

**PERSPECTIVES AND NOTES**

Fostering water resource governance and conservation in the Brazilian Cerrado biome

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Abstract

The Brazilian Cerrado, one of the most threatened biomes of our planet, illustrates the challenges and opportunities of reconciling economic development with conservation of land and water ecosystems. Here, we assess the state of the art of and present new information on the impacts of agricultural expansion, dams, and water use, and make recommendations for basin management, conservation, and restoration of water-related Cerrado ecosystems and rivers. The conservation of the Cerrado requires not only the preservation of remnants of its vegetation but also the ability to keep the hydro-geomorphological and ecological functionality of its rivers, particularly the Araguaia River, the last large well preserved and unregulated system. If business as usual continues, the Cerrado riverine ecosystems may never rebound.

KEYWORDS

biodiversity, Brazil, Cerrado biome, conservation, dams, water resources

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1 | INTRODUCTION

Rivers, floodplains, and riparian forests provide freshwater, land, and energy that propels economic development and sustain human life worldwide. These aquatic-related ecosystems are also highly biodiverse, but recent studies suggest that rivers around the world are under enormous anthropogenic stresses, hampering their integrity and future sustainability (Best, 2019; Latrubesse et al., 2017). Identifying major threats and proposing conservation insights is crucial for achieving water resource governance, and conservation in regional hotspots of freshwater diversity.

The Cerrado biome is strategic for water resources because it contains the headwaters and the largest portion of South American watersheds (the Paraná-Paraguay, Araguaia-Tocantins, and São Francisco river basins) and the upper catchments of large Amazon tributaries, such as the Xingu and Tapajós (Figure 1). The presence of large watersheds and fluvial drainages with topographic breaklines (knickpoints), also makes the Cerrado crucial for Brazil's energy sector, accounting for approximately

19% of the country's hydropower capacity (ANA). Despite its strategic importance, the impacts on riverine systems and related wetlands, and the key role those systems play in biodiversity and environmental functionality has yet to be properly addressed. Here we present our perspective on the anthropogenic impacts of land change, dams, and water uptake for irrigation on the Cerrado's aquatic ecosystems, and propose policies and recommendations for fluvial basin management. Our perspective is supported by the collection and analysis of multiple data on deforestation, dams, irrigation, percentage of conservation areas, and other relevant environmental information such as fish and wetlands-riparian biodiversity for each major fluvial basin of the Cerrado (Supporting Information Appendix S1).

2 | THE LINK BETWEEN TERRESTRIAL AND FRESHWATER HABITATS

Vegetation is a primary component of the hydrological cycle, and the high levels of deforestation and conversion of

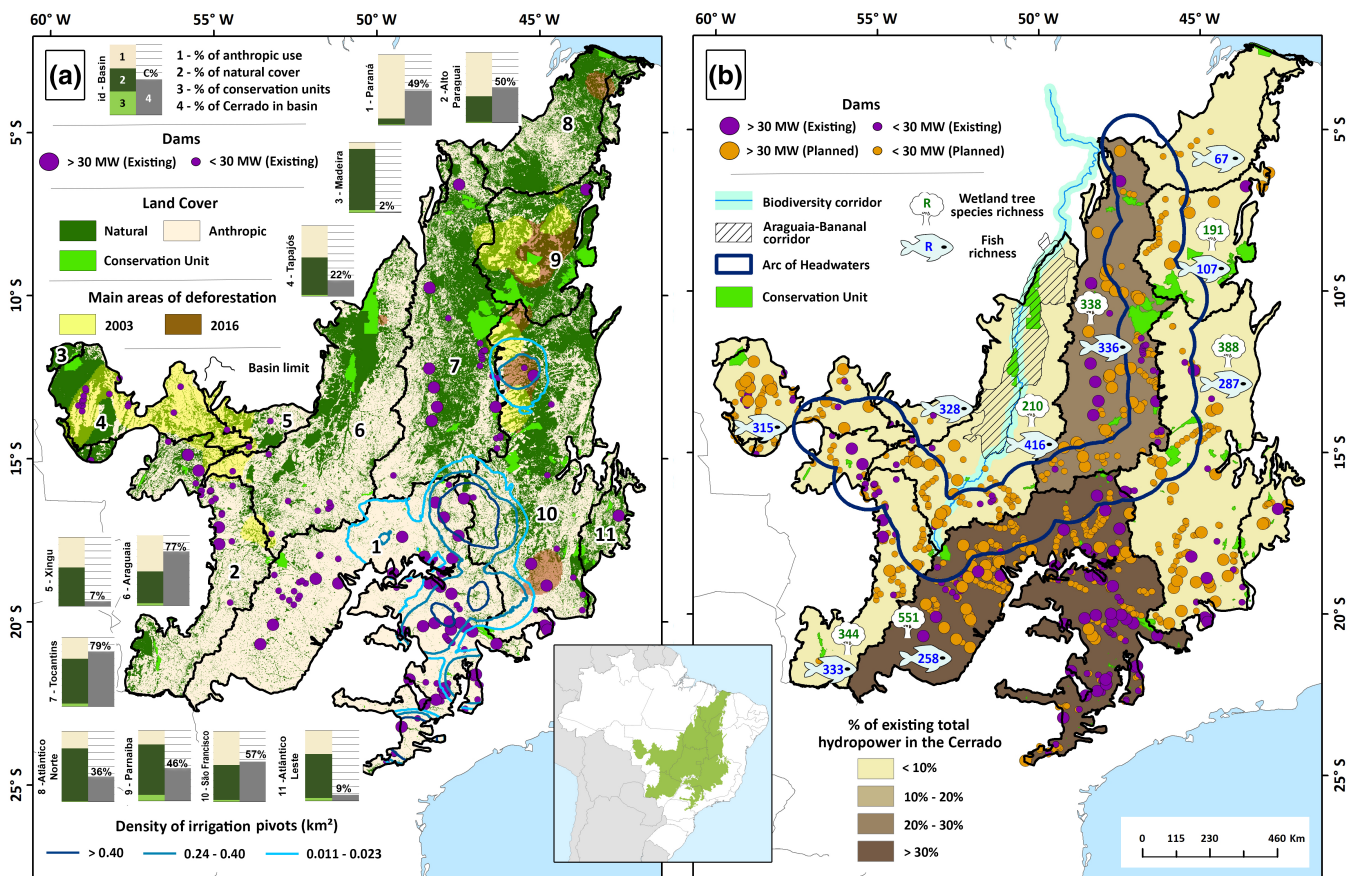


FIGURE 1 (a) Main fluvial basins of the Cerrado, percentage of land cover categories per basin into the Cerrado biome limit, and percentage of Cerrado biome area per total drainage area of the basin, dams (existing and planned), density of pivots for irrigation, and main areas of deforestation in 2003 and 2013–2016 showing the geographic trends of the expansion of the agricultural frontier. (b) Biodiversity richness of fish and wetlands trees per basin, planned and existing dams, installed hydropower per basin, existing conservation units and proposed units (Araguaia-Bananal Corridor, Araguaia Corridor of Diversity, and Arc of the Headwaters). Source and complementary data in Appendix S1

natural vegetation to crops, pasture, and sugarcane triggers hydrological, geomorphological, and biochemical changes in small and large rivers, and significant changes in land surface temperature (Coe et al., 2017; Coe, Latrubesse, Ferreira, & Amsler, 2011; Latrubesse, Amsler, De Moraes, & Aquino, 2009; Nóbrega et al., 2017; Silva, da Cunha Bustamante, Markewitz, Krusche, & Ferreira, 2011).

The opening of the Cerrado frontier spurred by the relocation of the capital to Brasília in 1960, road network investments, deforestation making way for planted pastures and croplands, and advances in agricultural technology, transformed the Cerrado and turned Brazil into the world's largest exporter of beef and soybeans (FAO, 2015; Oliveira, 2016; Walker et al., 2009). The Brazilian Cerrado tropical savanna lost more than half of its original 2 million km² in the last 55 years (Lapola et al., 2014; Sano, Rosa, Brito, & Ferreira, 2010) and concomitantly became Brazil's breadbasket, with more than 20 million ha of cropland and 56 million ha of cultivated pastures (MapBiomas, 2017). While agricultural expansion increased food supply, it came at the expense of unsustainable water and land uses.

The Cerrado's deforestation/catchment area ratio of major fluvial basins ranges from extreme conversion (e.g., Paraná = 90%) to moderate (e.g., Paranaíba = 19.9%), and a significant part of the remnant Cerrado has lost valuable ecosystem services due to excessive fragmentation (Appendix S1). Furthermore, the protected area/Cerrado ratio within basins is insignificant (0.8–4% in 10 of the 11 basins), well below the national rate of 28.44% of the conservation area in Brazil (Figure 1a). Because of extreme fragmentation, many of these conservation units do not guarantee the maintenance or representativeness of plant and animal species. Furthermore, the available Cerrado area for either future conservation or deforestation is meager in all the basins (Figure 1a and Table S1). In the Paraná basin, for instance, native Cerrado vegetation is almost non-existent to expand the protected area system. Similarly, only fragmented natural Cerrado patches are still available in the upper Tapajós and Tocantins basins. In the last decade, the agricultural and cattle ranching frontier expanded rapidly into the São Francisco and Parnaíba basins to the East, while consolidating its foothold in the Tapajós and Xingu basins in the West (Figure 1 and Appendix S1).

Deforestation of the riparian forest has also been extensive. In Goiás, a state within the Cerrado's core area, 69% of the watersheds larger than 500 km² have less than 50% of remnant vegetation. While environmental laws and regulations exist, 46% of these watersheds do not meet the requirements of the Brazilian Forest Code, which mandates 30% of the area to be preserved (i.e., 20% as a legal reserve, and 10% as a permanently protected riparian area, depending on the width of the river) (Bonnet, Ferreira Jr, & Lobo, 2006).

To make matters worse, recent changes in the Forest Code and amnesty for environmental crimes affected the legal status of 7.6 Mha of riparian forests in the Cerrado (Guidotti et al., 2017).

When the native Cerrado vegetation is converted to shallow-rooted, nonpermanent croplands, changes in the interaction between water and soil occur (Cabral, da Rocha, Gash, Freitas, & Ligo, 2015). Land conversion modified soil pH, bulk density and available P and K for croplands (Zago et al., 2018), while pollution of some rivers and streams by pesticides exceeds the Brazilian and European Union (EU) water quality limits (Hunke, Mueller, Schröder, & Zeilhofer, 2015). In Brazil, the use of fertilizers doubled from 80 to 160 kg/ha between 1992 and 2012 (IBGE, 2012) and the application of pesticides added 3.5 kg of petrochemicals per hectare, making Brazil the largest agricultural user of chemical fertilizers and pesticides per capita and per area (Wittmann et al., 2015).

Despite the widespread use of minimum-tillage technology, soil degradation by erosion is still ubiquitous. Diffuse surface runoff alone in areas with temporary crops, such as soybean, accounts for approximately 20 ton ha⁻¹ year⁻¹, close to 11 times more than in areas with permanent crops like coffee (de Castro & de Queiroz Neto, 2009). Linear erosion increases when mechanized agriculture compacts the soil. As a consequence, thousands of gullies (locally known as *voçorocas*), developed in the upper catchments of major rivers. More than 5000 gullies were recorded just in the upper Araguaia basin, and the river mainstem suffered sedimentation and fluvial metamorphism during the last four decades (Latrubesse et al., 2009).

Additional pressure on the water resources is produced by the use of surface water for irrigation, which skyrocketed in the border area of Goiás, Minas Gerais, and Bahia states, where more than 13,000 pivots for irrigation were identified in public records as of 2013 (Appendix S1). In terms of water usage, the Paraná and São Francisco basins concentrate 60% and approximately 30% of the irrigation volume, respectively (Figure 1a). Uncounted pivots continue to be installed, and the extraction of surface water for irrigation is devastating swamps, creeks, small lakes, and rivers. The number of irrigation pivots in operation illegally in the whole Cerrado is unknown but is likely to be a relevant amount. For example, just in the Goiás state, more than 2,600 pivots are operating without environmental licenses (Appendix S1).

3 | DAMS AND HYDROPOWER IN THE CERRADO

Dams trap sediments and modify the hydrological regime of rivers, thus impacting sediment and nutrient fluxes into the

floodplains, deltas, and the coastal ecosystems (Best, 2019, Syvitski & Kettner, 2011). They also change hydraulics, water transparency, temperature, and chemistry and represent barriers to the migration of aquatic and semi-aquatic organisms as well as of inorganic material (Nilsson & Berggren, 2000). Currently, more than 291 hydropower plants >30MW are operating in the Cerrado, and 829 new ones are planned (Figure 1a and b and Appendix S1). Two most heavily impacted areas are the Paraná and São Francisco basins, which concentrate 66% of the dams (planned and constructed). In the Paraná basin, 345 dams are either planned or already in operation; and 115 dams in the São Francisco basin. A total of 79 dams (planned and constructed) are in the upper Tapajós River, the river most threatened by dams in the Brazilian Amazon basin (Latrubesse et al., 2017). Thus, the environmental pressure to the Cerrado is set to increase.

The hydropower potential of the Tocantins-Araguaia basin has been slated for exploitation. The basin, formed by two similar-sized rivers with similar drainage basins and annual water discharge, has several large dams concentrated on the Tocantins sub-basin, such as Tucuruí, Estreito, and Serra da Mesa dams, and additional 90 new dams are planned (ANA-ANEEL, 2017). The Araguaia River, with nine small hydropower plants upstream, is the only major system free of dams downstream. However, with 70 dams proposed, including four large dams on the main channel (Figure 1), it is now also at risk. With a mean annual discharge of approximately 6420 m³, the Araguaia, the major fluvial artery of central Brazil and the Amazon-Cerrado ecotone, contains the most geodiverse floodplain of the biome, and is home to the Bananal plain, one of the most extensive seasonal flooded tropical savanna in the world, covering more than 100,000 km² (Valente, Latrubesse, & Ferreira, 2013).

Small and, usually illegal impoundments also impact the tributaries and upper courses of Cerrado's rivers. By 2010, just in the upper Xingu, over 40% of the creeks and smaller fluvial systems were disrupted by approximately 10,000 impoundments (Macedo et al., 2013). The total number of small impoundments is unknown, but likely to be orders of magnitudes higher.

4 | RIVERINE BIODIVERSITY

The Cerrado's most tree species-rich habitats are its riparian forests, with up to 800 flood-tolerant tree species (Wittmann et al., 2017). They provide refuge for many moist-sensitive tree species that overcome seasonal drought and wildfires by tapping into the high groundwater along rivers. The Cerrado's rivers are also important dispersal corridors for tree species from neighboring biomes, such as the Amazon and

the Atlantic rainforests. Mean alpha diversity of flood-tolerant tree species is highest in the southern (Paraná basin) and eastern parts (Atlântico Leste, Tocantins, and Araguaia basins), whereas it is comparatively low in the northern (Paraná basin) and western (upper Paraguay) parts (Figure 1b and Appendix S1, Table S2). Tree species composition might be highly variable between rivers and many locally-found, flood tolerant, rare species are at risk of extinction due to deforestation, habitat fragmentation, and modified flood and sediment regimes through river damming (Figure 1b). Habitat loss and fragmentation negatively affect vital ecosystem services such as drought mitigation and reduce the biodiversity of the aquatic, semi-aquatic, and terrestrial fauna.

Freshwater fish are also a fundamental concern for the conservation of the Cerrado biome. Regionally known as the "water cradle," the basins draining the Cerrado harbor up to 1600 species, a quarter of the entire South American fish diversity, within which 42% (131 species) are endangered in Brazil. The basins' biota is distinctive, often exceeding 300 endemic species (Figure 1b and Appendix S1, Table S3), and the composition is markedly distinct between assemblages (Dagosta & Pinna, 2017). The Araguaia River alone is home to more fish species than any other basin in the Cerrado (when typical lowland Amazonian and endemic species in its upper reaches are included, Figure 1b). Likewise, the upper Tocantins contains the largest number of endemic fish (Dagosta & Pinna, 2017). The combination of high richness, narrowly distributed species and human impacts make the conservation of the Cerrado biome critical for continued fish diversity.

5 | SAFEGUARDING THE CERRADO AQUATIC ECOSYSTEMS

While the green revolution transformed the Cerrado into one of the most productive agricultural frontiers (Borlaug, 2002) and dams helped sustain Brazil's economic development, they also degraded terrestrial and aquatic resources.

For some of the river basins in the Cerrado, such as the Paraná and São Francisco, the aggregate impacts from land change, water withdrawal, agrochemical pollution, and dams are already too large and the revitalization of these collapsed ecosystems would require fundamental changes in land use and the decommission of dams followed by expensive restoration programs, which is unlikely to occur within the next decades. The potential construction of hundreds of additional dams on these already deteriorated ecosystems will only exacerbate the problem.

For the watersheds with relatively preserved ecosystems (e.g., Araguaia and Paranaíba) threats from dam construction (see above) and agricultural expansion remain. Agricultural

lands are expected to increase from the current 60 million hectares to more than 70 million in the next 10 years in Brazil (MAPA, 2018), and the Cerrado continues to be lauded as the appropriate biome to accommodate that expansion due to low land prices, favorable climate, and topography (MAPA, 2018). Due to the complex economic forces acting upon the Cerrado, conservation of its remaining aquatic ecosystems and water resources will require a combination of policies, tailored to specific basins and watersheds.

An aquatic-system-based conservation approach will require a shift in how impacts are measured and policies are implemented (Table 1). We argue that riparian ecosystems and other wetland 'fluvial basins' should be the relevant units whereby impacts are measured, and policies are recommended due to the coupling between agricultural land use and impacts on the water resources. For instance, the Tocantins, Atlântico Norte, and Tapajós basins still contain large patches of Cerrado vegetation where new conservation areas could be created (Appendix S1). In contrast, the Xingu does not have any conservation unit encompassing the Cerrado biome, with only 2,953 km² of natural vegetation remaining in that basin, much of it likely within private properties (Figure 1a). The situation is critical in the Paraná basin, where only 0.8% of the original Cerrado area is protected, and approximately 90% is either deforested or highly fragmented. In such cases, incentives, such as payment for ecosystem services (PES) and enforcement of legally stipulated protection of riparian forests and preservation of at least 20% of the native Cerrado vegetation within each property should be a priority. Brazil's National Water Agency (ANA) is implementing a pilot PES program whereby landowners receive between US\$50-100 annually to abandon and reforest agricultural lands along rivers, streams, and water springs (ANA, 2019). PES programs such as these should be expanded.

Second, more than eight hundred planned projects >5MW make the Cerrado's rivers the most threatened by dams in the global tropics. We propose the Araguaia basin to remain a "dam-free" zone to preserve the most emblematic, ecologically essential, and less regulated basin of the Cerrado (Table 1). We base our recommendation on several factors. With 77% of the Araguaia drainage basin in the Cerrado, it contains the most complex and geodiverse floodplains, the most extensive wetlands of both the Cerrado and the Amazon-Cerrado ecotone, as well as the highest diversity of fish (416 species). Thus, despite being the most ecologically understudied large fluvial system, the Araguaia's riparian forests and its aquatic ecosystems are known to be highly biodiverse (Table S2). These conservation policies and dam-free initiative in the Araguaia would capitalize on and amplify the benefits from the already existing

conservation areas that were specifically created to preserve fluvial-riparian ecosystems and wetlands. Since the 2000s, the Ministry of the Environment of Brazil (MMA) has considered the creation of over nine million hectares of ecological corridors interlinking conservation units and indigenous areas, to protect large portions of the Araguaia floodplain, the Bananal Island, and the wetlands of the Mortes River (Figure 1b and Appendix S1). Moreover, a recent initiative called the Araguaia Corridor of Biodiversity, promoted by the MMA and NGOs proposes the creation of an eight-million hectares fluvial corridor, 20 km wide on each side of the Araguaia, and 1800 km long from Tucuruí dam to Emas National Park in the Araguaia headwaters (Figure 1b and Appendix S1). Another new initiative by the MMA calls for the protection along the "Arc of the Headwaters," linking the major basins through a narrow 50-100 km width belt to protect the headwaters of the rivers (Figure 1b and Appendix S1).

Brazil can borrow from the somewhat successful Amazonia's policy playbook, where political will, enforcement of legislation, expansion of the protected area system, and monitoring systems helped reduce deforestation rates, at least temporarily (Arima, Barreto, Araújo, & Soares-Filho, 2014; Nolte, Agrawal, Silvius, & Soares-Filho, 2013). The Cerrado is a hotspot for biodiversity conservation (Myers, Mittermeier, Mittermeier, Da Fonseca, & Kent, 2000), but laws and policies (e.g., forest code, environmental licensing) continue to favor agricultural expansion and dam construction in the Cerrado. Compounding matters further, the recently elected Brazilian president promised to streamline environmental licensing requirements and, at the same time, has appointed representatives of the agricultural caucus to lead environmental agencies.

Brazil should no longer ignore the Cerrado's environmental value and should strongly invest in conservation (and monitoring) of the remnants of such a devastated biome. A few actions to foster conservation of Cerrado biome, its hydric resources, and freshwater diversity are synthesized in Table 1.

The maintenance of Cerrado's water resources will require concerted efforts from the different stakeholders who benefit from the many environmental services the Cerrado provides. The effective and combined implementation of the Araguaia-Banal Corridor, the Araguaia Corridor of Diversity, and the Arc of the Headwaters is, therefore, a priority. If business as usual continues, the Cerrado freshwater ecosystems may never rebound, and society will lose ecosystem services provided by rivers (e.g., depreciated water stocks and polluted water). Time to save the remaining Cerrado and its rivers is running out, and urgent action by the Brazilian federal government, states, and the civil society to halt the current environmental degradation is required.

TABLE 1 Major threats, consequences, benefits, and costs of the business as usual scenario in the Cerrado biome, and a few actions to foster conservation and prevent terminal impacts on the Cerrado's freshwater biodiversity and water resources

Threat	Consequences	Benefits of BAU	Societal costs of BAU	Policy Recommendations
Deforestation of Cerrado and increasing share of agriculture within basins	<p>a. Hydro-physical impacts: decrease of evapotranspiration, increase of run-off, increase of soil erosion, fluvial incision & gullies in upper basins, increase of sediment yields, reduction of woody debris and organic content in rivers, fluvial metamorphosis, modification of sedimentation rates and sediment fluxes in main fluvial systems.</p> <p>b. Increased pollution through fertilizers and pesticides. Eutrophication. Loss of consumptive water.</p> <p>c. Biodiversity loss. Stream habitat simplification. Terrestrial primary productivity as a source of energy to riverine foodwebs is prevented.</p>	<p>Cropland expansion, higher agricultural production.</p> <p>Increase in commodities revenues.</p>	<p>a) Streamflow and water storage reduction.</p> <p>b) Loss of native species and ecosystem services -extinction or lower abundances and diversity of aquatic and riparian invertebrates, fishes and vegetation.</p> <p>-loss of spawning and resting sites for fishes and aquatic invertebrates.</p> <p>-biotic homogenization.</p> <p>-reduction in microhabitat diversity.</p> <p>-decrease of primary production of aquatic plants.</p> <p>-less energy uptake available to riverine community.</p> <p>c) Water pollution.</p>	<p>a) Payments for ecosystem services.</p> <p>b) Enforcement of protection laws for riparian forests and other wetlands.</p> <p>c) Arc of the Headwaters. Araguaia-Bananal Corridor.</p> <p>d) Identification of critical zones for the potential development of new areas of conservation.</p> <p>e) Identification at basin scale of critical minimum sustainable thresholds of vegetation cover/land use to support environmental functionality.</p> <p>f) Foster production on past-converted properties.</p>
Surface water withdrawal for irrigation	Reduction of water flow and volume in rivers.	Increased crop production and reduction in crop losses due to droughts.	Increase water shortage.	<p>a) Arc of the Headwaters.</p> <p>b) Enforcement of state and federal water resources-environmental laws. c) Improvements in the licensing process for irrigation.</p>
Building planned dams in free-flowing rivers	<p>a) Reduction of flow variability.</p> <p>Modified hydrological regimes.</p> <p>Deterioration of water quality, decrease of sediment fluxes and morphological/morphodynamics changes.</p> <p>Loss of floodplain area and dynamics.</p> <p>b) Blocking/decrease of aquatic connectivity, fish migration, and dispersal.</p> <p>Invasion of exotic species and reduction of fertility in riparian environments.</p>	Increase in energy generation.	<p>a) Decrease of native fishing stocks. Native fish species loss.</p> <p>b) Terrestrialization of floodplains and loss of alluvial forest and riparian vegetation diversity.</p>	<p>a) Araguaia-Bananal Corridor.</p> <p>b) Optimization of hydropower potential on already highly fragmented rivers.</p>

Note: The content is based on references and evidence described throughout the paper and personal insights.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHORS' CONTRIBUTION

E.M.L. initiated this research and coordinated the manuscript. All authors extensively contributed to the writing and analysis of results. M.E.F. and S.H.N. performed Geographic Information System analysis and figure.

DATA ACCESSIBILITY STATEMENT

The data included in this work is open access, including Appendix SI.

ETHICS STATEMENT

The authors declare that this manuscript is not published elsewhere.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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