Research, Society and Development, v. 13, n. 2, e5013244976, 2024
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v13i2.44976

The impact of climate change on piracema and the sustainability of aquatic resources

O impacto das mudanças climáticas na piracema e a sustentabilidade dos recursos aquáticos

El impacto del cambio climático en la piracema y la sostenibilidad de los recursos acuáticos

Received: 01/29/2024 | Revised: 02/09/2024 | Accepted: 02/11/2024 | Published: 02/14/2024

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Abstract
The impact of climate change on piracema and the sustainability of aquatic resources are essential topics in riverine conservation. Piracema refers to the reproductive period of fish, during which they masse migrate to specific locations for spawning. Thus, climatic variations altering environmental conditions directly affect this vital cycle. This study addresses the implications of these changes, emphasizing the vulnerability of the mentioned phenomenon and delineating its repercussions on aquatic biodiversity. Through scientific articles and academic works, it was analyzed that temperature elevation, irregular rainfall patterns, and extreme climatic events can compromise the migration and successful reproduction of fish. Therefore, conservation strategies, including community engagement, infrastructure adaptation, and continuous scientific research, are essential to mitigate these impacts. The sustainability of aquatic resources depends on a delicate balance between preserving piracema and active participation in adaptive management, fostering a healthy coexistence between riverine ecosystems and human communities.
Keywords: Ecological adaptation; Riverine biodiversity; Aquatic ecosystems; Sustainable management; Environmental changes.

Resumo
O impacto das mudanças climáticas na piracema e a sustentabilidade dos recursos aquáticos são temas essenciais na conservação fluvial. A piracema refere-se ao período reprodutivo dos peixes, durante o qual eles migram em massa para locais específicos a fim de desovar, sendo assim variações climáticas que alteram as condições ambientais irão afetar diretamente esse ciclo vital. Este estudo aborda as implicações dessas mudanças, destacando a vulnerabilidade do fenômeno citado e delineando suas repercussões na biodiversidade aquática. Através de artigos científicos e trabalhos acadêmicos, analisou-se que a elevação da temperatura, padrões de chuva irregulares e eventos climáticos extremos podem comprometer a migração e a reprodução bem-sucedida dos peixes, assim estratégias de conservação, incluindo o engajamento comunitário, adaptação de infraestruturas e pesquisa científica contínua, são essenciais para mitigar esses impactos. A sustentabilidade dos recursos aquáticos depende do equilíbrio entre a preservação da piracema e a participação ativa na gestão adaptativa, promovendo uma coexistência saudável entre ecossistemas fluviais e comunidades humanas.
Palavras-chave: Adaptação ecológica; Biodiversidade fluvial; Ecossistemas aquáticos; Gestão sustentável; Mudanças ambientais.

Resumen
El impacto del cambio climático en la piracema y la sostenibilidad de los recursos acuáticos son temas esenciales en la conservación fluvial. La piracema se refiere al periodo reproductivo de los peces, durante el cual migran en masa a lugares específicos para desovar. Por lo tanto, las variaciones climáticas que alteran las condiciones ambientales afectan directamente este ciclo vital. Este estudio aborda las implicaciones de estos cambios, destacando la vulnerabilidad del fenómeno mencionado y delineando sus repercusiones en la biodiversidad acuática. A través de artículos científicos y trabajos académicos, se analizó que el aumento de la temperatura, los patrones irregulares de lluvia y los eventos climáticos extremos pueden comprometer la migración y la reproducción exitosa de los peces. Por lo tanto, estrategias de conservación, incluyendo la participación comunitaria, la adaptación de infraestructuras y la investigación científica continua, son esenciales para mitigar estos impactos. La sostenibilidad de los recursos acuáticos depende de un delicado equilibrio entre la preservación de la piracema y la participación activa en la gestión adaptativa, promoviendo una convivencia saludable entre los ecosistemas fluviales y las comunidades humanas.
Palabras clave: Adaptación ecológica; Biodiversidad fluvial; Ecosistemas acuáticos; Gestión sostenible; Cambios ambientales.

1. Introduction

Piracema, an inherently linked phenomenon to the reproductive cycle of fish, represents a crucial component in the dynamics of aquatic ecosystems, serving as a catalyst for the maintenance and renewal of river populations (Leira et al., 2018). However, this complex ecological web is currently subjected to an imminent and concerning threat: climate change, whose contemporary manifestations are significantly reconfiguring the environmental variables that, throughout history, have meticulously orchestrated the piracema phenomenon (Robinson et al., 2009; Crozier & Hutchings, 2014).

As contemporary climate imperatives assert themselves, outlining a landscape of uncertainty for river ecosystems, piracema emerges as a particularly susceptible phenomenon (Peer & Miller, 2014). Gradual increases in average water temperatures result in significant alterations in fish physiology, directly influencing their behavioral patterns and, consequently, reproductive success during such periods (Parisi et al., 2022). Paradoxically, while the quest for ideal spawning grounds becomes more challenging, increased rainfall intensifies the risks associated with extreme weather events, such as sudden floods and abrupt variations in water levels, imposing additional obstacles to upstream migration (Das et al., 2012; Patrick et al., 2016). This complex panorama of climate change reverberates through the intricate trophic web of river ecosystems, as fish populations face adversities, and organism's dependent on their presence as a primary food source, along with predators at higher trophic levels, are confronted with feeding challenges and the need to recalibrate their ecological niches (Sabo et al., 2009; Ward et al., 2023).

The continuation of this challenging scenario suggests direct and indirect implications for riverine biodiversity. An example of this is the aquatic avifauna, whose species dependent on ichthyofauna as a primary food source during the reproductive period may face nutritional deficits, compromising reproductive health and, by extension, the populations of these birds (Morais, 2008). In the same context, riverine mammals, such as otters and dolphins, which include fish in their essential diets, encounter considerable feeding challenges due to the reduction in the availability of their traditional prey; these dynamic prompts the search for alternative food sources or potentially intensifies competition for scarce resources (Giuliani et al., 2022). The shift in migratory patterns of these animals during piracema also reverberates in aquatic macroinvertebrates, which often rely on the presence of fish for the dispersal of their eggs; this alteration has the potential to trigger changes in the populations of these organisms, causing cascading effects in food chains and associated ecosystem services (Solis-Murgas et al., 2011; Fernandes et al., 2016).

Finally, the implications extend beyond the biological realm, directly impacting human communities that historically depend on fishing during piracema (Braga et al., 2008). The decline in fish populations can pose economic and social challenges, compromising food security and the livelihoods of these communities (Pena Gomez, 2014; Ribeiro et al., 2015). Such complexities require an interdisciplinary approach in formulating adaptive conservation strategies that not only safeguard target species but also consider the intricate networks of interdependencies defining river ecosystems.

In this context, this literature review proposes an analysis of the interaction between climate change and piracema, highlighting not only the intrinsic vulnerability of the phenomenon but crucially delineating the implications for riverine biodiversity. A profound understanding of these connections is of paramount importance for the formulation of effective conservation and management strategies that transcend the protection of a singular biological manifestation and aim for the holistic preservation of ecological diversity.

2. Methodology

The present study constitutes a comprehensive review on the theme of "piracema" and the impact of climatic effects on this phenomenon. The review encompassed various sources, including scientific articles, monographs, theses, and dissertations available in databases such as Capes (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), Scielo

(Scientific Electronic Library Online), and Google Scholar. To ensure quality and relevance, studies without abstracts, those not addressing the study theme, as well as opinion articles lacking research data support or a systematic data collection approach, were excluded.

3. Contextualization of Piracema and Considerations on Fish Physiology During the Phenomenon

Originating from the Tupi-Guarani language, "piracema" translates to "fish migration," denoting the upstream migration of various species to specific spawning areas, typically in the headwaters of rivers. This event, which occurs seasonally in response to environmental stimuli, constitutes a complex and vital evolutionary process for the sustainability of ichthyological populations (De Sousa, 2014; Leira et al., 2018).

Among the protagonists of this migratory journey, the golden dorado (*Salminus brasiliensis*) stands out, an imposing fish found in South American rivers. During piracema, the golden dorado undertakes a challenging migration in search of specific spawning locations (Della Flora et al., 2010). Another notable species is the piraputanga (*Brycon hilarii*), commonly found in the rivers of the Paraguay River basin (Andrade & Yasui, 2003). The lambaris, belonging to the *Astyanax genus*, found in tropical rivers in Brazil and of modest size, migrate to ensure reproductive success. Even in their apparent simplicity, they contribute significantly to the dynamics of freshwater ecosystems (Pereira, 2007).

The physiology of these animals during the event is an essential component to understand the adaptive complexities of this phenomenon. Behavioral adaptations, primarily, play a central role in this narrative, as migratory fish not only adjust their feeding and movement behaviors but also recalibrate their migration routes in response to changes in environmental conditions, allowing them to explore and adapt to dynamic environments (De Moura & Val, 2019). Additionally, hormonal responses emerge as protagonists in these physiological narratives, as reproductive hormones such as gonadotropin trigger complex biological processes, synchronizing gonadal maturation and gamete production (Pereira, 2007; Honji et al., 2020). Metabolic adjustments, in turn, outline the third layer of this physiological fabric. In the study by Portella and colleagues (2021), aspects related to the reproduction of seven fish species in the Sorocaba River, the main tributary on the left bank of the Tiete River, were examined, playing a crucial role in preserving fish communities in the middle segment of this river system. The studied species included: *Astyanax lacustris*, *Psalidodon fasciatus*, *Megaleporinus obtusidens*, *Parodon nasus*, *Prochilodus lineatus*, *Salminus hilarii* and *Triportheus nematurus*. The study revealed a significant correlation between the capture of species and climatic parameters. It was also found a significant correlation between the stages of maturation and maturity of the species, temperature, and rainfall. This highlights the influence of these factors on the regulation of the reproductive cycle in the examined locations. Consequently, it was concluded that migratory species, such as *P. lineatus* and *S. hilarii*, showed their peak reproduction during the river's flood period. Increases in water temperature, a frequent marker of climate change, can directly impact the metabolism of fish (Nabi et al., 2014). Adaptive mechanisms, such as the regulation of metabolic rate and the optimization of energy efficiency, become imperative to meet the intensified energy demands associated with migratory efforts and reproductive activities (Ueda & Yamauchi, 1995; Yeşilbaş & Oğuz, 2022). Practical examples of these adaptations abound in Brazilian rivers, where, for instance, the golden dorado can adjust its feeding behavior to ensure the necessary energy reserve for migration (Portella et al., 2021). Simultaneously, piraputanga can synchronize its reproductive cycles with changes in environmental conditions, optimizing the chances of reproductive success (Monteiro et al., 2007).

In the intricate scenario of piracema, the mentioned animals embark on epic journeys, overcoming natural challenges such as rapids and waterfalls in search of suitable environments for their reproduction. However, in the face of current climate change, the ecological integrity of this delicate process is being severely threatened as the environmental variables historically responsible for orchestrating this reproductive symphony undergo adverse transformations (Robinson et al., 2009; Crozier & Hutchings, 2014).

Changes in rainfall patterns, for example, can result in modifications to river water levels, directly affecting the accessibility of spawning grounds. Sudden floods, driven by extreme weather events, can submerge crucial reproduction areas, compromising the viability of eggs and larvae and thus reducing reproductive success rates (Bem et al., 2021). A study by Röpke and colleagues (2022) on abnormal hydroclimatic events in the Amazon over the last two decades, impacting fish reproduction patterns, found that the effects of changes in hydrological conditions and fishing practices affected the reproduction and demographic parameters of the 16 most common fish species in flooded areas. The study revealed a reduction in the proportion of mature females after prolonged dry periods and abrupt increases in water levels. Many species also showed a progressive reduction in the size of mature females, average size of mature females, and the abundance of larger mature females. These effects were observed in both fished and non-fished species, indicating a widespread impact on fish populations. Another point is the increase in water temperatures, a direct manifestation of climate change, which can accelerate the metabolism of fish, influencing the critical timing of migration and reproduction (Pankhurst & Munday, 2011; Dadras et al., 2017). This acceleration is sometimes not synchronized with the biological cycles of the organisms that make up the river food chain, leading to imbalances in food availability and consequently negatively impacting species dependent on these migratory fish. Thus, climate change not only threatens to alter the physical dynamics of watercourses during piracema but also triggers cascading effects that reverberate throughout the aquatic food chain.

4. Impacts on Human Communities Dependent on Fishing During Piracema

Contemporary climate changes introduce a narrative of uncertainties and challenges, thereby imposing direct and multifaceted impacts on local riverine communities dependent on fishing. Much of this is due to the reduction in the availability of fishery resources during the phenomenon, emerging as a central point of concern (Santos & Santos, 2005; De Oliveira Barbosa et al., 2017). As climate patterns become more unpredictable, fish migrations, historically synchronized with the seasons, undergo alterations, resulting in a decrease in animal catches during critical periods, negatively affecting the subsistence and economy of these fishing-dependent communities (Zuanon et al., 2021).

The decrease in fish catches during the piracema period not only poses a threat to the food security of these riverine communities but also casts shadows over the foundations of their traditional livelihoods. This is because fishing activity, often rooted in cultural practices and transmitted across generations, is not merely a source of food but constitutes the economic backbone of these communities (Agostinho, Pelicice, Gomes, 2008). Any reduction in fish supply during this critical period deeply reverberates in the financial stability of these populations, impacting not only subsistence dynamics but also the social and cultural cohesion intrinsically linked to the ancestral practice of fishing (De Oliveira Barbosa et al., 2017).

The reverberation in financial stability resulting from the reduction in catches extends beyond the individual scope, affecting the community as a whole. Fishing, often carried out cooperatively, represents not only a source of income for individual fishermen but also fuels an interconnected local economic network (Castro & McGrath, 2003). Fish scarcity, therefore, not only compromises individual livelihoods but also threatens broader economic sustainability, generating ripples of economic challenges that extend throughout the community (Woodhead et al., 2018; Rogers et al., 2019).

The outlook for the food and nutritional security of these communities can be profoundly influenced by changes in fishing dynamics during piracema. In many regions, fish is not just a source of essential proteins but also a rich reserve of vital nutrients. The reduction in fish availability during this critical period can trigger a cascade of nutritional challenges, significantly impacting vulnerable groups, especially children and pregnant women (Jacob et al., 2001). Besides being a high-quality protein, fish is often a significant source of omega-3 fatty acids, vitamins, and essential minerals, all contributing to healthy development and overall well-being (Bogard et al., 2017; Boyd et al., 2022). The decrease in fish availability during piracema, therefore, not only compromises protein intake but also deprives these communities of a valuable source of essential

micronutrients (Rogers et al., 2019).

Children in the growth phase and pregnant women emerge as particularly susceptible groups to nutritional deficiencies resulting from fish scarcity (Starling et al., 2015). During critical periods of development, such as childhood and pregnancy, the demand for nutrients is exponentially high, and the lack of access to a nutrient-rich fish-based diet can result in deficiencies of iron, folic acid, and other essential substances, impacting the cognitive development, immune system, and overall health of these vulnerable groups (Bloomingdale et al., 2010). Additionally, it is noted that the long-term impact of nutritional deficiencies can perpetuate an intergenerational cycle of poor health, as children facing nutritional deficiencies during their development are more likely to experience health challenges throughout their lives, and pregnant women facing these deficiencies may transmit these vulnerabilities to their future generations (Browne et al., 2006).

In summary, the impacts on human communities dependent on fishing during piracema transcend the economic sphere, permeating food security, socio-economic stability, and the preservation of traditional ways of life. A comprehensive understanding of these impacts is essential to inform adaptation policies, promote sustainable subsistence strategies, and ultimately ensure the resilience of these communities in the face of ongoing climate change.

5. Conservation and Management Strategies to Alleviate the Effects of Climate Change on Piracema

As we project into the future, various promising perspectives and challenges emerge in the quest for sustainability, where technological advancements and innovative strategies can shape the landscape of river ecosystem conservation (Peer & Miller, 2014). A deeper integration of advanced climate modeling is essential to anticipate and respond to changes in environmental conditions, with systems predicting not only shifts in average temperatures but also rainfall patterns and extreme weather events providing a holistic view of the impact of climate change on piracema. This proactive approach allows for the implementation of adaptive conservation strategies and sustainable management of aquatic resources (Isaak et al., 2012; Sung et al., 2014).

Advancements in monitoring technology, such as remote sensors, drones, and artificial intelligence techniques, offer non-intrusive and effective methods to monitor fish migratory patterns, habitat conditions, and even water quality (Ficke et al., 2007; Radinger et al., 2019). Such tools enable a more detailed and real-time understanding of river dynamics, providing a solid foundation for informed decision-making.

The promotion of ecosystem connectivity emerges as a fundamental perspective. Strategies aiming to restore river corridors and implement fish passages in artificial barriers are crucial to facilitate successful migration and reproduction during piracema (Frederico et al., 2021). This approach, coupled with a deeper understanding of the specific needs of different species, contributes to the preservation of biological diversity (Geraldes et al., 2019).

In the face of growing environmental pressures, the assessment and adaptation of existing infrastructure, such as dams and reservoirs, become imperative to mitigate adverse impacts on fish migration and reproduction during this crucial period (Moura Júnior et al., 2011). The implementation of fish ladders and adaptable gates preserves the integrity of water bodies and also ensures essential connectivity between different stretches of rivers. This introduction, for example, provides a safe and effective passage, allowing species to overcome artificial obstacles, as these structures facilitate both upstream and downstream migration, essential for reproduction, and minimize the impact of human barriers on the genetic diversity of fish populations (Agostinho et al., 2005). The implementation of adaptable gates provides greater flexibility in water flow management, replicating more natural patterns that favor piracema (Mormul et al., 2010). This approach is not limited to the mitigation of environmental impacts but also aims to promote the sustainability of human activities associated with these infrastructures. The design and adaptive management of dams can balance hydroelectric energy production with the

conservation of river ecosystems, resulting in lasting benefits for communities dependent on these resources (Pegorini et al., 2005; Tundisi, 2007). Therefore, by aligning infrastructure with ecological needs, a symbiosis is sought that preserves both the functionality of structures and the integrity of ecosystems.

Community engagement emerges as another essential pillar in piracema conservation strategies. By actively involving fishermen, riverine communities, and other local stakeholders, a network of partnership is created that promotes mutual understanding and empowers communities to play an active role in preserving aquatic resources (Mielke & Pegas, 2013). The promotion of sustainable fishing practices, rooted in traditional and scientific knowledge, is a tangible outcome of this engagement (Medeiros et al., 2018). Communities, becoming guardians of their own resources, contribute to building a more resilient environment, spreading knowledge, and driving the co-creation of solutions (Waldez et al., 2013). The active inclusion of communities in the decision-making process, considering their needs and perspectives, results in more contextualized and sustainable conservation strategies. Examples include educational programs, workshops, and regular dialogues that facilitate the exchange of knowledge, strengthening awareness of the importance of piracema and the positive impact of sustainable practices (Bulhões et al., 2013). It's worth noting that by establishing a relationship of trust and partnership, community engagement can also catalyze sustainable economic initiatives. The development of alternative livelihoods that do not rely solely on indiscriminate fishing encourages environmental conservation as a means to ensure the well-being of communities (Lourenço & Guimarães, 2006; Lopes & Brito, 2021). Thus, community engagement transcends the role of a mere spectator, becoming an active agent in building innovative solutions to environmental challenges.

Finally, it is emphasized that continuous scientific research forms a robust foundation for the evolution and ongoing improvement of conservation strategies. Continuous immersion in scientific investigations allows for a meticulous analysis of fluctuations in climate patterns, hydrological dynamics, and species behavior during this critical period of reproduction (Camponogara et al., 2008; Cerati & Lazarini, 2009). Meticulous data collection, combined with rigorous assessments, not only specifically identifies the threats faced by fish populations but also enables a dynamic and informed adaptation of preservation strategies. Furthermore, continuous research fosters the discovery of innovative approaches, promoting active collaboration among scientists, environmental managers, and local communities. This synergy of knowledge not only enriches the understanding of the challenges faced but also inspires the development of sustainable and adaptable solutions (Chaves et al., 2013; El Tugoz et al., 2017). By fostering a culture of continuous learning, scientific research not only illuminates the complexities of river ecosystems in the face of environmental changes but also provides valuable insights to guide effective conservation policies and practices, aiming for long-term preservation and fortifying resilience against the dynamic challenges of the environment.

6. Final Considerations

In summary, understanding and addressing the impacts of climate change on the piracema are essential to ensure the sustainability of aquatic resources. The implementation of conservation strategies, such as community engagement, infrastructure adaptation, and continuous scientific research, plays a crucial role in this process. By promoting sustainable practices and harmonious coexistence between local communities and river ecosystems, we can aspire to a future where the piracema and aquatic resources are preserved, ensuring the health of rivers and the vitality of fish populations for future generations.

Acknowledgments

Thanks to FUNADESP - Fundação Nacional de Desenvolvimento do Ensino Superior Particular, nº 025/2023, Talents for Teaching Science - Veterinary Medicine 2023/2024, providing support to carry out the research.

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