Journal of Environmental Management 270 (2020) 110879

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Review

Multiscale land use impacts on water quality: Assessment, planning, and future perspectives in Brazil

Kaline de Mello[a,*], Ricardo Hideo Taniwaki[b], Felipe Rossetti de Paula[c], Roberta Averna Valente[d], Timothy O. Randhir[e], Diego Rodrigues Macedo[f], Cecília Gontijo Leal[c], Carolina Bozetti Rodrigues[g], Robert M. Hughes[h]

[a] Department of Ecology, Institute of Biosciences, University of São Paulo, R. do Matão, 321, São Paulo, SP, Brazil
[b] Engineering, Modelling and Applied Social Sciences Center, Federal University of ABC, Av. dos Estados, 5001, Santo Andre, SP, Brazil
[c] Department of Forest Sciences, "Luiz de Queiroz" College of Agriculture, University of São Paulo, R. Padua Dias, 11, Piracicaba, SP, Brazil
[d] Department of Environmental Science, Federal University of São Carlos, Sorocaba Campus, Rodovia João Leme dos Santos (SP-264), km 110, Sorocaba, SP, Brazil
[e] Department of Environmental Conservation, University of Massachusetts, 160 Holdsworth Way, Holdsworth Hall, Amherst, MA, USA
[f] Department of Geography, Institute of Geosciences, Federal University of Minas Gerais, Av. Antônio Carlos, 6627, Belo Horizonte, MG, CEP 31.270-901, Brazil
[g] Prática Socioambiental, Rua Capitão Alberto Aguiar Weissohn, 337, Guararema, SP, Brazil
[h] Amnis Opes Institute and Department of Fisheries & Wildlife, Oregon State University, 104 Nash Hall, Corvallis, OR, 7331-3803, USA

A R T I C L E I N F O

Keywords:
watershed management
ecosystem services
forest conservation
land use pattern
watershed modelling
water pollution

A B S T R A C T

Brazil contains the largest volume of freshwater of any nation in the world; however, this essential natural resource is threatened by rapid increases in water consumption and water quality degradation, mainly as a result of anthropogenic pressures. Declining water quality has become an increasingly more significant global concern as economic activities and human populations expand and climate change markedly alters hydrological cycles. Changes in land-use/land-cover (LULC) pattern have been recognized as a major driver of water quality degradation, however different LULC types and intensities affect water quality in different ways. In addition, the relationships between LULC and water quality may differ for different spatial and temporal scales. The increase in deforestation, agricultural expansion, and urban sprawl in Brazil highlights the need for water quality protection to ensure immediate human needs and to maintain the quality of water supplies in the long-term. Thus, this manuscript provides an overview of the relationships between LULC and water quality in Brazil, aiming at understanding the effects of different LULC types on water quality, how spatial and temporal scales contribute to these effects, and how such knowledge can improve watershed management and future projections. In general, agriculture and urban areas are the main LULCs responsible for water quality degradation in Brazil. However, although representing a small percentage of the territory, mining has a high impact on water quality. Water quality variables respond differently at different spatial scales, so spatial extent is an important aspect to be considered in studies and management. LULC impacts on water quality also vary seasonally and lag effects mean they take time to occur. Forest restoration can improve water quality and multicriteria evaluation has been applied to identify priority areas for forest restoration and conservation aiming at protecting water quality, but both need further exploration. Watershed modelling has been applied to simulate future impacts of LULC change on water quality, but data availability must be improved to increase the number, locations and duration of studies. Because of the international nature of watersheds and the consistent relationships between land use and water quality in Brazil, we believe our results will also aid water management in other countries.

* Corresponding author.
E-mail addresses: kaline.mello@usp.br (K. Mello), ricardo.t@ufabc.edu.br (R.H. Taniwaki), ferossetti@gmail.com (F.R. Paula), roavalen@ufscar.br (R.A. Valente), randhir@umass.edu (T.O. Randhir), diegorm@ufmg.br (D.R. Macedo), c.gontijoleal@gmail.com (C.G. Leal), cabreuva@gmail.com (C.B. Rodrigues), hughes.bob@amnisopes.com (R.M. Hughes).

https://doi.org/10.1016/j.jenvman.2020.110879
Received 24 October 2019; Received in revised form 23 March 2020; Accepted 28 May 2020

1. Introduction

Declining water quality has become a global concern as anthropogenic activities expand, and climate change threatens to cause serious alterations to the water cycle (Abbott et al., 2019). The global concern is to ensure sufficiency in water quantity for public health, food security, and water access demand. The estimated 2050 world population of 9.7 billion will increase world water demand by 20–30% (UNESCO, 2019) yet we already face challenges of meeting current demands for good quality water let alone guaranteeing this resource in the long-term.

Intensified and expanded anthropogenic land uses are one of the most important drivers of water quality degradation globally (Giri and Qiu, 2016; Su et al., 2016). However, diffuse water pollution is difficult to assess and control because it is not caused by an easily identifiable and treatable discharge site, but instead arises from multiple interactions between the hydrological cycle and land use and land cover (LULC) patterns. Therefore, relationships between LULC patterns and water quality vary depending on many factors such as spatial and temporal scales (i.e., spatial extent and temporal duration), watershed characteristics, landscape composition and configuration, land use intensity, and seasonal variations (Uriarte et al., 2011; Xiao et al., 2016). Understanding these relationships is essential for efficient watershed management and land use planning for protecting water quality.

Different land use types represent various degrees of risk to water resources, with urban and agricultural areas being the land use types most responsible for water quality degradation globally. Agricultural and urban effluents are also the greatest sources of diffuse pollution of Brazilian freshwater systems (Oliveira et al., 2017; Mello et al., 2018b; Ferreira et al., 2019). However, interactions with tropical climate, soils, vegetation and land management in Brazil lead to different LULC impacts on water quality.

Despite Brazil having the highest volume of freshwater resources of any nation in the world (ANA, 2019), this natural resource is becoming scarce because of increased consumption, extended droughts, precarious distribution, inadequate treatment infrastructure, and water quality degradation (Val et al., 2019), all driven by economic and population growth. In Brazil, some regions lack sufficient drinking water because water supplies are polluted by agricultural runoff, industrial effluents, and domestic sewage (Kelman, 2015; Oliveira et al., 2017; Ferreira et al., 2019). Thus, managing the immediate human requirements while maintaining long-term water supply capacity is an urgent need and a great challenge to the country.

Amazonia contains most of the country's surface water (ANA, 2019); however, the human population is concentrated in other regions of the country. A recent study showed that only 6.5% of the major rivers in the Atlantic Forest biome have good water quality (SOS Mata Atlântica, 2019). But more than 65% of the Brazilian population is concentrated in this biome, including the megacities of Rio de Janeiro and São Paulo (SOS Mata Atlântica, 2019). The Atlantic Forest biome exemplifies the precarious environmental conditions of many Brazilian aquatic ecosystems that are essential for human activities, public health, and ecosystem equilibrium. This situation will become even more critical as water consumption in Brazil is expected to increase by ca. 24% in the next 30 years (Val et al., 2019), and land use and climate change will continue to alter hydrological cycles and water quality (Lamparter et al., 2018; Taniwaki et al., 2017; Xie and Ringler, 2017).

Primary factors driving global LULC change include replacing tropical forests with agriculture, pasture, and urbanization (Song et al., 2018). In Brazil, particularly in the Atlantic Forest and Cerrado (neotropical savanna), the long history of past land use conversion (around 200 years ago) of the native vegetation to agriculture (coffee, pasture, sugar-cane, soy) resulted in sharp declines in forest cover (Victor et al., 2005; Ribeiro et al., 2009). This long-term/large-extent deforestation, coupled with extensive urbanization, is responsible for most water quality degradation observed in the streams of these biomes (Silva et al., 2007; Martinelli and Filoso, 2008; Mori et al., 2015; Taniwaki et al., 2017; Paula et al., 2018). This historical degradation amplifies concerns regarding recently expanded deforestation in Amazonia and the Cerrado because of the expansion of the agricultural frontier. Brazil reported the highest annual net loss of forest area in the world in 2018 (Global Forest Watch, 2020). Currently, 28.8% of Brazil is covered by farm land (agriculture and pasture) (MapBiomas, 2019), which is concentrated in the populous regions of the country (42% in the Cerrado and 62% in the Atlantic Forest biomes). Future projections of global land use change suggest that Brazil will be one of the world's most affected nations by cropland expansion over the next 30 years, especially in Amazonia and the Cerrado (Lamparter et al., 2018; Molotofs et al., 2018). In 2019, Brazil faced extensive fires and deforestation, with Amazonia reporting its highest forest loss in ten years (9,762 km^2) (INPE, 2020). This situation will likely worsen in 2020 because no changes were made to slow or stop deforestation, and January showed an increase of 108% in deforestation alerts compared to 2019 (INPE, 2020). The conversion of these forested areas in Brazil to other uses will severely degrade water quality, alter aquatic ecosystems and compromise human water supplies.

LULC change associated with increased water demand, population growth and climate change are likely to greatly affect water resources in Brazil. Thus, a science-based decision-making process is necessary to guarantee suitable watershed management focused on water security (Azevedo-Santos et al., 2017). Clearly, it is necessary to understand the spatial and temporal effects of LULC on water quality, as well as future projections of the potential impacts of land use change on water quality if Brazil is to sustain or improve the quality of life for its citizens.

Therefore, this paper presents a holistic review of the relationships between LULC and water quality in Brazil, aiming at understanding the effects of different LULC types on water quality, how spatial and temporal scales contribute to these effects, and how this knowledge can improve watershed management and future projections. For this, we collected relevant academic publications from SCOPUS and Web of Knowledge databases that were related to the relationship between LULC and water quality in Brazil. We prioritized articles published in English over the last 10 years but included important articles published in the last 20 years. Our intention was not to generate a quantitative review of the effects of LULC on water quality, but instead to focus on pertinent examples illustrating the major problems regarding water quality degradation in Brazil. The paper is organized in five sections. 1) Describe the main LULC types and their major effects on water quality. 2) Indicate how spatial and temporal scales affect LULC-water quality relationships. 3) Discuss how current knowledge has been applied to set priority areas for watershed management and water quality protection. 4) Summarize how watershed modelling has been applied to predict future impacts of LULC change on water quality. 5) List emerging threats, future perspectives, challenges and knowledge gaps regarding the impacts of LULC on water quality. We hope that our review will facilitate decision-making regarding watershed management and guide future studies about the relationships between LULC and water quality in Brazil and in similar countries that face comparable concerns regarding water quality degradation resulting from LULC changes.

2. LULC effects on water quality

Water quality is affected by several human activities that are linked to the different ways in which landscapes are transformed to benefit human society. However, these changes have been so intense in recent decades that hydrological cycles have shifted both locally and globally (Dey and Mishra, 2017). Altered hydrological cycles transform hydrologic dynamics in the landscape, directly affecting water quality (Wohl et al., 2012; Taniwaki et al., 2017). The conversion of native vegetation to human-dominated landscapes alters runoff, infiltration, and evapotranspiration in the catchment, which affect streamflow, flow dynamics, and nutrient, sediment and toxic loads to water bodies (Ogden et al., 2013; Palm et al., 2014; Hughes et al., 2019).

In Brazil, pasture (17%), agriculture (6.4%), a mix of pasture and agriculture (5.6%), silviculture (0.7%), urbanization (0.5%), and mining (<0.1%) represent the main anthropogenic land uses (MapBiomas, 2019). Native vegetation represents 66% (50% forest, 11.3% savannah and 4.7 grassland) and freshwater ecosystems cover 2.1% of the total area of the country (MapBiomas, 2019). These numbers vary according to the biome, with Amazonia having the highest remaining natural vegetation cover (84%) and Cerrado the lowest (19.5%) (Fig. 1). Since the 1980s, Brazilian biomes have lost >13% of their natural vegetation cover, with different rates per biome: the Cerrado and Pampa biomes lost almost 20% whereas other biomes have lost around 10% (Mapbiomas, 2019).

Each of those anthropogenic LULC types has somewhat differing effects on water quality, and the magnitude of those effects depend on the area occupied, intensity of management, configuration in the catchment, drainage patterns, catchment geological and geomorphological characteristics, and seasonal variations. For example, in the Atlantic Forest, recent conversion of low-intensity pastureland to high-intensity sugarcane cropland quadrupled the concentrations of nitrate in the water in small catchments (Taniwaki et al., 2017). Further, changes in water quality are influenced by the failure to respect potential land use, which generates use conflicts affecting surface water, groundwater, and aquatic life (Pacheco et al. 2014, 2018; Valle Junior et al 2014, 2015). In the case of agriculture and pasture, other factors also influence water quality, such as management practices, agricultural type, crop rotation, land use conflict, pasture conservation actions and runoff (Oliveira et al., 2019). We discuss below the potential impacts from the major land uses on water quality in Brazil.

2.1. Pasture

Pasture is the major anthropogenic land use in Brazil, which is the second largest producer and the largest exporter of beef in the world (USDA, 2019). However, more than half of Brazilian pastures are degraded, with problems associated with soil compaction and lack of soil nutrients (de Oliveira et al., 2004; de Oliveira Silva et al., 2017, Valle Junior et al., 2019). Changes in soil fertility are also observed in degraded pastures, such as declines in potassium, magnesium, organic

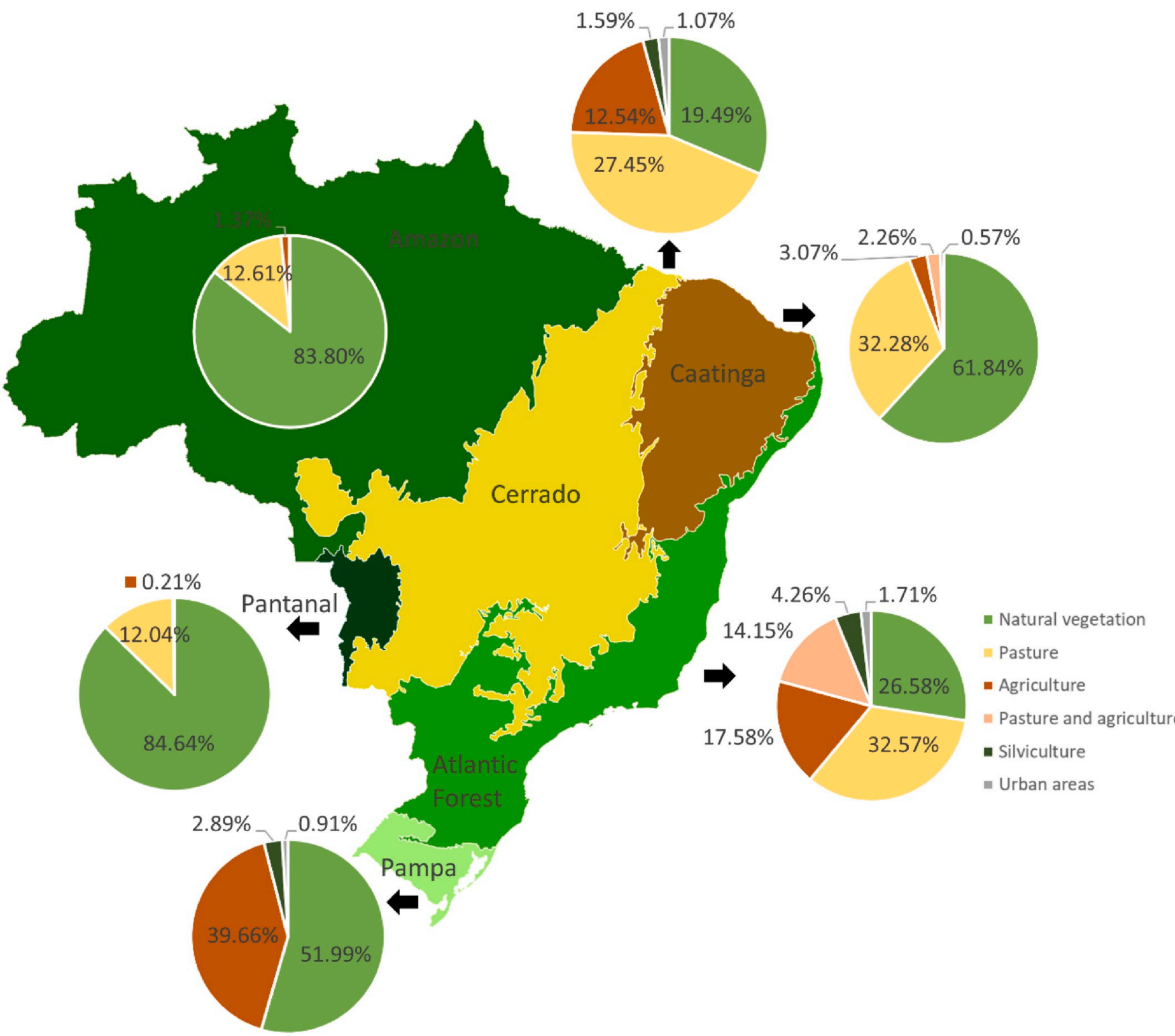

Fig. 1. Spatial distribution of the Brazilian terrestrial biomes and their major land-use/land-cover types. Data source: adapted from IBGE, 2019 and MapBiomas (2019).

matter and phosphorus content (Valle Junior et al., 2019). Soil compaction and devegetation have negative impacts on runoff dynamics, increasing water, nutrient and sediment runoff to aquatic ecosystems and increasing stream incision and intermittency (Beschta et al., 2013; Ogden et al., 2013, Table 1). Fertilizers applied to pasture with soil compaction are lost through runoff and transferred to aquatic ecosystems causing eutrophication, loss of aquatic biodiversity, and toxic algal blooms (Chellappa et al., 2008; Deegan et al., 2011; Ogden et al., 2013). Native vegetation conversion to pasture normally leads to increased water temperature and decreased dissolved oxygen (Pinto et al., 2013; Mello et al., 2018b, Table 1). Other combined factors that influence water quality in pasturelands include land use conflict, pasture conservation and runoff (Oliveira et al., 2019). Moreover, pastures on steep slopes are particularly prone to soil and channel erosion, leading to further increases in sediment and nutrients runoff into water bodies (Sattler et al., 2018) as well as accelerated channel incision and lowered water tables (Beschta et al., 2013).

However, pasture has mixed effects on water quality in Brazil (Hunke et al., 2015; Tanaka et al., 2016b; Mello et al., 2018b, Table S1) because effects depend on livestock intensity and potential natural vegetation. Many pasturelands in the country are natural grasslands with low productivities and low cattle densities, which may not markedly affect water quality but can affect other ecosystem services such as carbon storage and biodiversity (Strassburg et al., 2014).

2.2. Agriculture

Agriculture is one of the most important economic activities in Brazil, but is also a major cause of water quality degradation (Martinelli et al., 2010). Agricultural lands are responsible for increased sediment and nutrient loads into water courses, as well as toxic pollutants (Taniwaki et al., 2017; Mello et al., 2018b; Cruz et al., 2019b). Agricultural activities increase phosphorus, nitrogen, nitrate, ammonia and sediments in waterbodies in Brazil (Table 1). The use of fertilizers and pesticides in agriculture is a severe problem to aquatic ecosystems because they lead to eutrophication and groundwater contamination (Cunha et al., 2016; Taniwaki et al., 2017). Brazil is one of the major consumers of pesticides and fertilizers in the world, which have been widely detected in freshwater, groundwater and drinking water (Albuquerque et al., 2016; Montagner et al., 2017). Despite the high usage of pesticides, several contaminants are not monitored or regulated by the Brazilian government (Montagner et al., 2017). Besides their uncontrolled use, the Brazilian government approved the use of 201 new agrochemicals in 2019, some of which are prohibited elsewhere (Coelho et al., 2019). The combination of pesticides and fertilizers coupled with climate change will likely result in profound degradation of water quality and aquatic biota (Reid et al., 2018). Another critical problem related to the management of water quality in streams draining agricultural fields is that the majority of studies analyzing the impacts of agricultural activities in aquatic ecosystems do not specify the cultivated species, whether the agricultural activity is intended for food or biofuel production, or whether it is irrigated or unirrigated (Table 1). This lack of information hinders developing management actions because cultivation of each species employs different agrochemicals and different management techniques.

Table 1
Major effects of different land uses on water quality in Brazil.

Land Use	Major Effects	References
Pasture	Increases electrical conductivity, turbidity, total nitrogen, suspended solids, pH and temperature Decreases dissolved oxygen	Neil et al. (2001); Mori et al. (2015); Valente et al. (2015); Tanaka et al. (2016b); Ferreira-Marmotel et al. (2018); Molina et al. (2017); Mello et al. (2018b)
Agriculture	Increases total phosphorus, total nitrogen, turbidity, suspended solids, electrical conductivity, pesticides, nitrate and ammonia	de Souza et al., 2013; Aguiar et al. (2014); Mori et al. (2015); Zeihofer et al. (2016); Taniwaki et al. (2017); Mello et al. (2018b); Mello et al. (2018c); Cruz et al. (2019b)
Silviculture	Increases suspended solids, turbidity and electrical conductivity after clearcutting	Câmara Lima (1999); Vital et al. (1999); Rodrigues et al. (2019)
Urban Areas	Increases total nitrogen, total phosphorus, fecal coliforms, ammonia, nitrate, nitrite, organic material, biochemical oxygen demand, electrical conductivity Decreases dissolved oxygen	Zeilhofer et al. (2010), 2016; Cak et al. (2016); Cunha et al. (2016); Oliveira et al. (2016); de Souza et al. (2017); Tromboni and Dodds (2017); Rodrigues et al. (2018); Mello et al. (2018b); Figueiredo et al. (2019)
Mining	Increases mineral oxides, metals, and turbidity, and suspended solids	Gomes et al. (2017); Rudorff et al. (2018); Cruz et al. (2019a); da Silva et al. (2019)

2.3. Silviculture

Plantation forests in Brazil occupied 7.83 million ha in 2018, producing 91% of the wood used for local industrial purposes (IBÁ, 2019). The main genera planted in the country are *Eucalyptus* (5.7 million hectares, 73%) and *Pinus* (1.6 million ha, 20%) (IBÁ, 2019). Both are non-native, and 7% of the planted area is composed of native species, such as *Hevea brasiliensis* (rubber).

Studies of the effects of plantation forests on water quality under different management systems and in different regions show that forest management operations, such as the construction and maintenance of unpaved roads, harvesting, tillage, and fertilization change nutrient and solids concentrations and exports (Binkley and Brown, 1993; Binkley et al., 1999; Feller, 2005; Grace III, 2005; Baillie and Neary, 2015). Despite the limited studies of plantation forests in Brazil, some studies showed that *Eucalyptus* plantations have lower impacts on water quality than annual crops, such as sugarcane (Silva et al., 2007). Although harvesting *Eucalyptus* forest products can alter concentrations of nutrients and solids, this change is not always significant and has lower impacts than in temperate forests (Câmara and Lima, 1999; Vital et al., 1999; Rodrigues et al., 2019, Table 1). Regarding pesticides, some studies showed that water samples collected from *Eucalyptus* forests revealed no sulfluramid (pesticide) or glyphosate (herbicide) concentrations in the water (Gardiman Junior et al., 2018).

The reduced impact of plantation forests on water quality compared to other crops can be related to improved management practices. Forest certifications have driven changes in the management of plantation forests in Brazil and worldwide, whereby past practices such as indiscriminate conversion of native vegetation areas into forest plantations, use of fire, and various types of pesticides were banned (Payn et al., 2015). With the implementation of forest certification, the silviculture sector in Brazil improved its compliance with environmental laws, including the Forest Act, increasing the protection of riparian zones, Legal Reserves and the establishment of private Natural Heritage Reserves (da Silva et al., 2017; Leite et al., 2017). This indicates that compliance with appropriate laws can result in water quality improvement (Mello et al., 2017).

2.4. Urbanization

Urban areas contribute to water quality degradation in Brazil and are the major driver of severe water quality degradation worldwide. Urban areas represent a small proportion of the country (0.6%). However, the São Paulo metropolitan area is the largest urban agglomeration in the Southern Hemisphere with more than 21 million people (IBGE, 2019). It is also located in the most urbanized watershed in the country, with 24% (1,407 km^2) of urban coverage (FABHAT, 2019). The Tietê River is the main river in the watershed, and is one of the most polluted water bodies in Brazil (Cunha et al., 2011; Ferreira et al., 2019). Recently, São Paulo faced a severe water crisis, which was not only related to meteorological conditions but also to poor watershed management, including reductions of legally stipulated riparian buffers and increased headwater deforestation (Cohen, 2016; Mello and Randhir, 2018). Another example is the Rio das Velhas in Minas Gerais State, which is degraded by pollution from Belo Horizonte domestic and industrial sewage (Pompeu et al., 2005; Oliveira et al., 2016); although conditions have improved somewhat as a result of recently implemented sewage collection and treatment (de Carvalho et al., 2019).

Most urban streams and rivers in the country are highly enriched by organic wastes, fecal coliforms, phosphorus and nitrogen (Table 1) because of the lack of sewage collection and treatment facilities coupled with rapid urbanization and degraded riparian zones (e.g., França et al., 2019). Even when there is sewage treatment, stormwater runoff continues to degrade water quality by carrying incorrectly disposed garbage, detritus and road toxics to water bodies (Walsh, 2000; Walsh et al., 2005). In addition, Brazilian sewage treatment systems are separated from stormwater drainage systems and only the former receive treatment. Therefore, modest increases in urban land use can cause substantial impacts on water quality if not well planned (Tromboni and Dodds, 2017).

Urbanization also alters the hydrological conditions of freshwater systems, causing shifts in flow regimes through increased impervious cover, which affect water quality (Tucci, 2007). Also, urban areas are responsible for low levels of dissolved oxygen (Table 1), which is also a limiting factor for aquatic fauna. The high contamination of urban aquatic ecosystems has eliminated sensitive freshwater species and shifted community dynamics through the homogenization of ecosystem functions performed by native species and favoring the colonization of non-native species (Feio et al., 2015; Peressin et al., 2018; de Carvalho et al., 2019). Furthermore, in-channel and floodplain sand exploitation driven by urban growth in Brazil degrades river systems by increasing erosion rates, siltation and turbidity (Venson et al., 2017), compromising water supplies to human populations.

Despite the importance of water resources for urban regions, few actions have been implemented to mitigate water pollution. For example, ca. 100 million Brazilians (48% of the population) lack access to sewage collection and ca. 3.5 million who live in Brazil's 100 largest cities discharge untreated sewage into water bodies (Trata Brasil, 2019). Those cities treat around 50% of their sewage and only 10% treat over 80% of their sewage (Trata Brasil, 2019).

2.5. Mining

Despite covering a small percentage of the country's area, mining has enormous local impacts on water quality. Mining located at the headwaters of large watersheds threatens water quality, water security, and human life, as demonstrated by recent dam collapse events and river contamination in Minas Gerais State. Mining is a major source of several environmental impacts through contamination of surface waters and sediments by heavy metals and nutrients threatening aquatic ecosystems (Hughes et al., 2016; da Silva et al., 2019) (Table 1). Mining areas generate fine sand and mud that carry metals and other toxic elements, even in de-activated mining areas (Cruz et al., 2019a). Another mining activity that degrades water quality in Brazil is gold mining in the Amazon, which contaminates watercourses with mercury (at least 2,000 tons of mercury have been released to the environment) and mining leads to deforestation (Begotti and Peres, 2019).

Water degradation through mining activities is a common problem in the country. Moreira et al. (2016) assessed the impacts of mining on water quality in two river impoundments that receive wastewater from iron and kaolin mining at Minas Gerais State. They found high concentrations of Al, Ba, Mn, and Zn in both reservoirs that contaminate flows into streams during the rainy period. Da Silva et al. (2019) observed contamination of sediments by mineral oxides like Al_2O_3 and metals such as Zn, Zr, and Pb in rivers at prospecting sites with semi-precious rocks in Southern Brazil. In the Amazon, a floodplain lake connected to the Trombetas River received ca. 18 million m^3 per year of bauxite tailings from 1979 to 1989 (Fonseca and Esteves, 1999). Consequently, 30% of the lake total area was silted with the effluent rich in fine clays and high concentrations of iron, aluminium, and silicate oxides, causing high turbidity during low flow periods (Bozelli and Garrido, 2000).

The concern of river contamination from mining areas increased after the recent dam collapses in Brazil. The Mariana mining dam collapse polluted one of the most important rivers in the country (Rio Doce) for more than 650 km, extending its impacts to the Atlantic coast and affecting more than 1 million people (Fernandes et al., 2016; Hatje et al., 2017; Garcia et al., 2017). It is considered the greatest environmental catastrophe in the history of Brazil, affecting water supplies, fishing and agriculture activities of local communities (Zago et al., 2019). Less than four years later, the Brumadinho dam collapse contaminated the Rio São Francisco, the largest river entirely in Brazil, leaving hundreds of people missing and affecting many communities downstream (Campos-Silva and Peres, 2019).

The collapse of the dams quickly changed the rivers' shapes as a result of the rapid displacement of large volumes of material over a short time and across vast areas (Santos et al., 2019; Cionek et al., 2019). There were enormous increases in turbidity and suspended sediments in both cases (Rudorff et al., 2018). The sediments carried heavy metals and other toxic elements in the river. In the Rio Doce (Mariana), there were high loadings of iron, silica, aluminium and toxic trace metals, such as Cr, Cd and Pb (Gomes et al., 2017). The water analysis from the Rio Paraopeba (a tributary of the Rio São Francisco affected by the Brumadinho dam collapse) showed values of total lead and mercury increased 21 times above the acceptable level. Ni, Cd and Zn were also found at levels indicating risk to human and animal health (Cionek et al., 2019). There were also other impacts such as decreased oxygen levels, increased suspended sediment loads, and aquatic and riparian habitat loss (Cionek et al., 2019). In addition, high concentrations of heavy metals have permanently contaminated floodplain water and soil in the Rio Doce and Rio São Francisco floodplains, making them unsafe for cultivation.

Forest restoration is one suggested strategy to mitigate the impacts of tailings dam failures on these floodplains, although the metal contaminants are likely to limit tree survival and growth (Pires et al., 2017). Nonetheless, concerns about new disasters remain because Brazil has 196 mining dams with potential risk, including 59 classified as having high potential risk (ANM, 2019). Other South American countries, such as Bolivia and Peru, also face problems with water quality degradation from mining (Moya et al., 2011; Asner and Tupayachi, 2017; Romero-Muñoz et al., 2019), as do the North American nations of Canada, Mexico, and the USA (Hughes et al., 2016).

2.6. Forest regeneration

The conversion of natural forests to agriculture in Brazil is mostly through the establishment of large-scale pasturelands. However, many areas are abandoned after some years of pasture use, allowing secondary forest regeneration (Fearnside, 1996; Lennox et al., 2018). This natural regeneration on abandoned pasture represented 38% of the increase in secondary forest in Amazonia between 2004 and 2014 (INPE and Empraba, 2016). In the Atlantic Forest, forest regeneration has also been observed. The abandonment is mainly in regions near rivers and streams that have low agricultural potential and are protected by law (Ferraz et al., 2014; Molin et al., 2017).

Secondary forests provide several ecological functions and ecosystem services including the recovery of water quality (Heartsill-Scalley and Aide, 2003; Uriarte et al., 2011; Paula et al., 2018). Water quality is improved through reduced turbidity because regenerated forests improve water infiltration and reduce runoff of contaminants (Heartsill-Scalley and Aide, 2003; Uriarte et al., 2011; Filoso et al., 2017; Lozano-Baez et al., 2019). Reduced primary production rates and water temperatures were also observed after years of regeneration because recovered canopies increase stream shading (Heartsill-Scalley and Aide, 2003; Uriarte et al., 2011; Paula, 2018).

Although increased rates of forest regeneration have been observed in recent years in Brazil, there are few studies evaluating its effect on water quality. Most of those studies were conducted in the Atlantic Forest, where some forest cover is under regeneration (Ferraz et al., 2014; Molin et al., 2017) after long periods of intensive land uses (Victor et al., 2005; Ribeiro et al., 2009). Studies found that secondary forests contributed only small improvements in water quality, possibly because of the high levels of forest fragmentation, especially in riparian zones (Mori et al., 2015; Paula et al., 2018). In Amazonia streams, Paula (2018) found that forest regeneration decreased primary production levels and Paula (unpublished data) observed that secondary forests benefited several fish assemblage indicators.

3. Multiscale relationships between LULC and water quality

To better manage the impacts of LULC on water resources, it is important to consider streams as complex ecosystems that operate at varying spatial and temporal scales. Ward (1989) described four dimensions that affect stream ecosystems: lateral (movement/exchange between the terrestrial and aquatic system), longitudinal (downstream movement of water, materials, and organisms; upstream movement of migratory fishes), vertical (movement/exchange between the water column and the hyporheic zone), and finally, the temporal dimension. The temporal dimension includes seasonal changes, long-term climate change and the time-lag of some effects on water quality resulting from LULC changes. Thus, defining the appropriate scale (spatial and temporal dimension) is crucial for understanding the LULC impacts on water quality, because different water quality parameters reflect various impacts at different scales (Uriarte et al., 2011).

3.1. Spatial scale

LULC impacts on water quality are evaluated at mainly three different spatial scales: site, riparian network or catchment (Fig. 2). Most studies in Brazil have adopted only one of these scales but recently studies have been conducted using a multi-scale approach, showing that anthropogenic activities at different scales lead to different impacts on water quality (Leal et al., 2016; Tanaka et al., 2016b; Molina et al., 2017; Mello et al., 2018b; Paula et al., 2018). Riparian widths vary in studies based on the objectives, and multiple widths can be tested (Valera et al., 2019). Also, different catchment areas can be used, varying from local-segment catchments, small-stream catchments to entire river basins (Hughes et al., 2019). The relative importance of those three scales on water quality, hydrology and biology depends on the relative extent and intensity of the land use pressures in each scale (Hughes et al., 2006, 2019).

Replacing natural riparian vegetation by other land uses at the local scale (site or reach) (Fig. 2A) leads to water quality degradation because this vegetation cover is essential for providing shade and for buffering the effects of diffuse pollution (Maillard and Santos, 2008; Shen et al., 2015). In Amazonian streams, the removal of local riparian forests reduced stream shading, leading to increased temperature and primary production, but also affecting concentrations of nutrients and dissolved oxygen (Leal et al., 2016; Paula et al., 2018; Ilha et al., 2018). Tree removal causes bank erosion because the absence of roots destabilizes stream banks (Allmendinger et al., 2005; Paula et al., 2018); the resulting erosion increases suspended sediments in the water and leads to higher turbidity and streambed sedimentation.

Significant point-source discharges at the site extent can affect water quality for hundreds of kilometers downstream because downstream reaches are connected to upstream reaches, and are thus highly dependent on conditions in upstream reaches (Vannote et al., 1980). Therefore, impacts on water quality from LULC changes in headwaters can result in cascading effects on receiving river networks (Gomi et al., 2002) as well as lakes and reservoirs (Hughes et al., 2019). Studies in Brazilian headwater streams have shown that such LULC changes have substantial effects on water quality far downstream (Taniwaki et al., 2017; Mello et al., 2018b; Feijó-Lima et al., 2018).

At the riparian network scale (Fig. 2B), the absence or reduction of riparian forests facilitates increased nutrient and sediment loading to streams from the surrounding deforested areas (de Souza et al., 2013; Tanaka et al., 2016a). de Souza et al. (2013) showed that the reduction in riparian forest cover results in increased ammonium concentrations because of low nitrification rates and ammonium runoff from agricultural sources. In the Atlantic Forest, conversion of riparian forests to pastures or agricultural lands resulted in negative impacts on streams

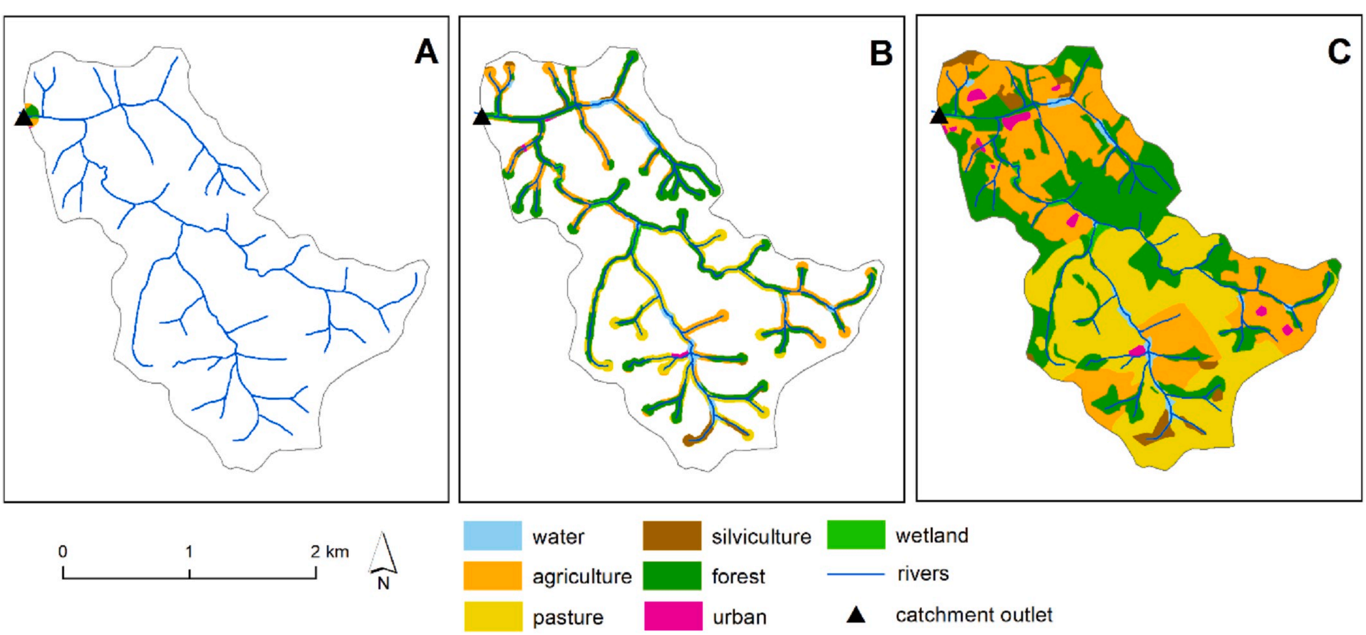

Fig. 2. Spatial scales commonly used to evaluate the relationship between land-use/land-cover pattern and water quality: site (A), riparian network (B) and catchment (C). Data source: Mello et al. (2018b).

that include reduced water quality (Fernandes et al., 2014; Paula et al., 2018; Mello et al., 2018b), habitat structure (Paula et al., 2011) and functional processes (Tanaka et al., 2016a). However, runoff pathways in agricultural watersheds may severely reduce the mitigation capacities of buffer strips (Gomes et al., 2019). In addition, studies have shown that the minimum riparian width required by law in Brazil (~30m) is not sufficient to buffer the impact of water quality in agricultural watersheds (Mello et al., 2018b; Valera et al., 2019).

The influence of LULC on water quality also needs to be considered beyond the riparian zone, because studies have shown that LULC at the catchment scale (Fig. 2C) is often a better predictor of water quality (Tanaka et al., 2016b; Mello et al., 2018b). Water quality parameters associated with runoff (e.g. nitrogen, phosphorus, organic carbon, fine sediments and other pollutants) from upland agricultural lands have been related to LULC at a catchment scale in the Atlantic Forest region (Tanaka et al., 2016b; Mello et al., 2018b; Gomes et al., 2019). The conversion of extensive areas of native vegetation to monoculture in Brazil is likely to affect larger spatial extent (watershed) processes such as water infiltration, runoff, and soil erosion (Hunke et al., 2015). Increased runoff and erosion in the catchment result in materials, nutrients, and sediments carried to the streams, which will be transported downstream and cause severe impacts on water quality and aquatic biota (Macedo et al., 2018).

In addition to LULC composition, LULC configuration like forest fragmentation pattern affects water quality in Brazilian catchments (Mori et al., 2015; Mello et al., 2018c; Paula et al., 2018). When residual forests are left in the landscape, these forests may be distant from streams and recharge areas in the watershed, or have low forest complexity, reducing their ecological functions of stream and water protection (Fernandes et al., 2014; Tanaka et al., 2016a; Mori et al., 2015; Paula et al., 2018). Besides, forest remnants in Atlantic Forest watersheds are characterized by high levels of fragmentation (Ribeiro et al., 2009), which compromises their ecosystem services, such as water regulation and purification (Ferraz et al., 2014). In agricultural landscapes of the southeast Atlantic Forest, high nitrate concentrations were found in streams surrounded by network riparian forest, possibly caused by the level of riparian forest fragmentation (Mori et al., 2015). In the same region, streams in catchments dominated by sugarcane had altered nitrate, conductivity, and dissolved carbon because of deforested headwaters (Taniwaki et al., 2017). However, the impacts of LULC configuration and forest fragmentation on water quality still needs to be better explored in Brazil.

When considering the effects of land use spatial scale on surface water quality, we caution analysts and managers to use true watersheds or catchments—not hydrologic units which are true catchments, watersheds or river basins only about half the time (Omernik, 2003; Omernik et al., 2017). Using appropriate spatial units can reduce some of the inherent variability, and increase the clarity, of LULC-water quality relationships (Hughes et al., 2019).

3.2. Temporal scale

Seasonal variation is an essential aspect of water quality studies, which is responsible for water parameter alteration associated with marked differences in precipitation associated with yearly wet and dry seasons. In watersheds covered by natural vegetation, the first peak flows in the rainy season are responsible for mobilizing and transporting organic material (especially in the dissolved form), increasing water turbidity and organic material concentrations (Lewis Jr., 2008). After the first rains, water turbidity and dissolved organic matter concentration are reduced (Lewis Jr., 2008) because runoff is minimal as a result of forest cover promoting water interception and infiltration (Hamilton and King, 1983). However, in agricultural landscapes, LULC effects can be more pronounced during the rainy season when increased runoff washes off soil, releasing large amounts of sediments, nutrients, and pesticides to surface waters (Mello et al., 2017; Shi et al., 2017). For example, in the Atlantic Forest and Caatinga biomes, suspended sediments peaked during high flows, followed by nutrient increases in agricultural watersheds (Mello et al., 2018c; Cruz et al., 2019b). However, in pasture-dominated catchments in Amazonia, nutrient concentrations were higher in the dry season than the wet season because pollutants were diluted in the latter (Neill et al., 2001).

Impacts of anthropogenic activities can take time to manifest in streams and lakes and past land-uses leave legacies of contamination in the landscape with lasting consequences over many years. For instance, water temperature is expected to increase rapidly following local riparian deforestation (usually in days), whereas changes in nutrient cycling and hydrological processes occur over years (Likens et al., 1978; Leal et al., 2016). In the same way, past land use legacies manifest in terms of how long water quality and discharge may take to return to pre-disturbance conditions after apparent ecosystem recovery. Nonetheless, forest regeneration at different spatial scales has the potential to recover stream attributes over time (Likens et al., 1978; Liébault et al., 2005; Giling et al., 2013; Yeung et al., 2017; Paula, 2018). Some attributes such as water temperature, dissolved oxygen, and primary production have a faster recovery (on a scale of years or a decade because of the relatively rapid reestablishment of tropical forest canopy; Paula, 2018). Other parameters, for instance discharge and suspended sediments, may take longer to recover because they are associated with a slower recovery of forest stand structure and functional processes of the forest ecosystem (which regulate infiltration, evapotranspiration, and runoff (Liébault et al., 2005; Lozano-Baes et al., 2019).

The recovery of forest attributes following intense past degradation may take even longer (Chazdon, 2008), and have a slow recovery of water attributes (Filoso et al., 2017; Lozano-Baes et al., 2019). Past land use intensity is widely considered in studies of forest recovery in the tropics (Jakovac et al., 2015; Zarin et al., 2005), but how this can affect the recovery of water quality and discharge in agricultural landscapes is still not well studied in Brazil. Although the issues of temporal scales and time lags complicate watershed management, it is crucial to incorporate them to achieve positive results in water resource assessments, planning and management.

4. Priority areas for watershed management

Previously we indicated that water conservation depends on the conservation of other natural resources, especially natural vegetation, and it requires management that incorporates an integrated and holistic ecosystem perspective (Leopold, 1949; Hughes, 2019). Thus, watershed management is essential to ensure the protection of water resources, striking a balance between water demand and natural habitat conservation. Watershed management integrates all environmental, social, and economic aspects aiming at conserving soil, vegetation and water resources while benefiting human society (Mander, 2008; Callisto et al., 2019). Systematic conservation planning of watersheds through spatial prioritization of conservation, restoration actions, and implementation of best practices in both agricultural and urban watersheds are important to achieve water body protection in Brazil (Moilanen et al., 2011; Vettorazzi and Valente, 2016; Langemeyer et al., 2016; Fan et al., 2018). Spatial prioritization can optimize watershed management practices, maximizing benefits while minimizing costs (Vollmer et al., 2016; Crouzeilles et al., 2016; Strassburg et al., 2019).

In this context, multi-criteria evaluation (MCE) is a promising modelling tool for decision support in order to define priority areas for watershed management, integrating LULC planning and clean water ecosystem services (Vettorazzi and Valente, 2016; Langemeyer et al., 2016; Martínez-López et al., 2019). MCE facilitates the prioritization of areas, considering their ability to aggregate spatial information that represents landscape features (composition, configuration, and physical aspects) and processes. The first step in MCE is determining long-term general goals (e.g., water quality, water yield) and short-term objectives (specific drinking water criteria, naturalized flow regime) (Gregory et al., 2012). Different goals and objectives regarding water resource management will influence the next steps of setting appropriate criteria and weights. Thus, it is important to have clear goals and objectives to ensure that the results will reflect stakeholder values and expert opinion and correspond to rational planning processes and implementation (Randhir and Shriver, 2009).

The criteria setting process is also important because it represent the landscape critical characteristics that are generally defined from participatory methods (Randhir and Shriver, 2009). For these reasons, MCE has been widely used in decision analysis and natural resource management Randhir and Shriver (2009). MCE has been demonstrated to be a convenient approach for stakeholder participation (Luck and Nyga, 2018). Decision-makers, NGOs, political and scientific experts, landowners and other stakeholders involved with watershed management can be involved in participatory methods. However, it is important to highlight that different opinions will result from varied proposals for a problem, even when using the same set of criteria (Mello et al., 2018a), which makes it important to have consensus and transparency among stakeholders and their representations.

MCE has been applied in Brazil to identify priority areas for forest conservation and restoration in urban and agricultural watersheds (Giordano and Riedel, 2008; Silva et al., 2010; Valente et al., 2017; Santos et al., 2018), but only a few studies have applied this method for water quality maintenance or improvement (Vettorazzi and Valente, 2016; Mello et al., 2018a). Duarte et al. (2016) evaluated priority areas for conserving multiple ecosystem services, including water quality in the Iron Quadrangle, an important Brazilian mining province at the interface of the Cerrado and Atlantic Forest biomes. In the same ecotone, Vettorazzi and Valente (2016) identified priority areas for forest restoration aimed at water conservation and found that proximity to surface water and soil erodibility were the main criteria established by a participatory technique. Macedo et al. (2018) also used a multicriterial approach to assess the potential erodibility of four hydrologic units in the Cerrado and validated their results using an instream sediment survey. The most common criteria used in the studies conducted in Brazil were proximity to water bodies, LULC type, distance to urban areas, slope, distance to road network, soil type, geology and erodibility (Silva et al., 2016; Vettorazzi and Valente, 2016; Mello et al., 2018a; Macedo et al., 2018). Silva et al. (2016). Vettorazzi and Valente (2016) and Mello et al. (2018a) applied the participatory technique to select criteria for forest restoration, and showed that it is a good framework for determining landscape characteristics that are important for meeting management objectives.

Brazil has discussion fora for water resource management, such as basin committees, where participatory techniques can be explored for defining priority areas, expanding the use of spatial prioritization to optimize watershed management. The National Water Agency (ANA) is the authority for implementing the National Water Resources Management System and works directly with basin committees and state water resource management agencies. One of its main goals is water resource planning. The knowledge obtained from previous studies about the relationship between LULC and water quality can be used for setting criteria in spatial prioritization and decision-making in a science-based process. The potential impacts of the proposed land use management on water quality and implications of land use change from agricultural and urban expansion can be evaluated by using watershed modelling, discussed in the next section.

5. Predicting future impacts on water quality

Future land-use changes related to agriculture expansion and urban sprawl in Brazil are likely to significantly degrade water quality, and it is crucial to predict these impacts to take actions to avoid or reduce water quality degradation and to protect water supplies for current and future generations. Removal of native vegetation and soil degradation will continue to affect water quality negatively, and there is a need to measure those impacts, link the impacts through the use of ecological risk assessments (USEPA, 2016), and report the results to the public and scientific community. Changes in seasonal patterns associated with increased peak discharges in the rainy season and lower streamflow in the dry season have been predicted through future simulations of deforestation in Brazil (Blainski et al., 2017; Lamparter et al., 2018) as have subsequent increases in sediment and nutrient loading (Blainski et al., 2017; Mello et al., 2017).

The Native Vegetation Protection Law (NPVL; Law 12.651; Brasil, 2012, also known as the New Forest Act) requires the protection of riparian forest and a percentage of the rural property (Legal Reserve), which represents opportunities to improve water quality through vegetation protection and restoration. In the State of São Paulo, ca. 692,000 ha of riparian vegetation is to be restored and 358,000 ha of Legal Reserves are to be restored or compensated (Tavares et al., 2019). Future scenarios of riparian restoration to comply with the NPVL have predicted water quality improvement, through reducing nutrient and sediment loads (Monteiro et al., 2016; Mello et al., 2017). The impacts of protecting or restoring Legal Reserves on water quality have not yet been studied. Another major restoration program in Brazil is the Atlantic Forest Restoration Pact, which targets restoration of 15 million ha by 2050 (Viani et al., 2017). One of the goals of this pact is to incentivize landowners to comply with the NPVL. Those restoration targets can improve the provisioning of many ecosystem services such as water purification, which can be evaluated through modelling future scenarios. Studies have shown that future forest restoration and best practices in agricultural watersheds through Payment for Ecosystem Services (PES) programs can improve water quality by reducing future sediment and nutrient loads (Rocha et al., 2012; Strauch et al., 2013; Taffarello et al., 2018; Kroeger et al., 2019).

Future scenarios of LULC change and water quality in Brazil depend on governmental policies and practices. The current national government favors aggressive economic development policies that are environmentally detrimental (Abessa et al., 2019). Moreover, it has created acts and decrees lowering environmental licensing requirements, suspending protection of indigenous lands, reducing the size of protected areas, and discouraging landowners from complying with environmental laws (Rochedo et al., 2018). The current state of environmental policy in Brazil will affect not only forest and biodiversity conservation, but will be detrimental to water quality in freshwater ecosystems (Guidotti et al., 2020).

Combined with LULC change, climate change will also degrade water quality in tropical agricultural watersheds. Nutrient production in freshwater ecosystems is sensitive to variations in temperature and precipitation, and such changes triggered by climate change will influence critical biophysical processes underlying nutrient loading (Xie and Ringler, 2017). Global projections of nutrient exports show that Brazil, China, India, and the United States account for more than half of estimated global N and P loadings, and agriculture expansion will further increase the expected impact of climate change on nutrients (Xie and Ringler, 2017). Climate change will alter streamflow and consequently sediment loading through soil loss (Talib and Randhir, 2017), thus the impacts of land use will likely be even more pronounced (Lapola et al., 2013). Climate change is also expected to increase variability in stream flows and thereby increase hydrologic uncertainty (Tsvetkova and Randhir, 2019). Thus, it is crucial to evaluate the impacts of all possible future scenarios (ranging from the worst to the best scenario) of LULC change on water quality, while also considering climate change. To achieve this, watershed models have been applied to predict water quality changes related to both LULC and climate changes.

Watershed modeling studies in Brazil have been primarily through statistical and simulation studies. Models used in watershed modeling in Brazil include the Annualized Agricultural Nonpoint Source (AnnAGNPS; Zema et al., 2018), Soil Water Assessment Tool (SWAT; Deus et al., 2018; Santos et al., 2019; Hamel et al., 2020), Sacramento Soil Moisture Accounting (SAC-SMA; Silva et al., 2016), Lavras

Simulation of Hydrology (LASH; Beskow et al., 2016), and Storm Water Management Model (SWMM; Seidl et al., 2018). Spatial modeling efforts have employed multivariate parameter sets using a variety of statistical models (Mello et al., 2018b; Dongli et al., 2017; Santos et al., 2017). With immense potential to relate the movement of contaminants across a watershed, watershed modeling enables accurate assessment and prediction of sources, transfers, and fates of contaminants. It is possible to quantify the improvement that can be achieved by managing the land use. For example, Mello et al. (2017) showed that riparian restoration under current environmental legislation in the Sarapuí River basin could decrease annual loads of nitrogen, phosphorus, and suspended solids by 22%, 8%, and 9%, respectively. Thus, watershed modelling is useful in developing policies and strategies that are comprehensive in addressing land use impacts on water quality.

Watershed models also have been applied in Brazil to evaluate water quality in future deforestation scenarios (Blainski et al., 2017; Lamparter et al., 2018), conversion of pasture or croplands, especially to sugarcane cultivation (Hernandes et al., 2018), and the impacts of the reduced vegetation protection requirements resulting from recent legislation (Guidotti et al., 2020). Studies have simulated future scenarios of forest restoration and best management practices (Rocha et al., 2012; Strauch et al., 2013; Monteiro et al., 2016; Mello et al., 2017; Tafarello et al., 2018; Kroeger et al., 2019) using the SWAT model. Others have used ANNAGNPS (Zema et al., 2018) and WaterWorld (Ferreira et al., 2019). The most common water quality variables modeled in these studies were sediments, suspended solids, and nutrients (N and P mostly).

The majority of the studies were performed in watersheds located in southern and southeastern Brazil (Bressiani et al., 2015a), mostly in the Atlantic Forest biome (Rocha et al., 2012; Blainski et al., 2017; Mello et al., 2017; Tafarello et al., 2018; Zema et al., 2018; Kroeger et al., 2019; Ferreira et al., 2019). Additional regions need to be studied, especially as the agricultural frontier advances across the Amazonia and Cerrado biomes. Lamparter et al. (2018) studied the hydrological impacts of future agricultural expansion in southern Amazonia, across Cerrado and Amazon Forest biomes, but their study did not consider water quality variables. Other studies have simulated future scenarios of land use in the Cerrado biome, but most of them have evaluated hydrological and sediment responses, omitting the impact on nutrient loading (Strauch et al., 2013; Monteiro et al., 2016; Hernandes et al., 2018). According to Bressiani et al. (2015a), most of the studies that have applied SWAT modelling in Brazil reported only hydrological results, not water quality results.

The small number of watershed modelling studies in Brazil that evaluated future scenarios of LULC change on water quality, especially nutrients, and the disproportionate spatial distribution in the country are related to the lack of continuous and high-resolution data. Watershed models like the SWAT model require several large datasets for model calibration and validation of results, including LULC, soil type, elevation, precipitation, temperature, humidity, streamflow, sediment loads and water quality inputs. However, such data for Brazilian watersheds are scarce, which makes it infeasible to apply these complex hydrologic and water quality models (Zema et al., 2018). For example, soil information is frequently a challenge, because available soil maps usually do not have the necessary resolution for the model application, and many parameters related to soil properties required by the model are not easy to obtain or to measure (Bressiani et al., 2015a). The resolution of soil and LULC maps will influence model calibration and validation. Thus, choosing an appropriate spatial resolution for the study is an essential step in watershed modelling (Fisher et al., 2018).

In many regions, there are very few weather stations and weather data are often not representative for the entire watershed (Rocha et al., 2012), similarly, there are too few streamflow gages and water quality monitoring sites in Brazil. Studies have reported challenges in calibrating and validating models, especially for water quality parameters because of scarce data (Strauch et al., 2013; Monteiro et al., 2016; Blainski et al., 2017; Mello et al., 2017). Weather data resolution is also important for model calibration, and it can have a great influence on the results (Bressiani et al., 2015b).

Another aspect is the high variability in topography as developed in the river network database available for Brazil. The Brazilian Institute of Statistics and Geography (IBGE) and Brazilian Army Geographic Division (DSG) have collaborated in developing drainage networks by extracting topographic information from 1960's aerial photographs. But the maps have different levels of resolution (1:50,000 below 20° S latitude, 1:100,000 above it, 1:250,000 in Amazonia), resulting in a markedly heterogeneous national hydrographic map (Silva et al., 2018). Although currently there are some standardized hydrological databases available on a national scale, they do not have the same cartographic quality as the drainage network built through aerial photographs.

Clearly, it is necessary to improve hydrological and geomorphological data availability in Brazil, and to improve water quality monitoring, spatially and temporally (Strauch et al., 2013). Efforts have been conducted or are underway to organize more easily and freely accessible national or state-level databases in Brazil (Bressiani et al., 2015b). These include the hydrologic database developed and/or gathered by the National Water Agency (ANA; https://www.snirh.gov.br/hidroweb/publico/apresentacao.jsf), the weather database of the National Institute of Meteorology (INMET; http://www.inmet.gov.br), the Environmental Spatial Data System of São Paulo State (DataGEO; http://datageo.ambiente.sp.gov.br/), the State Infrastructure of Spatial Data of Minas Gerais (IEDE; http://iede.fjp.mg.gov.br/) and those of the National Infrastructure of Spatial Data (INDE; https://inde.gov.br/). Thus, future watershed modelling application in Brazil are promising, even with multiple data limitation challenges (Bressiani et al., 2015b). Policies for research investments and improving monitoring frequency and completeness are necessary to address these data and modelling challenges in Brazil.

These databases can be used together with images from orbital sensors or aerial surveys because these can assist in the adjustment, correction, and extrapolation of hydrological and water quality data to areas uncovered by monitoring stations. Satellite data and images from aircraft can be used to evaluate some water quality variables in reservoirs, lakes and river systems (Becker et al., 2016; Jacobson et al., 2019; Swain and Sahoo, 2017). In addition, images from active and passive remote sensors can be useful in regionalization and flow modeling (Aires et al., 2018; Frapart et al., 2019). WorldClim global climatic models (https://www.worldclim.org) used satellite images and statistical modeling to make data from weather stations available worldwide (Fick and Hijmans, 2017), and a similar initiative was carried out by Alvares et al. (2013) to create the climate map of Brazil.

6. Future perspectives and knowledge gaps

Concerns regarding water conservation in Brazil have increased in recent decades. It has been recognized that LULC change is the leading cause of water quality degradation, and watershed management is crucial to prevent its impacts. Also, there has been substantial progress in water resource science, following the improvements in the infrastructure of Brazilian universities and project funding that helped to increase the number of scientists dedicated to this topic. Specifically, the Brazilian government made substantial investments in public higher education and science and technology programs in the past decade (CAPES, 2020). In addition, increased recognition that water conservation is strongly linked with more productive and sustainable economic activities, especially for agriculture and pasture, was extremely important for accelerating water conservation studies, determining major pressures, stressors, and impacts, and then adopting better practices for mitigating those negative impacts on water resources (Martinelli and Filoso, 2008). Studies conducted in Brazil and elsewhere have shown that protecting native vegetation is crucial for maintaining and improving water quality across all Brazilian biomes. However, the conversion of natural ecosystems still threatens water resources.

Pasture is the dominant land use by area in Brazil, and the main driver of deforestation in the border between the Amazonia and Cerrado biomes; however, many pasturelands have been abandoned because of low suitability or productivity, leading to water quality impacts with no economic benefits (Zu Ermgassen et al., 2018). Thus, pasture must be better planned and managed to avoid additional forest deforestation, increase forest restoration in degraded pasturelands, and improve water quality.

Agriculture is the second most important land use in Brazil, and projections show increases because of market forces, especially for soy and sugarcane (Carvalho et al., 2019). Studies conducted in Brazil showed that agriculture is the second most important LULC affecting water quality (after urban areas). Thus, forest conservation and restoration, land use planning and best agricultural practices are essential for protecting and improving water quality in agriculture watersheds. The enforcement of the NPVL is essential for protecting water quality in rural areas by protecting fragile ecosystems and mitigating impacts from the cultivated areas and reducing forest cover fragmentation along the drainage network. The studies also show that not only riparian vegetation, but also the forest cover within the whole watershed, is important for protecting water quality, highlighting the importance of the Legal Reserves required by law (Metzger et al., 2019). This relationship has also been documented recently for biological responses in Amazonian (Leal et al., 2018; Leitao et al., 2018; Brito et al., 2020), Cerrado (Macedo et al., 2014; Silva et al., 2018) and Atlantic Forest (Pinto et al., 2006; Terra et al., 2015; Gerhard and Verdade, 2016) streams.

Silviculture and mining have recently shown differing successes in water quality management. Silviculture has produced advances in management practices and market forces for certification, which resulted in improvements in water quality. However, there are still too few studies about water quality in Brazilian silviculture landscapes. On the other hand, the mining sector has produced water quality degradation and environmental disasters in recent years. Enforcement of environmental laws, inspection and control from environmental agencies, application of fines, and pressure from society are strongly needed to avoid water quality contamination from mining and continued disasters (Bowker and Chambers, 2017).

Brazil still faces major problems with water quality degradation in urban areas. Improved sewage collection and treatment is strongly needed in all cities. Urban water quality degradation affects not only the environment but also human health (Eisenberg et al., 2016). In addition to sewage collection and treatment, stormwater collection and treatment as well as natural or constructed wetlands and riparian zones are needed to minimize polluted urban runoff to rivers (Ceballos et al., 2001). In Brazil, we have few urban river rehabilitation projects (Wantzen et al., 2019) but those that do exist indicate that improvements in water quality and flow control can be cost-effective here, just as they have been in other urban areas (Yeakley et al., 2014).

The studies conducted in Brazil also show that it is crucial to consider temporal and spatial scales in water quality studies. LULC impacts on water quality can vary according to seasonal variation in streamflow and temperature, time-lag effects from LULC, and influence of upstream areas. Both temporal and spatial conditions are important for setting strategies for forest restoration or conservation.

Prioritizing fragile and ecologically important areas for forest conservation and restoration need to be based on knowledge of the relationship between LULC and water quality for cost-effective watershed management. Brazilian water and forest management policies should be implemented based on that scientific knowledge.

Past and present studies provide the bases for future projections of water quality in Brazil. Predicting future scenarios is important to guide decision-making processes and to evaluate impacts of decisions about probable LULC changes (Hulse et al., 2004). We show in this paper that the scientific community in Brazil is prepared to give the necessary information to decision-makers regarding water resource protection.

Nevertheless, we still face barriers regarding data availability and quality, and we need to better understand the effects of fragmentation, crop type, fertilizer and pesticide uses, and road and dam impacts, and we need to expand studies along the Amazonia-Cerrado agriculture frontier. Also, recent political changes to cut scientific funding and relax environmental legislation and enforcement threaten both the continuation of research and the protection of water resources. We list below key knowledge gaps and challenges to guide future studies about LULC-water quality relationships in Brazil.

- Most studies analyzing the effects of agricultural activities on water quality do not specify crop type and management practices. This lack of information hinders understanding the major problems and solutions with water quality in agricultural areas. Therefore, we recommend that future water quality studies conducted in agricultural landscapes thoroughly describe the crop types analyzed, the types and application rates of the fertilizers and pesticides used in the agricultural landscape, the planting, tilling and harvesting periods and methods, and whether and how the crops are irrigated or not. Such information will allow us to propose better management actions than we can do now.
- Roads and small dams affect the downstream and upstream fluxes of water, materials, energy, and organisms through riverscapes (Pringle, 2003). Small water impoundments are common in small agricultural catchments throughout Brazil, usually for local water supply, recreation, and irrigation (Macedo et al., 2013; Leal et al., 2016; Taniwaki et al., 2018). In the Brazilian Amazon, agriculture expansion is the main driver of river network fragmentation by road construction (Pocewicz and Garcia, 2016). These impacts are still poorly known in Brazil and there is minimal information on how they affect water quality in downstream reaches.
- Most studies about the relationship between LULC patterns and water quality are conducted in few sites and at the catchment scale, considering only LULC composition and not LULC configuration. Studies considering greater numbers of catchments, a multi-scale approach considering land use composition and configuration (especially forest fragmentation) are needed to better understand the local, regional and national relationships between LULC and water quality (Hughes et al., 2019).
- Forest regeneration has the potential to improve water quality and secondary forests are increasing in Brazil. However, there are increasing threats that may compromise forest recovery (i.e., land use intensification and the indiscriminate use of fire; Barlow and Peres, 2004; Laurance, 2006), which likely influence water quality recovery. It is necessary to understand how these increasing threats will affect the regeneration process and water quality recovery times.
- There are few studies about priority areas for conserving and restoring forests focused on water conservation, and they are concentrated in the Atlantic Forest biome. These studies are important to aid decision-makers in setting priorities, better conserving and restoring forests, and providing ecosystem services. Land use policies must focus on the maintenance of ecosystem services, not only agriculture expansion (Gawith and Hodge, 2019), and keeping water clean is one of the most critical ecosystem services provided by natural vegetation. Thus, water resources must be included in area prioritization.
- There is still a problem in accessing watershed modelling data in Brazil, despite the efforts that have been conducted at national and state scales. Increased quality and availability of government data is crucial for scientific productivity and sustainable economies. It is therefore necessary to invest in more detailed GIS datasets, including detailed soil, hydrography, land use, road, and geology maps.
- The majority of water quality studies are conducted in the Atlantic Forest biome and/or in Southeast Brazil, creating a large gap in other regions, especially in the North and Midwest, where the agricultural frontier is advancing rapidly across the Amazon and Cerrado biomes

as a result of deforestation. Brazil desperately needs LULC-water quality studies across this rapidly changing ecotone.

- Local-extent, short-term studies by different researchers applying different methods fail to develop a nationally consistent and comprehensive database. Instead, rigorous, comprehensive, statistically designed national (e.g., Hughes and Peck, 2008; USEPA, 2016) and state (e.g. Yoder et al., 2005; Mulvey et al., 2009) surveys using standard methods is needed. Ideally, a wealth, resource-rich nation such as Brazil should have a substantial effort led by state and national governments to organize collaborations among university, state, and federal institutions so as to be most efficient and to maximize data exchanges and a centralized national database in an on-line platform.
- Finally, future studies are necessary to provide information about the risks and impacts from recent changes in environmental policies and decisions on water quality in Brazil, reinforcing the importance of basing environmental policies on scientific evidence, versus ideological or political orientations (Abessa et al., 2019).

7. Summary & conclusions

This study reinforces the importance of watershed management and the need to protect native vegetation for providing ecosystem services, particularly water-related services. Considering the fundamental nature of watersheds, we provided essential information regarding the relationships between LULC and water quality in Brazil and, presumably, other nations. The increased pressure on existing forest from agriculture, pasture, urbanization and mining expansions in Brazil and similar countries (Metzger et al., 2019; Asner and Tupayachi, 2017; Romero-Muñoz et al., 2019) threatens water quality. Thus, decisions based on the knowledge presented here are important for water resource management at continental and international levels, particularly for tropical and subtropical nations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank the National Institute for Space Research (INPE) for promoting the Brazilian Symposium on Remote Sensing, which gave us the opportunity to conduct a symposium about LULC and water quality, and the São Paulo Research Foundation (FAPESP) for supporting the speakers' participation. The insightful comments and suggestions of four anonymous reviewers greatly improved the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110879.

Funding

KM was funded by FAPESP grants 2013/0358-6, 2014/19093-1 and 2017/24028-2. RHT was funded by FAPESP grant 2017/02455-6 and the National Council for Scientific and Technological Development (CNPq grant 407502/2018-1). FRP was funded by FAPESP grant 2018/12341-0. RAV was funded by FAPESP grant 2018/21612-8. TOR was funded by the National Institute of Food and Agriculture (CSREES, U.S. Department of Agriculture, Massachusetts Experiment Station, Project MAS00036). CGL was funded by FAPESP grant 2017/25383-0. DRM was funded by Brazilian Electricity Regulatory Agency and Electric Power Company of Minas Gerais (CEMIG-P&D-ANEEL GT599). RMH was funded by Fulbright Brasil.

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