & Hamazaki (1997)
	High flow	Increased diversity and density of mayflies	Brazil	3rd to 4th	Nolte et al. (1997)
	High flow	Reduced density and richness of macroinvertebrate communities	Australia	2nd and 3rd	Rosser & Pearson (1995)
	High flow	Reduced abundance of macroinvertebrate communities in riffles	Costa Rica	4th	Ramirez & Pringle (1998)
Rainfall decrease	Low flow, increase in flow variability and instability	Not evaluated	Hawaii	1st to 3rd	Strauch et al. (2015)
	Low flow	Reduced density and richness of macroinvertebrate communities, increase in the dominance of a mayfly genus	Brazil	3rd to 4th	Nolte et al. (1997)
	Low flow, isolated pools	Increase in dominant species (*Atya lanipes* Hothuis, 1963), decrease in reproductive output, decrease in dominant shrimp (*Macrobrachium* spp. Bate, 1868)	Puerto Rico	1st and 2nd	Covich et al. (2003, 2006)

the stream channel, which can create large pools favoring sediment retention (Johnson et al., 2006; Wohl & Ogden, 2013). In a climate-change context, the magnitude of these processes will exceed their current natural variation due to the predicted changes in the global hydrological cycle and are likely to be more severe in modified landscapes. For example, in modified catchments, sediment export rates from terrestrial soils to streams are higher due to soil instability induced by vegetation removal, soil exposure, and faster runoff (Dunne, 1979; Allan, 1995). Changes in riparian vegetation are expected due to longer periods of exposure to flooding and other changes in streamflow dynamics (Auble et al., 1994; Garssen et al., 2015). Therefore, shifts in riparian vegetation composition and catchment sediment yield are expected in small tropical streams, depending on the land use and climate change intensity in the catchment, with consequences for biological community structure due to shifts in allochthonous organic matter inputs and streambed modifications.

Another flow-related consequence of climate change is that droughts are expected to become more severe, particularly in some tropical regions (Hirabayashi et al., 2008; Li et al., 2009; IPCC, 2014). Although recovery of stream ecosystems after droughts is often rapid, their impacts can be disproportionally severe once critical thresholds are exceeded (Boulton, 2003). During the tropical dry season, streamflow dynamics are typically stable and, in the case of intermittent streams, flow often ceases completely. In natural environments, these changes in flow dynamics contribute to shaping biological communities (Lake, 2000). For example, drying events in low-order intermittent streams can decrease the diversity and biomass of periphyton, with disproportionate declines in algae leading to bacterial-dominated, heterotrophic stream metabolism (Sabater et al., 2016). When combined with changes in catchment land use such as agriculture and urbanization, the dry-season flow dynamics in tropical streams can result in more variable flows with higher pollutant loadings, with implications for locally adapted species and shifting biodiversity patterns (Nolte et al., 1997; Longo et al., 2010).

It is well established that some of the main problems related to flow regime modifications are due to human land-use activities and poor landscape management, such as dam construction and agricultural water abstraction, both in temperate regions (Power et al., 1996; Poff et al., 1997; Bunn & Arthington, 2002; Allan, 2004; Dudgeon et al., 2006) and in the tropics (Wu et al., 2007; Chaves et al., 2008; Germer et al., 2009). These problems are even more serious in the tropics where agricultural intensification is a key factor for human development, via food production and climate mitigation (DeFries & Rosenzweig, 2010). Evidence suggests that tropical forest cover is among the most important factors for the protection of streams, and existing research recognizes the critical role played by forests in maintaining soil permeability and thus producing more base flow in streams during the tropical dry season (Bruijnzeel, 2004; Ogden et al., 2013). However, in many parts of the humid tropics, the areas covered by disturbed forests (e.g., logging, slash-and-burn agriculture, and mining) have become larger than those covered by undisturbed forests, and this trend is ongoing (Wohl et al., 2012; Hansen et al., 2013; Kim et al., 2015; Lawrence & Vandecar, 2015). Because disturbed tropical forests are less efficient at reducing streamflow variability during heavy rainfall events or droughts (Ferraz et al., 2014), disturbed forests may not be able to mitigate climate-change effects in agricultural landscapes. Therefore, well-designed, large-scale forest restoration programs are urgently needed throughout the tropics (Latawiec et al., 2015), in order to reinstate the original hydrological patterns and alleviate climate change effects in small tropical streams.

Water temperature

Rising air and water temperatures are the most commonly observed symptom of global climate change to date, with accelerating further increases forecast for the future (IPCC, 2014). Rising temperatures have been observed since the last century and are correlated with atmospheric carbon concentrations (IPCC, 2014). In streams, water temperature controls a multitude of processes, regulating the metabolic activity from individuals to ecosystems (Brown et al., 2004). Tropical streams have lower seasonal climatic variation and higher water temperatures compared to temperate streams (Mora et al., 2013), which are subjected to higher chemical weathering due to the year-round warm temperatures (Lewis Jr., 2008), receive higher annual rates of organic matter due to the year-round litterfall in tropical forests (Clark et al., 2001) and generally exhibit higher biodiversity compared to temperate streams (Dudgeon et al., 2006; Boulton et al., 2008; Ramirez et al., 2008). When combined, these characteristics suggest that tropical streams may be particularly vulnerable to climate-change-induced increases in temperatures. Despite this, the effects of rising water temperatures on small tropical streams remain poorly understood (Table 2). Due to the importance of water temperature on biological communities in small tropical streams, temperature-sensitive taxa may become excluded at elevated temperatures, causing reduced diversity.

Previous studies have documented the effects of water temperature on benthic macroinvertebrate communities in small tropical streams (Jacobsen et al., 1997; Siqueira et al., 2008; Yule et al., 2009). Benthic invertebrates play an important role in stream ecosystem functioning, for example for nutrient cycling, secondary productivity, organic matter decomposition, and translocation of materials (Wallace & Webster, 1996). Few studies in tropical streams have investigated temperature effects on macroalgae, diatoms, or fish (Table 2). These groups of organisms also play important roles in stream community

Table 2 Ecological responses of stream communities to increasing water temperatures in the tropical zone

Response	Location	Stream order	References
Reduced abundance and richness of shredding aquatic insects	Malaysia	1st to 3rd	Yule et al. (2009)
Increase in aquatic insect orders and families	Ecuador	1st to 3rd	Jacobsen et al. (1997)
Increase in the emergence of the aquatic insect Orthocladiinae (Chironomidae)	Brazil	1st	Siqueira et al. (2008)
Shifts in macroalgae community	Mexico	3rd to 5th	Bojorge-Garcia et al. (2010)
Increase in the respiration rates of stream whole metabolism	Puerto Rico	1st to 3rd	Ortiz-Zayas et al. (2005)
Shifts in fish community structure	Brazil	3rd to 5th	Rolla et al. (2009)
	Brazil	1st to 4th	Pinto et al. (2009)
Increase in leaf breakdown	Costa Rica	1st	Benstead (1996)
	Colombia	4th	Mathuriau & Chauvet (2002)
	Brazil	3rd	Abelho et al. (2010)
	Brazil	1st to 4th	Rezende et al. (2014)

structure and functioning, and changes in these communities have been shown to modify and destabilize aquatic food webs (Motta & Uieda, 2005; Coat et al., 2009). Together, microbial communities and primary producers regulate stream metabolism rates, which are strongly temperature dependent and may be compromised by climate-change-induced warming (Ortiz-Zayas et al., 2005; Rezende et al., 2014).

Existing research recognizes the critical role played by temperature on leaf litter decomposition in small tropical streams, an integral functional process for energy flux through stream ecosystems (Benstead, 1996; Mathuriau & Chauvet, 2002; Abelho et al., 2005, 2010). Recent evidence suggests that climate-change effects on tropical streams will likely accelerate microbial litter decomposition via raising water temperatures, while reducing detritivore-mediated decomposition via loss of detritivore species (Boyero et al., 2011). Thus, although net decomposition rates may remain unchanged, carbon dioxide production by microbial activity is likely to increase, possibly further accelerating climate warming and having additional adverse ecological effects (Boyero et al., 2011). Consequently, it is expected that carbon dioxide production in tropical streams will increase more than that in temperate streams as the Earth keeps warming, despite the higher rates of ecosystem metabolism in tropical streams (Ortiz-Zayas et al., 2005). The resulting increase in carbon dioxide production could be considerable, given that a recent study found that about 28% of the carbon dioxide emission from stream and rivers in temperate regions was produced by aquatic metabolism (Hotchkiss et al., 2015).

Human land use

The Millennium Ecosystem Assessment (2005) notes that land-use change to agriculture remains the dominant driver of biodiversity change in terrestrial and freshwater ecosystems worldwide. Agriculture is one of the key human activities in the context of biodiversity loss and climate change in the tropics, because tropical regions will need to increase their food production while, at the same time, mitigate climate-change effects (DeFries & Rosenzweig, 2010). Water demands for agriculture represent nearly 85% of total human-consumptive use (Gleick, 2003), and agriculture is the largest source of nutrients in freshwaters and coastal zones (Carpenter et al., 1998; Bennett et al., 2001; Foley et al., 2005). Hydrological modifications and construction of dams for irrigation are other important stressors often associated or coinciding with agricultural activities. They also create opportunities for biological invasions, another globally relevant stressor (Dudgeon et al., 2006), through changes in water temperature, water quality, resource fluctuations, and food web alterations (Amalfitano et al., 2015). When combined with climate change, the detrimental effects of agriculture in tropical regions may become even more severe, due to reduced freshwater availability and rising water demand (Vörösmarty et al., 2000; Elliott et al., 2014), leading to increased water abstraction and eutrophication. Climate change is also predicted to have negative effects on agricultural development and production in the tropics, due to changes in temperature, precipitation, and soil moisture (Lawrence & Vandecar, 2015). Therefore, tropical regions urgently need to improve their climate-change mitigation/adaptation strategies to ensure the sustainability of agricultural systems.

The main impacts of agriculture on stream ecosystems are related to increased inputs of nutrients, fine sediment and agrochemicals, changes in streamflow dynamics due to land-use conversions, and water temperature changes caused by forest removal (Poff et al., 1997; Tilman, 1999; Lawrence & Vandecar, 2015). Tropical streams are likely to suffer increasingly from these impacts because agricultural intensification for food production is predicted to rise by at least 50% in the tropics by 2050 (DeFries & Rosenzweig, 2010; Godfray et al., 2010). Consequently, many tropical regions are subjected to high rates of deforestation, agricultural expansion and increasing erosion (Ramirez et al., 2008). When combined with climate-change effects, the resulting challenges for tropical stream ecosystems are likely to worsen due to increasing surface runoff and erosion rates driven by rainfall increases (in quantity and/or intensity) (Tucker & Slingerland, 1997), and due to the interactive effects of rising water temperatures coupled with agricultural contaminants (see below).

Effects of agricultural practices on small tropical streams have been studied in various organisms. In fish communities, high functional redundancy (i.e., different species performing similar functions in the ecosystem) has been observed in agricultural landscapes and deforested streams, due to reduced habitat heterogeneity by grass dominance instead of forest in the riparian zone (Casatti et al., 2015; Teresa et al., 2015). In macroinvertebrate communities, reduction of biodiversity and elimination of rare taxa was related to deforestation for agricultural practices (Benstead et al., 2003; Lorion & Kennedy, 2009; Siqueira et al., 2015). Key ecosystem processes in streams are also modified by agricultural practices, such as organic matter decomposition (Silva-Junior et al., 2014) and stream metabolism (Guecker et al., 2009). Moreover, these changes in stream communities and ecosystem dynamics may be increased by climate-change effects via nonadditive interactions of nutrient and sediment addition, flow dynamics changes, and temperature changes (see next section). Because it remains unknown how such interactions will affect tropical stream communities, this represents an important area for future research.

Climate change and multiple stressors

A stressor can be defined as a variable that, as a result of human activity, exceeds its range of normal variation and adversely affects individual taxa or community composition (Townsend et al., 2008). Most present-day ecosystems, including those in running waters, are affected by multiple stressors acting simultaneously (Vinebrooke et al., 2004; Crain et al., 2008; Townsend et al., 2008; Ormerod et al., 2010; Nõges et al., 2015) or sequentially (Christensen et al., 2006). Studies in freshwaters have shown that stressors interact frequently, resulting in complex, nonadditive outcomes that cannot be predicted based on the effects of the individual stressors involved (Folt et al., 1999). Synergistic interactions occur when the combined outcome of multiple stressors is larger than predicted based on the individual effects involved, and antagonistic interactions occur when the combined outcome is less than predicted (Folt et al., 1999; Piggott et al., 2015d).

Studies examining effects of multiple stressors on running water ecosystems exist mainly from temperate regions. A recent meta-analysis considering 286 responses of freshwater ecosystems to paired stressors revealed more antagonistic responses than synergistic or additive ones, possibly due to the environmental variability of streams that foster the potential for acclimation and co-adaptation to multiple stressors (Jackson et al., 2016). Disentangling the mechanisms for these complex interactions remains a pressing ecological challenge (Piggott et al., 2015d; Côté et al., 2016).

Climate change and intensive agricultural activities are two important stressors for small streams and have pervasive effects for stream biota. A streamside mesocosm experiment in New Zealand (Piggott et al. 2015a, b, c) manipulated two key agricultural stressors (nutrients and deposited fine sediment) and water temperature (to simulate climate warming up to 6 degrees Celsius above ambient temperatures), to determine the individual and combined effects of these stressors on periphyton and macroinvertebrate communities and organic matter decomposition. In this experiment, stressors had pervasive individual effects, but in combination produced many synergistic or antagonistic effects, both at the population and community levels. For example, all the three invertebrate community-level metrics of stream health routinely used around the world showed complex three-way interactions, with either a consistently stronger temperature response or a reversal of its direction when one or both agricultural stressors were also in operation (Piggott et al., 2015c). Moreover, the negative effects of added sediment on invertebrate communities were often stronger at raised temperatures, but less so when nutrients were added as well, suggesting that streams already impacted by high sediment loads may be further degraded under a warming climate, but the degree to which this will occur may also depend on in-stream nutrient conditions. While the mechanisms driving these interactive patterns remain speculative, it is likely that increasing temperature influenced the invertebrate community both by changing the physical and chemical conditions in the sediment (oxygen concentration, nutrient dynamics) and the energy base of the invertebrate food web (algal and microbial species composition/productivity and organic matter decomposition rates) (Piggott et al., 2015a, b). In another mesocosm study in a tropical stream, increases in macroinvertebrate drift abundance were observed in response to elevated nutrient concentrations, and increases in macroinvertebrate drift abundance and taxon richness in response to elevated fine sediment levels were observed as well (O'Callaghan et al., 2015).

As discussed above, small tropical streams are exposed to a number of stressors originating in agricultural activities (nutrient enrichment, sedimentation, deforestation, flow regime, and water temperature changes due to deforestation), and these stressor impacts are likely to be modified by climate-change effects. Consequently, complex interactions between multiple stressors and climate change are highly probable, and studies in small tropical streams are urgently needed.

Conclusions and future research needs

We have identified six key areas urgently requiring future research efforts to advance our understanding and management of small tropical streams in the face of global change:

(1) More studies on temperature effects on tropical streams. There is a lack of information about the influence of water temperature on tropical stream communities. Due to the ongoing effects of global climate change, we need to increase our knowledge on this topic in order to prevent biodiversity loss and maintain the functioning and ecosystem services provided by small tropical streams, such as provision of drinking water and nutrient recycling.

(2) Drought and flood effects on tropical streams. More extreme droughts and floods are expected under a climate-change scenario in tropical streams, and such extreme events are already happening in several parts of the tropics. These events can change the structure of streams and are stressful for aquatic communities, especially in systems where these events were less common in the past. Therefore, we encourage studies taking advantage of such events to help improve our understanding of shifts in aquatic communities and biodiversity loss.

(3) More studies on applied topics to help alleviate agricultural and climate-change pressures. Agriculture is a key human activity in the tropics, providing food, labor, and development. Therefore, more research focusing on methods to alleviate agricultural impacts on tropical streams, combined with best landscape and catchment planning to avoid excessive surface runoff during heavy storms and maximize the efficiency of nutrient use, should be conducted. Such research is required to maintain the sustainability of agriculture and water resources in the tropics in the face of climate change.

(4) Studies on multiple-stressor effects in tropical streams. The role of multiple stressors in shaping tropical freshwater communities

including streams is poorly understood. Therefore, more realistic and powerful experiments should be performed to understand the effects of the key agricultural stressors (e.g., nutrients, fine sediment, pesticides, and light excess due to riparian deforestation), urbanization and climate-change effects (e.g., water temperature and streamflow) on tropical stream communities and biodiversity loss.

(5) Climate-change mitigation policies and strategies to ensure the sustainability of tropical freshwater resources. There is scant information about how climate change will interact with agricultural stressors in tropical streams. Consequently, policies to manage small tropical streams and agriculture under climate change are absent or poorly informed. This is important due to potential unpredictable nonadditive outcomes that are likely to affect freshwater biodiversity and ecosystem services. Therefore, after a comprehensive study on multiple-stressor effects in tropical streams, policies and strategies should be established to avoid damage to these ecosystems.

(6) Restoration of tropical streams. Most existing studies of tropical stream restoration examined the implementation of riparian vegetation buffers, which is one of the most important components for the stream function and dynamics. However, implementations of other techniques to avoid habitat loss, invasive species, flow alterations, sedimentation, and bank instability should also be investigated, especially due to the particular tropical soil characteristics and ongoing expansion of agricultural frontiers in the tropics.

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