The impact of tropical land-use change on downstream riverine and estuarine water properties and biogeochemical cycles: a review

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Abstract

Tropical primary forests have been disappearing quickly to make use of the land for commercial purposes. Land-use change has an impact on downstream aquatic processes, but those impacts have mainly been studied in temperate climate regions. The present article reviews the impacts of various tropical land-use changes caused by human activities on downstream riverine and estuarine water properties and biogeochemical cycles, focusing especially on the behaviors of nitrogen (N) and phosphorus (P). Logging of tropical primary forests, subsequent establishment of pasture lands, and occasional wildfire or intentional burning have decreased terrestrial N fixation and increased the discharge of P combined with soils, which has lowered the N:P ratio of dissolved inorganic nutrients in the adjacent stream waters and downstream rivers. Agricultural fertilizers and aquacultural practices basically cause nutrient enrichment in downstream riverine and estuarine waters, changing the N:P ratio depending on the source. Finally, urbanization causes eutrophication in many tropical estuaries, where a halocline forms easily because of a warm temperature throughout the year and the water at the bottom of the estuary tends to become hypoxic or anoxic. Overall, the impact of land-use change on aquatic processes may be more serious in tropical regions than in temperate or cold climate regions because of (1) a higher biomass and nutrient stock in original tropical forests; (2) higher precipitation, more frequent episodic flooding, and warmer temperatures in tropical regions; and (3) certain practices that are rapidly expanding in tropical regions such as land-based aquaculture. Various land-use changes are causing downstream nutrient enrichment or disturbance of the nutrient balance at tropical land-sea interfaces, and the overall N:P ratios in the aquatic ecosystem seem to be declining. Nonetheless, if proper management is conducted and the discharge of nutrients and soils ceases, tropical aquatic systems may have the potential to recover faster than those in other climate regions because of their abundant precipitation and warm temperature. Long-term monitoring and more attention to elemental stoichiometry are important areas for future research.

Keywords: Deforestation, Land-use change, Eutrophication, Water quality, Hypoxia, Environmental monitoring, Aquatic conservation, Water resources
Introduction

Primary forests have been globally cut down with increasing human populations and expanding commercial land use; in particular, tropical forests have been lost faster than those in other climate regions during the past several decades (Gibbs et al. 2010; Miettinen et al. 2011; Achard et al. 2014; Rosa et al. 2016). As a result, for example, the eastern lowlands of Sumatra and the peatlands of Borneo lost approximately half of their peat swamps for conversion to industrial plantations from 2000 to 2010 (Miettinen et al. 2011), and the Brazilian Amazon lost 15% of the primary forest by 2010 (Maia and Schons 2020). Not only inland forests but also coastal forests have been cut down quickly. Tropical coastal areas are often bordered by mangrove forests, but it was estimated that 35% of global mangroves were already lost from 1980 to 2000 (Valiela et al. 2001), although recent rates seem to be declining (Friess et al. 2019). At the global level, the gross loss of tropical forests has been estimated to be 8 million ha per year from 1990 to 2010 (0.5% annually; Achard et al. 2014). These deforested lands have been replaced with commercial lands for various purposes: agricultural fields (e.g., rice, soybeans, and oil palm), aquaculture ponds, or ranching and poultry farms, depending on the demands of the region (Chen et al. 2013; Richards and Friess 2016).

Generally, tropical forests and their soil have higher carbon (C) and nitrogen (N) stocks than those in other climate regions because of active photosynthesis and biological N fixation throughout the year (Cleveland et al. 1999; Jobbágy and Jackson, 2000; Hedin et al. 2009; Sarma et al. 2011; Abril et al. 2014). However, along with the disappearance of tropical primary forests, less organic matter is produced on land, and more organic matter is discharged downstream by increased erosion, which results in a reduction in the stock of soil organic C and N (Brown and Lugo 1990; Brouwer and Riezebos, 1998; Don et al. 2011; Drake et al. 2019; Hattori et al. 2019). Therefore, the impact of deforestation on downstream limnological processes is expected to be greater in tropical regions than in other climate regions.

Conversely, artificial nutrient loading, such as the application of fertilizers, increases with human land use after deforestation because many human activities involve the use of nutrients (Downing et al. 1999). In agriculture, more than half of applied fertilizers are often not recovered by plants but can accumulate in soils, volatilize to the atmosphere, or leach from the land to ambient streams and rivers through groundwater or surface water runoff (Rocha et al. 2019). The impact of fertilizers may remain in the soil even after several decades (Sebilo et al. 2013). The fluxes of total N (TN) or NO₃⁻ in rivers are correlated with population densities in the watershed, and TN fluxes have increased by 2- to 20-fold in temperate rivers since industrialization (Howarth et al. 1996), although the trend is specific to the catchment and is also highly affected by climatic drivers, such as hydrology and temperature (Argerich et al. 2013). The discharge of total phosphorus (TP) and PO₄³⁻ has also been increasing with wastewater discharge, artificial drainage systems, and erosion (Nieminen et al. 2017; Williams and King 2020). Because tropical regions often experience more rainfall than other climate regions, more N and phosphorus (P) might be discharged with water from tropical lands.

The impacts of land-use change on downstream aquatic processes have mainly been studied in temperate regions, and some reviews are available (Howarth et al. 2011; Statham 2012; Bauer et al. 2013). However, reviews of the impacts on tropical regions are scarce (Downing et al. 1999; Camara et al. 2019; Thomaz et al. 2020), even though the impacts are expected to be different from those seen in other climate regions, as introduced above. To summarize our present understanding of changing tropical aquatic processes, the present article reviews the impacts of various tropical land-use changes on the water properties and biogeochemical cycles in adjacent streams, rivers, and estuaries. We focused on six major land-use changes: (1) logging of primary forests, (2) pasture including ranching, (3)
Logging

Tropical land-use change starts from deforestation by logging primary forests. At this stage, both above- and belowground plant biomasses are drastically and quickly removed from the land, where the soil is dug up and loosened. Subsequent transportation of timber by tractors further disturbs the ground, which causes runoff of surface water and soils downstream after rainfall (Nykvist et al. 1996; Chappell et al. 2004). Moreover, total evaporation (or evapotranspiration) from the land may be reduced due to less vegetation, and more rainwater flows into the adjacent streams and rivers after logging (Chappell et al. 2005; Ling et al. 2016). The groundwater baseflow also increases because of the reduced uptake of infiltrated rainwater by terrestrial plants. In the Bukit Berembun catchments in Peninsular Malaysia, the average water yield increased by 50–70% after commercial logging (Nik and Harding 1992; Chappell et al. 2005). The increased volume and velocity of water flows erode stream banks, making the stream increasingly wider (Iwata et al. 2003; Neill et al. 2006).

Most previous studies on the effects of logging on downstream riverine water properties have focused on the monitoring of suspended solids (SS) or turbidity, and increases in these water variables have been recorded at many study sites during and after logging (Table 1). The increase in SS and turbidity is mainly caused by soils, but dissolved inorganic nutrients (e.g., NO₃⁻ and PO₄³⁻), minerals (e.g., K⁺, Mg²⁺, and Ca²⁺), and organic matter are also discharged from soils (Table 1). Because terrestrial plant-derived organic matter generally has a higher C:N ratio than aquatic microbes in rivers, the discharge of terrestrial organic matter from logging sites increases the C:N ratio of total organic matter in the river (Ward et al. 2015; Zhang et al. 2019). In the Changhuajiang River basin, China, the C:N ratio of POM increased from 7 to 10 during the wet season, where more terrestrial particles were discharged downstream due to high precipitation and strong soil erosion (Zhang et al. 2019). In addition, the N:P ratio of tropical plant leaves is occasionally very high due to the active N fixation of the forest ecosystem compared to temperate or cold climate regions (Hedin et al. 2009). This finding suggests that the N:P ratio of POM in the downstream river might be higher in tropical regions than expected in other climate regions.

River water pH can also be altered due to terrestrial inputs because most soils in the humid tropics are acidic (e.g., pH = 4.5–6.4; Grip et al. 2005). This acidity has both biological and chemical causes: microbial processes (e.g., aerobic oxidation, methanogenesis, sulfate reduction, nitrification) enrich the soil pore water with H⁺, and various forms of oxidized C and N (e.g., CO₂, CH₄, NO₃⁻) (Melling et al. 2005; Ríos-Villamizar et al. 2017).
and weathering of parent material may also directly acidify adjacent aquatic systems by reacting with precipitation or moisture. For example, acid sulfate soil (ASS) is widely distributed in tropical regions and is stable under anoxic conditions. However, when ASS is exposed to oxygen (atmosphere) with water, which is often driven by logging during a rainy season, ASS starts to be oxidized, producing H\(^+\) and causing severe acidification of the downstream rivers (Sammut et al. 1996; Vuai et al. 2003; Van Ha et al. 2011). In the Kahayan River in Central Kalimantan, Indonesia, the surface water pH dropped to as low as 3 due to ASS during a rainy season (Haraguchi 2007).

Because P combines with certain soil minerals (e.g., calcium, iron, and aluminum), enhanced soil runoff due to logging would involve a drastic transportation of P from the surface land to the downstream aquatic ecosystem, decreasing the N:P ratio (Chappell et al. 2005). In the downstream estuary, suspended particulate P desorbs from the soil particles, and PO\(_4^{3-}\) becomes available for primary producers (Zhang and Huang 2011; Lin et al. 2012; Nguyen et al. 2019a). The sorption/desorption of P is chemically affected by the water temperature and salinity; PO\(_4^{3-}\) desorption is enhanced with decreasing temperature or increasing salinity (Zhang and Huang 2011). However, in a turbid tropical estuary of Saigon, Vietnam, the SS concentration was the greatest factor in determining the P content in the water because of the high flocculation of cohesive sediments (Nguyen et al. 2019a). These properties of P indicate the importance of the management of soil discharge from logging sites to prevent P overloading in downstream aquatic ecosystems. All the above types of runoff (i.e., water, soil, organic matter, and nutrients) would be alleviated by riparian vegetation because the vegetation zone functions as a filter (Williams et al. 1997; Gomi et al. 2006; de Souza et al. 2013).

The effects of logging on downstream riverine and estuarine water could last for months to years until the terrestrial soil is gradually stabilized and plants regrow naturally or artificially. During the recovery period, the discharge of N and P into the adjacent river seems to return to the original level before logging earlier than other mineral ions (e.g., K\(^+\), Ca\(^{2+}\), Mg\(^{2+}\)) (Malmer and Grip 1994; Chappell et al. 2005). For example, in the rivers of the Mendolong catchment, Malaysia, the concentration of NO\(_3^-\) returned to the original level within 2 years after clear felling, but the K\(^+\) concentration was still high even after 5 years (Malmer and Grip 1994). This difference suggests that N and P often limit the growth of terrestrial vegetation after logging and thus are subject to active absorption by the vegetation for regrowth, while other minerals, such as K\(^+\), are relatively sufficient for plants because they are continuously leached from soil and rock through weathering (Malmer and Grip 1994; McDowell 1998; Chappell et al. 2005). However, from a longer-term viewpoint, the removal of terrestrial vegetation and the gradual erosion of soils decrease the storage of nutrients and minerals on land (Recha et al. 2012; Hattori et al. 2019), which would eventually lower the concentration of these ions in the downstream river and estuarine water.

To summarize this section, logging increases the discharge of terrestrial soils, including nutrients and organic matter that are stored in the forest (Table 2). Because tropical forest soils store larger biomass stocks than those of other climate regions, the impact of logging on organic matter and nutrient discharge would be greater in tropical regions, especially when episodic heavy rainfall occurs. The discharge of soils might increase the C:N ratio of organic matter and decrease the N:P ratio of dissolved inorganic nutrients in the downstream river and estuary (Table 2). The increase in turbidity caused by soil and organic matter might reduce aquatic photosynthesis in the downstream river and estuary, but in contrast, the discharged nutrients have the potential to increase productivity. The final productivity would be determined by the balance of these effects.

**Pastures and ranches**

After deforestation, the land is often changed to pasture by natural sprouts or seedings of a target species of grass. The grown pasture may be repeatedly burned to remove unwanted weeds and used for ranches (Neill et al. 2001, 2017). If fertilizers are not added to pasture lands, nutrient stocks in the soil may gradually decline from the original stock in primary forests (Hattori et al. 2019; López-Poma et al. 2020). Because of deforestation and conversion to pasture, the primary production and standing stock of biomass are decreasing globally on tropical lands (Erb et al. 2016). Ranching of aviculture, swine, and cattle for livestock production is the major use of pasture lands, especially in Latin America. Brazil alone accounts for almost half of the livestock

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**Table 2** A summary of the common effects of tropical land-use change on the downstream riverine and estuarine water properties. The arrows indicate that the water properties would increase (↑), decrease (↓), or not change (→). See the list of abbreviations for water properties.

| Land use               | SS  | TN  | TP  | OC:ON | TN:TP | DO  |
|------------------------|-----|-----|-----|-------|-------|-----|
| Logging                | ↑   | ↑   | ↑   | ↓     | ↓     | ↓   |
| Pasture and ranching   | ↑   | ↑↓  | ↓   | ↓     | ↓     | ↓   |
| Agriculture            | ↑↑  | ↑   | ↓   | ↑     | ↑     | ↓   |
| Burning                | ↑   | ↑↑  | ↑   | ↑     | ↑     | ↓   |
| Aquaculture            | ↑↑  | ↑   | ↑↑  | ↓     | ↑     | →   |
| Urbanization           | ↑   | ↑   | ↓   | ↓     | ↓     | ↓   |
production in Latin America and the Caribbean (OECD/FAO 2019).

Because of its extensive area and long history, the impacts of the conversion of tropical primary forest to pasture on adjacent stream waters have been frequently studied in the Amazon region (de Mello et al. 2020; Thomas et al. 2020; Table 3). In the Amazonian state of Rondonia, Brazil, forest reserves were logged from 1987 to 1990 and were mostly planted with Brachiaria grass species for extensive cattle ranching (Thomas et al. 2004; Nóbrega et al. 2018). The planted grasses had lower productivity compared to the primary forest (Nóbrega et al. 2018). Due to the conversion from primary forest to grasses, decreased canopy densities allowed more sunlight to reach streams, which increased the temperature and primary production in the stream water (Thomas et al. 2004; Lorion and Kennedy 2009). Most of the measured organic and nutrient contents in the stream waters were higher alongside pastures than the streams surrounded by primary forest during the dry season, although the difference was smaller or negligible during the wet season because of the dilution by rainwater (Biggs et al. 2004; Neil et al. 2006; Thomas et al. 2004; Deegan et al. 2011; Nóbrega et al. 2018). Higher POM and DOM would be derived from aquatic vegetation, which became dominant on the stream banks in pastures due to increased light availability (Neil et al. 2001; Nóbrega et al. 2018). NH$_4^+$ and PO$_4^{3-}$ also increased through the mineralization of the organic matter produced by aquatic vegetation in the stream, which led to lower dissolved oxygen (DO) in the water (Thomas et al. 2004).

Conversely, NO$_3^-$ may decrease in the pasture streams because less N fixation, mineralization, and nitrification could occur on the pasture lands than in the original primary forest (Neil et al. 2001; Thomas et al. 2004; Figueiredo et al. 2020). The reduced NO$_3^-$ concentration lowered the N:P ratio of dissolved inorganic nutrients in the stream waters of the Amazon regions, shifting from a P limitation in forest streams to an N limitation in pasture streams for aquatic primary producers (Neil et al. 2001; Figueiredo et al. 2020). A similar reduction in N:P ratios in stream waters was also observed in pasture-dominated watersheds in Panama (Valiela et al. 2013). Because tropical primary forests have high N fixation and provide excess N downstream (McDowell 1998; Hedlin et al. 2009; Brookshire et al. 2012), this reduction in NO$_3^-$ and the N:P ratio would be more impactful in tropical regions than in other climate regions. The total fluxes of these nutrients would be greatly affected by water discharge, and therefore, long-term monitoring is important to observe seasonal changes and to assess annual budgets (Williams et al., 1997; Nóbrega et al. 2018).

Pasture lands are often used for ranching to raise livestock animals. The grazing of grass by those animals

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**Table 3** A summary of the effects of the conversion of primary forest to pastures and ranches on the downstream riverine and estuarine water properties. The arrows before the water properties indicate that the subsequent water properties increased (↑), decreased (↓), or did not change (→). See the list of abbreviations for the water properties.

| Study sites | Effects on downstream water properties | Sources |
|-------------|-----------------------------------------|---------|
| Rayu River, Sarawak, Malaysia | → pH, NO$_3^-$, NO$_2^-$, NH$_4^+$, PO$_4^{3-}$ | Iwata et al. (2003) |
| Rivers, Queensland, Australia | ↑ PON, NO$_3^-$ | Furnas (2003) |
| Rondônia, Amazon Basin, Brazil | ↑ TDN, TDP, PP | Biggs et al. (2004) |
| | ↑ SS, POC, PON, DON, PO$_4^{3-}$, NH$_4^+$ | Neil et al. (2001) |
| | ↓ TDN, NH$_4^+$, NO$_3^-$, TDP, DIN:DIP, DO | Thomas et al. (2004) |
| | ↓ NO$_3^-$, DIN:DIP, DO | Neill et al. (2006) |
| | ↑ SS, NH$_4^+$, PO$_4^{3-}$, Chl a | Deegan et al. (2011) |
| | ↓ NO$_3^-$, DIN:DIP, DO | Neill et al. (2006) |
| Paragominas streams, Pará, Brazil | ↑ pH, DO | Figueiredo et al. (2010) |
| | ↓ NO$_3^-$ | Figueiredo et al. (2010) |
| Novo Progresso (Amazon) and Campo Verde (Cerrado), Brazil | ↑ TOC, DOC, TN, NO$_3^-$ | Nóbrega et al. (2018) |
| Sarapuí River Basin, São Paulo, Brazil | ↑ SS, turbidity, TP | de Mello et al. (2018a) |
| Sixoa River streams, Limón, Costa Rica | ↑ Chl a | Lorion and Kennedy (2009) |
| Veraguas rivers and estuaries, Panama | ↑ SS, Chl a | Valiela et al. (2013, 2014) |
| | → PO$_4^{3-}$, NH$_4^+$, DIN:DIP | Valiela et al. (2013, 2014) |
| Streams, Puerto Rico | ↑ Turbidity, TN, TP | Uriarte et al. (2011) |
generally enhances (1) the cycling of plant decomposition and nutrient regeneration through digestion and excretion by animals (Assmann et al. 2017; Arnuti et al. 2020) and (2) soil erosion from fragile stream banks (McCulloch et al. 2003; Brodie and Mitchell 2005). Dung nutrients are recycled by terrestrial plants or utilized as manure fertilizer for agriculture (Sileshi et al. 2017), but some of them can flow into adjacent streams with precipitation. In the Amazon catchment, the fluxes of total inorganic C (TIC) and TN increased by 5 and 3.7 times, respectively, in the streams surrounded by pasture lands with extensive cattle ranching compared to those in primary forests (Nóbrega et al. 2018). This increase in TIC was caused by the practice of liming (CaCO₃) in the pasture to raise the pH of the indigenous acidic soils. A meta-analysis of the chemical composition of animal manure from sub-Saharan countries showed that 77% of manure had N:P ratios less than 5, which is lower than the N:P requirement of major crops (Sileshi et al. 2017). When plants take up available nutrients, the N:P ratio of the residue would decrease further. The accumulation of P relative to N was also found in subtropical pastures with livestock grazing in Florida, USA (Ho et al. 2018). The discharge of these P-rich residues into streams may shift the limitation factor from P to N for primary production in downstream aquatic ecosystems (Jennerjahn et al. 2008; see “Agriculture”).

If deforested lands or pasture lands are abandoned, they will gradually regenerate trees by natural seeding or artificial plantations as secondary forests. Generally, it takes a longer time for tropical lands to recover their floral and faunal diversity than temperate lands because of the higher diversity in the original tropical forest (Meli et al. 2017). In the Rayu River catchment of Borneo, Malaysia, slash-and-burn agricultural practices were performed until 1989, but then the area was protected as a national park, and a secondary forest was redeveloped. In 1998, the dissolved inorganic nutrients, electrical conductivity (EC), and pH in the stream water of the secondary forest were no longer different from those of the original primary forest (Iwata et al. 2003). However, the stream substrates were finer and the banks were more eroded in the secondary forest, most likely because of the loss of the riparian primary forest during the initial deforestation. Because of this physical alteration of habitats, the diversity and abundance of aquatic organisms (e.g., periphyton, aquatic insects, shrimp, and fish) were still lower in the streams surrounded by the secondary forest than in those surrounded by the primary forest (Inoue et al. 2003; Iwata et al. 2003). These observations suggest that even if secondary forest develops, the recovery of aquatic habitats and ecosystems would take a longer time than that of chemical water properties (Feio et al. 2015).

To summarize this section, the conversion of primary forest to pasture lands enables more sunlight to reach the ground and adjacent lotic ecosystems, increasing the temperature and primary production in the water. Because terrestrial N fixation declines with deforestation, the NO₃⁻ concentration and the N:P ratio of dissolved inorganic nutrients in the downstream riverine and estuarine waters would decrease (Table 2), and this reduction would be more drastic in tropical regions than in other climate regions. Ranching further decreases the N:P ratio in the water due to the input of animal excretion. Both aquatic primary production and the input of animal excretion increase DOM and POM in downstream rivers and estuaries, causing high turbidity and low DO in the water (Table 2).

Agriculture
Primary forests are frequently converted to lands for agriculture in tropical regions. The net agricultural production in Southeast Asia has increased by approximately 3% per year over the past several decades (OECD/FAO 2017). In Southeast Asia, rice cultivation was the main agricultural activity until the 1980s, but the percentage of rice production to the total agricultural production has been decreasing for the past 40 years; instead, palm oil and poultry production are increasing because of the higher income they generate (OECD/FAO 2017). In Latin America and the Caribbean, soybeans are the major agricultural products, and their production has increased fourfold during the past 40 years (OECD/FAO 2019). As seen in logging and pasture lands, agricultural lands also cause increased runoff of surface water and soil. In the Nandi district, Kenya, the water runoff increased twofold after the primary forest was converted to croplands (Recha et al. 2012).

In agricultural fields, synthetic fertilizers, which are commonly composed of soluble inorganic nutrients (e.g., ammonium chloride, diammonium phosphate, potassium chloride) or organic nutrients that decompose rapidly, such as urea, are frequently used, although natural organic fertilizer (e.g., animal manure and vegetable compost) has recently received attention (Ding et al. 2019). Synthetic fertilizers are created to quickly dissolve and be efficiently absorbed by crop plants, but in general, only 10–50% of applied N and P fertilizers are recovered as crop harvests (Prasertsak et al. 2002; Chen et al. 2008; Ding et al. 2019). The remaining N percolates through soil into groundwater, discharges with surface water runoff, or it is released into the atmosphere through volatilization (e.g., NH₃) or denitrification (e.g., N₂ and N₂O) (Downing et al. 1999; Rivett et al. 2008; Maranguit et al. 2017). Conversely, P tends to remain in the surface soil or be discharged with sediment as surface runoff because of its ability to bind to...
certain soil minerals (Faithful and Finlayson 2005; Zhang and Huang 2011; Nguyen et al. 2019a).

In the Brazilian Amazon and Cerrado, the major crops are soybean, maize, corn, and cotton, and the effects of fertilizers on the adjacent stream water quality have been frequently reported (Figueiredo et al. 2010; Silva et al. 2011; Riskin et al. 2017; Neill et al., 2017; Figueiredo et al., 2020; de Mello et al. 2020). After the land use shifted from pasture to agriculture, the concentration of most of the measured nutrients, minerals, and EC increased, while DO decreased in the stream surrounded by agricultural fields with the use of fertilizers (Figueiredo et al. 2010; Silva et al. 2011; de Mello et al. 2018b; Table 4). Even though the concentration appeared to be unaffected, the impact of fertilizer may become obvious when annual export is measured. In the Brazilian state of Mat Grosso, the nutrient concentration in stream waters was not affected by soybean cropping compared to primary forest, but the annual export of nutrients was higher from soybean fields than the forest watershed because of the increased water discharge from the soybean fields (Riskin et al. 2017).

Oil palm plantations are one of the most extensive agricultural crops in the tropics and consume the largest amount of commercial fertilizers in Southeast Asia (Maranguit et al. 2017), but the effects on adjacent streams or rivers have not been well studied (Ah Tung et al. 2009; Comte et al. 2012, 2015; Gandaseca et al. 2015; Table 4). Because of fertilizer use, the rivers surrounded by new oil palm plantations in Sarawak, Malaysia, had higher NH$_4^+$ and biological and chemical oxygen demands (BOD and COD, respectively) than the controlled forest sites (Gandaseca et al. 2015). The surface runoff from the mature oil palm farms of Papua New Guinea also had higher NH$_4^+$ concentrations than the controlled sites, and the nutrient and water balance implied that a considerable amount of N was lost as deep drainage by leaching (Banabas et al. 2008). The groundwater collected from the well in the oil palm plantation of Sabah, Malaysia, had high NH$_4^+$ and K$^+$ concentrations, which were likely derived from fertilizer (Ah Tung et al. 2009). The NO$_3^-$ concentration was not significantly affected by fertilizer at these oil palm sites in Southeast Asia, demonstrating that nitrification is not a major process in N transformation in these agricultural lands. Because of the high precipitation in Southeast Asia, fertilizer-derived NH$_4^+$ could be discharged into streams and rivers before being oxidized into NO$_3^-$. At an oil palm plantation in Sumatra, Indonesia, the use of organic fertilizer caused a high BOD and COD level in the adjacent stream water, which also suggests a short residence time of fertilizer-derived organic matter in the surface soil (Comte et al. 2015).

Conversely, NO$_3^-$ may become the major fertilizer-derived nutrient in regions where precipitation percolates and travels underground as groundwater with a relatively long residence time. In northern Queensland, Australia, sugarcane and banana cultivation have been the major industries over the last century, and the details have been reviewed in several articles (Furnas 2003; Brodie and Mitchell 2005; Davis et al. 2016). In brief, the use of fertilizer in this region increased the NO$_3^-$ concentration in the groundwater through nitrification (Thorburn et al. 2003), and fertilizer-derived NO$_3^-$ flowed into adjacent streams and rivers as baseflow (Mitchell et al. 2001, 2009). The N:P ratio of dissolved inorganic nutrients in the Tully River was much higher than the Redfield ratio (N:P = 16) throughout the year (Faithful and Finlayson 2005), indicating that P limited aquatic primary production in the river. High N:P ratios of dissolved inorganic nutrients in groundwaters or river waters affected by agricultural fertilizers have also been reported in many other tropical and subtropical regions, e.g., Hawaii (USA), Java (Indonesia), Okinawa (Japan), and São Paulo (Brazil), where the major N form is NO$_3^-$(Blanco et al. 2010; Bishop et al. 2017; Taniwaki et al. 2017; Oehler et al. 2018).

The impact of fertilizer would also be different depending on the type of fertilizer: in the Kallada River, India, where a large part of the catchment is dominated by agricultural plantations (e.g., rice, coconut, tea, and rubber), low N:P ratios of dissolved inorganic nutrients were measured in the downstream river region (Jennerjahn et al. 2008). The ratio of NO$_3^-$ to PO$_4^{3-}$ ranged from 2.9 to 8.0; the lowest value was measured during the wet season. This low N:P ratio seems to have been caused by the use of organic fertilizers such as urea and manure in this region (Jennerjahn et al. 2008). Similar effects are expected to occur by ranching, as mentioned in the above section.

To summarize this section, the effect of agricultural fertilizer on the adjacent stream and river waters is not straightforward but is affected by various factors (e.g., chemical composition and amount of fertilizer, soil properties, precipitation). Simply speaking, if fertilizer-derived nutrients are quickly flushed downstream with rainfall, the N:P ratio in the discharged water would be affected by the residue of the fertilizer. In contrast, if fertilizer-derived nutrients remain in the soil or percolate into groundwater with a long residence time, the groundwater would have high N:P ratios of dissolved inorganic nutrients because P tends to be chemically trapped in soils. Considering the climate of tropical regions, the former case could occur more commonly or frequently than in other climate regions. Regardless of which case occurs, downstream primary production would increase due to fertilizer-derived nutrients.
Wildfire and intentional burning

Humid tropical forests are generally resistant to burning, but the transition from primary to secondary forests, shrubs, pastures, and agricultural plantations increases the frequency of fires (da Silva et al. 2018; Adrianto et al. 2020). Not only natural wildfires but also intentional burning to remove weeds for agriculture may trigger extensive fires. In Southeast Asia, 50% of forests were affected by fire from 2003 to 2017 (Reddy et al. 2019). The area of forest fires increased 36-fold in the Amazon region from 1984 to 2016 (da Silva et al. 2018).

Forest fires provoke airborne release and deposition of suspended matter and gaseous chemicals, causing extensive haze in tropical regions (Tacconi 2016). The effects of forest wildfire or intentional burning on the adjacent stream and river water quality have been studied well in temperate regions, such as North America, but they have not been frequently studied in tropical regions (Earl and Blinn 2003; Smith et al. 2011; Rust et al. 2018). Basically, terrestrial organic matter is combusted into ash, black carbon, or volatized chemicals, which are released into the atmosphere or transported into the adjacent aquatic ecosystem. The composition and amount of ash or black carbon (including both organic and inorganic matter) change with the temperature and duration of burning: a higher combustion completeness decreases the organic matter content and increases the relative content of minerals (Audry

| Study sites | Effects on downstream water properties | Sources |
|-------------|----------------------------------------|---------|
| Jambi estuary rivers, Sumatra, Indonesia | ↑: SS, TOC | Sanderson and Taylor (2003) |
| Streams at the Petapahan area, Sumatra, Indonesia | →: DIN, TP | Comte et al. (2015) |
| Rivers at Sibu and Tatau, Sarawak, Malaysia | ↑: COD, NH₄⁺, ↓: pH, DO | Gandaseca et al. (2015) |
| Rajang River, Sarawak, Malaysia | ↑: SS, ↓: pCO₂ | Müller-Dum et al. (2019) |
| Sundar River, Sarawak, Malaysia | ↑: EC, turbidity, NH₄⁺, COD | Rosli et al. (2020) |
| Groundwater at Tawau, Sabah, Malaysia | ↑: NH₄⁺ →: NO₃⁻ | Ah Tung et al. (2009) |
| Buyhang watershed streams, Leyte, Philippines | ↑: Turbidity ↓: NO₃⁻, PO₄³⁻ | Dessie and Bredemeier (2013) |
| Surface runoff at Sangara and Dam, Papua New Guinea | ↑: NH₄⁺ →: NO₃⁻ | Banbasas et al. (2008) |
| Tully River, Queensland, Australia | ↑: SS, PON, NO₃⁻, PO₄³⁻, ↓: DON, PP, DOP | Mitchell et al. (2001), Furnas (2003) |
| Tully and Murray Rivers, Granite Creek, Queensland, Australia | ↑: SS, TN, TP | Faithful and Finlayson (2005) |
| Herbert River, Queensland, Australia | ↑: SS, TN, TP | Bramley and Roth (2002), Mitchell et al. (1997) |
| Cudgen Catchment, New South Wales, Australia | ↑: pH ↓: pCO₂ | Jeffrey et al. (2016) |
| Kallada River and Ashtamudi estuary, Kerala, India | ↑: SS, NO₃⁻, PO₄³⁻, ↓: DIN:DIP | Jennerjahn et al. (2008) |
| Nawuni Catchment, Ghana | ↑: Turbidity, NH₄⁺ | Tahiru et al. (2020) |
| Federal District streams, Brasilia, Brazil | ↑: EC, NO₃⁻, NO₂⁻, NH₄⁺ →: DON, PO₄³⁻, ↓: DO | Silva et al. (2011) |
| Tanguro Ranch, Mat Gross, Brazil | ↑: EC, SS, DOC, NH₄⁺, PO₄³⁻ | Riskin et al. (2017) |
| Paragominas streams, Pará, Brazil | ↑: EC, pH, turbidity, NO₃⁻ →: PO₄³⁻, ↓: DO | Figueiredo et al. (2010) |
| Sarapuí River Basin, São Paulo, Brazil | ↑: SS, turbidity, POM, TN, TP | De Mello et al. (2018a, b) |
| Streams, Puerto Rico | ↑: DO, TP | Uriarte et al. (2011) |
et al. 2014; Bodi et al. 2014). Because ash is easily discharged from burnt forests with surface water runoff after rainfall (Malmer and Grip 1994; Ice et al. 2004; Dittmar et al. 2012), episodic, heavy rainfall that frequently occurs in tropical regions could cause a more rapid loss of nutrients and organic matter from the land compared with temperate regions (Marques et al. 2017).

In the Mendolong catchments of northern Borneo, Malaysia, the effects of the conversion of humid primary forest to Acacia mangium plantations as well as agricultural use have been monitored since 1985 (Malmer 1992; Nykvist et al. 1996). After clear felling, the practice of intentional burning increased the concentration of ash and major nutrients in the adjacent streams, and high concentrations were detected in the baseflow even after 3 years (Malmer and Grip 1994; Malmer 1996; Table 5). The C:N ratio of organic matter in the stream water increased with burning (Malmer and Grip 1994), which suggests that more terrestrial organic matter was carried downstream as ash or black carbon than before burning (Bodi et al. 2014; Marques et al. 2017). Moreover, less vegetation due to burning would decrease the absorption of nutrients and organic matter from the land compared with temperate regions (Marques et al. 2017).

In the tropical savanna of northern Australia (Kakadu National Park), fires in the late dry season caused high concentrations of total suspended solids (TSS), volatile suspended solids (VSS), N, and P in the adjacent stream after episodic storms and runoff, but fires in the early dry season did not have similar impacts (Townsend and Douglas 2000, 2004; Table 5). Because leaf litter and vegetation accumulate during the preceding wet season, ash and soil are retained by the litter, and nutrients are absorbed by the remaining vegetation in the early dry season (Townsend and Douglas 2004). Conversely, in the late dry season, a lower canopy cover and less vegetation and litter caused higher overland flows of ash and water, which increased the concentration of the aforementioned water quality variables in the stream (Townsend and Douglas 2000). These observations showed that the impacts of wildfire on the adjacent water properties are affected by the season of the fire and that forest management in the late dry season is especially important to prevent destructive wildfires and subsequent drastic changes in the downstream riverine and estuarine water properties.

The combustion of terrestrial biomass transports nutrients to adjacent rivers and the coastal sea through the atmosphere (i.e., dry and wet depositions). During extensive forest fires in Southeast Asia in 2006, N and P concentrations in both dry (aerosol) and wet (rainwater) depositions increased in Singapore (Sundarambal et al. 2010a). These depositions would considerably increase nutrient concentrations in coastal seawater and might increase the productivity of phytoplankton (Sundarambal et al. 2010b). Because the volatilization temperature of N is much lower than that of P (Bodi et al. 2014), more N would be lost during combustion, and the N:P ratio in atmospheric deposition is expected to decrease after fire events.

To summarize this section, the frequency and area of wildfires or intentional burning are increasing in tropical regions because of the conversion of primary forests to pasture and agricultural lands. Combustion changes the chemical compositions of terrestrial material and increases its mobility into adjacent streams and rivers. Because of the discharge of plant-derived materials and the

Table 5 A summary of the effects of wildfire or burning on the downstream riverine and estuarine water properties. The arrows before the water properties indicate that the subsequent water properties increased (↑), decreased (↓), or did not change (→). See the list of abbreviations for the water properties.

| Study sites                                 | Effects on downstream water properties | Sources                                      |
|---------------------------------------------|----------------------------------------|----------------------------------------------|
| Mendolong catchment, Sabah, Malaysia        | ↑: TN, NO₃⁻, NH₄⁺, TP, PO₄³⁻, DOC      | Grip et al. (1994), Malmer and Grip (1994), Malmer (1996) |
|                                             | ↑: TN, NO₃⁻, NH₄⁺ → PO₄³⁻              | Malmer (2004)                                |
| Rain waters and aerosol deposition during smoke haze events, Singapore | ↑: TN, NO₃⁻ + NO₂⁻, NH₄⁺, TP, PO₄³⁻ | Sundarambal et al. (2010a, b)                |
| Kakadu National Park catchments, Northern Territory, Australia | ↑: SS, TN, TP                          | Townsend and Douglas (2000)                  |
|                                             | ↑: TN                                   | Townsend and Douglas (2004)                  |
|                                             | →: SS, TP                               |                                              |
leaching of N, the downstream river waters would have a higher C:N ratio of organic matter and a higher N:P ratio of dissolved inorganic nutrients than those before burning (Table 2). Tropical lands might lose organic matter and nutrients more quickly than other climate regions because of frequent heavy rainfall events in the tropics.

**Aquaculture**

Due to the global consumption of seafood, aquacultural production is currently almost equivalent to capture fisheries. Production from inland (land-based) aquaculture, where earthen ponds are created or culture tanks are placed on land, is almost twice as high as that from marine aquaculture and increased by 30% from 2011 to 2016 worldwide (FAO 2018). Asia alone accounted for 93% of global inland aquacultural production in 2016 (FAO 2018). Because aquaculture ponds are usually located beside coasts and estuaries to obtain and release water efficiently, mangroves and coastal forests are the major vegetation types that have been lost due to land-based aquaculture. On the coast of Hainan, China, 76% of the mangrove loss was attributed to the creation of new aquaculture ponds (Herbeck et al., 2020). The difference in water properties between the influent and effluent through an aquaculture pond is considered a potential impact of this practice on the downstream environment.

Land-based aquaculture usually involves the feeding of organic pellets to raise target species as fast as possible (Rout and Bandyopadhyay 1999; Correia et al. 2014). However, a large part of the feed is not recovered as harvests but is wasted with the water discharged from the pond or accumulates in the sediment of the pond (Jackson et al. 2003; Islam et al. 2004; Anh et al. 2010). Therefore, most studies have shown that the effluent from aquaculture ponds tends to be eutrophic compared to the influent that enters the pond (Table 6). This eutrophication is largely composed of DOM and POM rather than dissolved inorganic nutrients such as NH$_4^+$ (Jackson et al. 2003; Costanzo et al. 2004; Islam et al. 2004; Molnar et al. 2013). For example, the total dissolved and particulate organic nitrogen (DON and PON, respectively) accounted for approximately 60–80% of the total N in the effluents from shrimp ponds in Queensland, Australia (Jackson et al. 2003; Costanzo et al. 2004); a value of 98% was reported for shrimp ponds along the west coast of New Caledonia (Thomas et al. 2010), and a value of 70% was reported for shrimp ponds in Hainan, China (Herbeck et al. 2013). These high percentages of organic N relative to inorganic N are most likely caused by extra feed pellets, feces excreted from cultured organisms, and/or the microbes that proliferate in the pond (Jackson et al. 2003; Thomas et al. 2010; Herbeck et al. 2013).

Laboratory experiments showed the release of N with different chemical forms specific to the source: while

| Study sites | Effects on downstream water properties | Sources |
|-------------|---------------------------------------|---------|
| Shrimp and fish ponds, Wenchang and Wenjiao Estuary, Hainan, China | ↑: DOC, DON, DOC:DON, DIN, NH$_4^+$, PO$_4^{3-}$, Chl $a$ →: NO$_3^-$, NO$_2^-$ ↓: SS, POC, PN, POC:PN, DIN:PO$_4^{3-}$ | Herbeck et al. (2013), Herbeck et al. (2011) |
| Shrimp ponds, Can Gio, Vietnam | ↑: pH, POC, TN, DIN ↓: SS, POC:PN | Vivier et al. (2019) |
| Shrimp ponds, the Bay of Bengal, Bangladesh | ↑: TN, NO$_3^-$, NO$_2^-$, NH$_4^+$, Chl $a$ →: DO, pH ↓: SS, TP, PO$_4^{3-}$ | Islam et al. (2004) |
| Shrimp ponds, Cardwell, Queensland, Australia | ↑: TN, PON, DON, NH$_4^+$, Chl $a$ ↓: SS, NO$_3^-$, NH$_4^+$, TP, DIN:DIP, Chl $a$ →: PO$_4^{3-}$ | Jackson et al. (2003) |
| Shrimp ponds, Saint Vincent Bay, New Caledonia | ↑: TN, PON, DON, TDN, NH$_4^+$, TP, PP, TDP, PO$_4^{3-}$ | Costanzo et al. (2004) |
| Shrimp ponds, Teremba Bay, Chambeyron Bay, New Caledonia | ↑: SS, turbidity, POC, TN, PON, TP, Chl $a$ →: DIN, DIP | Thomas et al. (2010) |
| Fish and shrimp ponds, Hawaii, USA | ↑: SS, turbidity, TN, NH$_4^+$, TP, Chl $a$ ↓: NO$_3^-$, NO$_2^-$ ↑↓: PO$_4^{3-}$ | Ziemann et al. (1992) |
cultured shrimp released a mixture of NH$_4^+$ and DON (including urea), formulated feed pellets released more DON compounds than shrimp (Burford and Williams 2001). Because these pellet-derived DON compounds would be chemically more complex than urea (e.g., proteins and peptidoglycan remnants), the DON leached from feed pellets was less degradable for microbial communities in the water than shrimp-derived DON (mainly urea). These results suggest that when aquacultural wastewaters are discharged to adjacent rivers or estuaries, the impact of pellet-derived DON may be different from that of organism-derived DON and may reach farther downstream from the source (Thuy et al. 2011; Vivier et al. 2019).

Among inorganic N species in aquaculture ponds, NH$_4^+$ usually constitutes the largest proportion, and NO$_3^-$ and NO$_2^-$ are much lower (Jackson et al. 2003; Costanzo et al. 2004; Thomas et al. 2010; Herbeck et al. 2013). NH$_4^+$ is directly excreted from cultured organisms and is also produced through the degradation of labile DON, such as urea, contained in their feces (Ziemann et al. 1992; Burford and Williams 2001). Relatively low proportions of NO$_3^-$ and NO$_2^-$ in aquaculture ponds indicate that (1) NH$_4^+$ is quickly absorbed by phytoplankton or discharged from the pond before nitrification proceeds (Jackson et al. 2003), (2) nitrification is not a major process of N transformation in aquaculture ponds because the process mainly occurs only at the aerobic sediment surface (Hargreaves 1998), and/or (3) even if NO$_3^-$ is produced through nitrification, NO$_3^-$ is again reduced through dissimilatory nitrate reduction into NH$_4^+$ (DNRA) in anoxic pond sediment (Molnar et al. 2013). DNRA is generally enhanced by high temperature, high organic matter, and sulfate availability, all of which are likely to occur in the sediment of tropical aquaculture ponds in brackish and coastal areas (Christensen et al. 2003; Nizzoli et al. 2006; Dong et al. 2011). In fact, the proportion of DNRA to total NO$_3^-$ reduction (DNRA + denitrification) increased in the sediment receiving effluents from shrimp ponds in New Caledonia, which resulted in a higher retention of N within the sediment due to the coupling of nitrification and NO$_3^-$ reduction (Molnar et al. 2013).

It should be noted that the concentration of NH$_4^+$ often increased, but PO$_4^{3-}$ was relatively constant or even decreased in some aquaculture ponds, leading to elevated N:P ratios of dissolved inorganic nutrients in the pond water (Ziemann et al. 1992; Costanzo et al. 2004; Islam et al. 2004; Table 6). For example, the N:P ratio of dissolved inorganic nutrients increased from 14 (influent) to 214 (effluent) in shrimp ponds in Queensland, Australia (Costanzo et al. 2004). Increased N:P ratios would be caused by the retention of P in the pond sediment and microbes (Reddy et al. 1999). While N is relatively mobile and transformed by bacteria through nitrification or reduction (e.g., DNRA and denitrification), P needs to be stored in bacterial cells (e.g., nucleic acids and phospholipids) to maintain their basic cellular structures. In addition, inorganic P tends to be chemically bound with minerals such as Ca$^{2+}$, and the formed particulate solids are deposited on the sediment under low water turbulence. These processes would lead to the accumulation of P in aquaculture pond sediments, gradually increasing the N:P ratio of dissolved inorganic nutrients in the water column. In the sediment receiving aquacultural effluents in New Caledonia, the N:P ratio of dissolved inorganic nutrient fluxes from sediment to the overlying water was 42, which was much higher than the N:P ratio of organic matter fluxes (8.2), indicating that PO$_4^{3-}$ was retained in the sediment (Molnar et al. 2013). In downstream aquatic ecosystems receiving aquacultural effluents with high N:P ratios, the growth of phytoplankton might be limited by the availability of P (Costanzo et al. 2004).

However, even if P tends to be trapped in the pond compared to N, this does not mean that aquacultural practices do not cause P enrichment in the downstream environment; providing feed pellets basically has the potential to increase the enrichment of both N and P (Ziemann et al. 1992; Herbeck et al. 2013; Molnar et al. 2013; Table 6). In fact, the water quality in aquaculture ponds is affected by many factors: the chemical composition and feeding amount of feed pellets (Rout and Banerjopadhyay 1999; Correia et al. 2014), the density and species of cultured organisms (Ziemann et al. 1992; Thomas et al. 2010), and the aeration and water residence time (exchange rate) in the pond (Hopkins et al. 1993; Martínez-Córdova et al., 1997). Modifications of aquacultural systems using microbial activities or engineering techniques to minimize environmental impacts have been reviewed in previous articles (Hargreaves 2006; Mook et al. 2012; van Rijn 2013; Martínez-Córdova et al. 2015; Li et al. 2020).

To summarize this section, a considerable portion of feed pellets may be discharged from aquaculture ponds as organic matter. While organism-derived urea is quickly decomposed, pellet-derived organic matter might be less degradable, and the impact of the effluent might reach far downstream from the aquaculture site. The discharge of NH$_4^+$ derived from cultured organisms supplies another major impact on the downstream ecosystem because the nutrients contained in the freshwater provided from tropical primary forests are mainly NO$_3^-$. Because inland aquacultural practices are rapidly expanding in tropical regions, especially in Southeast Asia, these changes in aquatic processes will further increase in the future.
Urbanization
With the increasing human population, tropical regions have urbanized faster than other climate regions (Montgomery 2008). Deforested tropical lands may be used for building private houses, commercial facilities, and industrial plants, where wastewaters are sometimes directly discharged into the adjacent environment without proper treatment. The chemical compositions of these wastewaters differ depending on the source, but various types of wastewaters from different sources are commonly mixed in urbanized rivers and estuaries (Davis and Koop 2006; Cunha et al. 2011; Fontana et al. 2014; Peyman et al. 2017). Even if wastewater is treated at a treatment plant, it is technically difficult to remove all dissolved inorganic nutrients from the water, which could cause eutrophication of the downstream aquatic ecosystem (Burford et al. 2012b). Other sources reviewed in the above sections, such as agricultural lands, may still affect urbanized areas through surface water runoff and/or groundwater seepage if the source is located upstream.

The effects of urbanization on riverine and estuarine water quality have been studied at many sites in tropical regions (Table 7). Because these previous studies have already reported water quality variables such as nutrient concentration, this section mainly focuses on the characteristics of biogeochemical or microbial processes in tropical regions that could differ from those in cooler regions. Typically, the organic matter contained in eutrophic riverine or estuarine water is first decomposed by aerobic bacteria if DO is available, where nutrients are converted to N2. Because a high NH4+ availability and DO depletion are basic requirements for anammox, eutrophic rivers and estuaries (especially sediment) are expected to be a hotspot of this bacterial activity (Liu et al. 2020). Moreover, anammox bacteria prefer a warm temperature, which makes tropical aquatic environments further suitable for anammox to actively proceed (Tomaszewski et al. 2017). Although anammox was previously considered minor compared to denitrification, the recently revised isotope technique revealed that 64–86% of the total N loss in the seagrass sediment at Shaws Bay, Australia, was caused by anammox (Salk et al. 2017). A higher contribution of anammox than denitrification to the total N loss was also reported in the sediment from oyster farming in the Wallis Lake estuary, Australia (Erler et al. 2017), although the balance between anammox and denitrification is not consistent among studies (Dong et al. 2011; Jiao et al. 2018; Tan et al. 2019). The proportion of anammox and denitrification is affected by various environmental factors, such as DO and salinity (Jiang et al. 2017; Liu et al. 2020). Although relatively small contributions of microbial N removal through anammox and denitrification have been reported in cooler regions (Mulholland et al. 2009; Hellemann et al. 2017; Liu et al. 2020), the removal of N may be more significant in tropical environments because of the warmer temperature...
Table 7  A summary of the effects of urbanization on the downstream riverine and estuarine water properties. When most minerals (e.g., Na⁺, Mg²⁺, Cl⁻, K⁺, Ca²⁺) increased, they were collectively described as EC increased. The arrows before the water properties indicate that the subsequent water properties increased (↑), decreased (↓), or did not change (→). See the list of abbreviations for the water properties.

| Study sites                                      | Effects on downstream water properties | Sources |
|-------------------------------------------------|----------------------------------------|---------|
| Malacca river, Malacca, Malaysia                 | ↑: EC, pH, SS, turbidity, BOD, COD    | Hua (2017) |
| Penchala River, Selangor, Malaysia               | ↑: EC, NH₄⁺, BOD, COD → pH            | Mahazar et al. (2013) |
| Kuantan, Belat and Galing River, Malaysia        | ↑: EC, pH, DIN, NH₄⁺, TP, COD ↓ DO   | Kozaki et al. (2016) |
| Day River, Red River Delta, Vietnam              | ↑: TN, NH₄⁺, TP, PO₄³⁻, Chl a ↓ TN, TP, DO | Hoang et al. (2018) |
| Day River, Red River Delta, Vietnam              | ↑: DOC, NH₄⁺, PO₄³⁻, pCO₂, Chl a      | Duc et al. (2009) |
| Saigon-Dongnai Rivers, Vietnam                   | ↑: POC, TN, NH₄⁺, TP, PO₄³⁻, Chl a    | Nguyen et al. (2019b) |
| Can Gio estuary, Vietnam                         | ↑: pCO₂ ↓ DO                          | David et al. (2018) |
| Can Tho, Mekong Delta, Vietnam                   | ↑: Turbidity, TN, NH₄⁺, PO₄³⁻, COD → NO₃⁻, NO₂⁻ ↓ DO | Wilbers et al. (2014) |
| Brantas River Basin, Java, Indonesia             | ↑: DON, NO₃⁻, PO₄³⁻                    | Jennerjahn et al. (2004) |
| Ciliwung watershed, Jakarta, Indonesia           | ↑: TP, BOD, COD ↓ DO                  | Permatasari et al. (2017) |
| Kholpetua-Ar郎agashia rivers, Sundarbans, Bangladesh | ↑: NH₄⁺, PO₄³⁻, NO₃⁻ → NO₂⁻ ↓ DO   | Rahaman et al. (2013) |
| Manimala River, Kerala, India                    | ↑: EC, NO₃⁻, NO₂⁻, TP, PO₄³⁻ ↓ DO    | Padmalal et al. (2012) |
| Piracicaiba River, São Paulo, Brazil             | ↑: NH₄⁺, pCO₂, SS, NO₃⁻ ↓ DO          | Ballester et al. (1999) |
| Streams, São Paulo, Brazil                       | ↑: PO₄³⁻ ↓ DO, NO₃⁻                    | Martinelli et al. (1999) |
| Streams, São Paulo, Brazil                       | ↑: TN, NH₄⁺, TP BOD                   | Cunha et al. (2011) |
| Monjolinho basin, São Carlos, Brazil             | ↑: EC, turbidity, TN, NO₃⁻, TP, PO₄³⁻, BOD ↓ DO | Bere and Tundisi (2011) |
| Guanabara Bay, Rio de Janeiro, Brazil            | ↑: DO, NH₄⁺, PO₄³⁻, Chl a ↓ pCO₂      | Cotovicz Jr et al. (2015) |
| Streams, Rio de Janeiro, Brazil                  | ↑: TN, NH₄⁺, TP ↓ TN, TP               | Tromboni and Dodds (2017) |
| Una River, São José da Vitória, Brazil           | ↑: EC, SS, turbidity, PON, DON, NO₃⁻, NH₄⁺, PP, DOP, PO₄³⁻ → pH ↓ DO | Santos and De Paula (2019) |
| Urban streams, Federal District, Brazil          | ↑: Turbidity, DOC, NO₃⁻, NO₂⁻, NH₄⁺ ↓ DO | Silva et al. (2011) |
| Cachoeira River estuary, Bahia, Brazil           | ↑: NH₄⁺, PO₄³⁻, Chl a ↓ DO, DIN, DIP | Silva et al. (2013) |
| Madeira River, Rondônia, Brazil                  | ↑: TDN, TDP                           | Biggs et al. (2004) |
| Streams, Puerto Rico                             | ↑: Turbidity, TN, TP ↓ DO             | Uriarte et al. (2011) |
| Streams, Mayagüez, Puerto Rico                   | ↑: EC ↓ DO                            | Wengrove and Ballester (2012) |
| Rio Pedras Watershed, Puerto Rico                | ↑: EC, DOC, DON, NH₄⁺, PO₄³⁻ ↓ DO, NO₃⁻ | De Jesús-Crespo and Ramírez (2011), Potter et al. (2013), Ramírez et al. (2014) |
et al. 2019b), these impacts of urbanization might gradually lower the availability of P (McDowell et al. 2019; Molnar et al. 2013; Erler et al. 2017; Salk et al. 2017; Domangue and Mortazavi 2018).

While N follows a pathway of release into the atmosphere through anammox or denitrification, P tends to remain in the aquatic system or to flow downstream by attaching to sediment particles, and this property of P sorption becomes stronger at higher temperatures (Zhang and Huang 2011; Nguyen et al. 2019a). This difference between N and P gradually lowers the N:P ratio in water or sediments in tropical estuaries (Cotovicz Jr et al. 2013). Therefore, the discharge of wastewater from urban areas would accelerate the decrease in the N:P ratio because (1) sewage itself generally has a low N:P ratio compared to freshwater from pristine forests, and (2) after organic matter is decomposed, eutrophic, oxygen-depleted conditions potentially promote microbial N removal through anammox and denitrification (Sarma et al. 2009; Dong et al. 2011; Hoang et al. 2018; Tan et al. 2019). At the sites upstream of the Day River, Vietnam, much lower TN:TP ratios (a minimum of 2.9) than the Redfield ratio (N:P = 16) were measured and were attributed to sewage discharge, agricultural and industrial water runoff, and denitrification (Hoang et al. 2018). In addition, a low TN:TP ratio (10) was detected in the streams of the State of Rio de Janeiro, Brazil, which was considered to be due to the discharge of phosphate-based detergents from the ambient urbanized area (Tromboni and Dodds 2017). Although many pristine tropical rivers have high N:P ratios of dissolved inorganic nutrients, where primary production is limited by the availability of P (McDowell et al. 2019; Nguyen et al. 2019b), these impacts of urbanization might gradually shift the metabolic conditions to N limitation. The potential to decrease N:P ratios with these microbial and chemical processes would be basically higher in tropical environments than in other climate regions due to the warmer temperature.

To summarize this section, urbanized rivers and estuaries that receive a variety of wastewaters typically have high concentrations of nutrients and minerals and low concentrations of DO (Table 2). The TN:TP ratio in the water would decrease with these eutrophication processes because excess P is often discharged as wastewater, and a portion of the N is lost from the aquatic ecosystem through anammox and denitrification under hypoxic or anoxic conditions. The decline in N:P ratios would be more severe in tropical regions than in other climate regions because N removal and P sorption processes are facilitated under warm temperature conditions.

Conclusions and future research

The present review shows that the impact of tropical land-use change on downstream rivers and estuaries is specific to the land use and human practices carried out on land, but overall, it appears that the impact is often more serious, and the biogeochemical processes are more enhanced in tropical regions than in temperate or cold regions. This difference derives mainly from the characteristics of the tropics: (1) tropical primary forests have a higher biomass and nutrient stocks supported by active photosynthesis and N fixation; (2) tropical regions have a higher precipitation, more frequent episodic flooding, and warmer temperatures; and (3) certain practices such as land-based aquaculture are rapidly expanding in tropical regions.

The actual impacts that downstream rivers and estuaries receive from changing land use depend on the intensity of each land-use effect; therefore, it is not easy to quantitatively evaluate the combined effects (Davis et al. 2016; Hapsari et al. 2020). For example, nutrient discharge may not enhance downstream primary production if sufficient light is not available for phytoplankton due to high precipitation and subsequent discharge of terrestrial soils (Burford et al. 2012a). The combined effects of land-use change and climate-related precipitation change should also be considered in the actual environment (Hapsari et al. 2020). Because these land-use changes are usually extensive, and nonpoint sources such as groundwater seepage also contribute to downstream water properties, it is challenging to understand the proportions of each land-use impact and their combination. The test of stable isotopes (e.g., δ13C and δ15N) might be a useful tool to identify the source and contribution of wastewater (Taillardat et al. 2020).

Impacts such as eutrophication or imbalanced nutrient supplies due to these tropical land-use changes would not recover quickly even if the cause was removed. A recent meta-analysis showed that terrestrial biogeochemical functions recovered more slowly after agricultural practices than after logging, most likely due to fertilizer use (Meli et al. 2017). Another meta-analysis on coastal ecosystem restoration projects showed that even 10 years after the reduction or cessation of anthropogenic nutrient inputs, the recovery completeness was only 24% of the original baseline condition (McCrackin et al. 2017). Because most of the data used for this analysis were from temperate climate regions such as Europe and North America, there may be some differences at tropical sites. For example, the high annual precipitation and occasional intensive rainfall in tropical regions would help eutrophic ecosystems flush away accumulated nutrients downstream. Additionally, if denitrification or anammox proceeds faster at warmer temperatures, N might be removed from the eutrophic
site more quickly than in temperate cases. However, as it takes a longer time for tropical lands to recover their original biodiversity than temperate lands (Meli et al. 2017), the aquatic processes in the downstream river and estuary might also require a longer time for recovery in tropical regions. To evaluate recovery from eutrophication or disturbance of nutrient balance, long-term monitoring of more than 10 years is necessary, but such cases cannot be found in tropical regions at this time.

Another important aspect for future research is the change in elemental stoichiometry, such as the C:N:P ratio. Most previous studies have measured the concentration of target variables, but reports of the impact on element stoichiometry are relatively scarce. In temperate estuaries, primary production was expected to shift from N limitation to P limitation because of the increased inputs and retention of N (Howarth et al. 2011), although the limiting nutrients would be highly affected by regional factors. The present review has shown that the N: P ratio in tropical estuaries may decline with changes in land use due to different loading and removal processes between N and P. Additionally, the C:N ratio of the available organic matter predominantly affects microbial processes of N transformation (e.g., DNRA, anammox, denitrification) (Erler et al. 2017). Thus, more research with accurate measurements of elemental ratios is needed to evaluate the ecological impacts of tropical land-use change on downstream aquatic processes.

Abbreviations
BOD: Biological oxygen demand; Chl. α: Chlorophyll a; COD: Chemical oxygen demand; DIN: Dissolved inorganic nitrogen; DIP: Dissolved inorganic phosphorus; DOC: Dissolved organic carbon; DON: Dissolved organic nitrogen; DOP: Dissolved organic phosphorus; EC: Electrical conductivity; OC: Organic carbon; ON: Organic nitrogen; pCO₂: Partial pressure of CO₂; POC: Particulate organic carbon; POM: Particulate organic matter; PON: Particulate organic nitrogen; PP: Particulate phosphorus; SS: Suspended solids; TDN: Total dissolved nitrogen (= DON + DIN); TDP: Total dissolved phosphorus (= DOP + DIP); TN: Total nitrogen; TOC: Total organic carbon; TP: Total phosphorus

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YT had a concept for this article; YT, EM, and WR performed the literature search and collection; YT drafted and revised the manuscript; All authors read and approved the final manuscript.

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