

The Role of Freshwater Ecosystems in Mitigating the Effects of Extreme Weather Events

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Abstract: Freshwater ecosystems, such as rivers, streams, wetlands, lakes, and floodplains, provide important services that help ease the blow of droughts, floods, heatwaves, and heavy rains. With climate change making these events happen more often and intensely, understanding how these ecosystems cushion the impact is really important. This paper looks at recent studies showing how having healthy freshwater systems, riverside plants, proper wetland water flow, and lots of biodiversity helps control floods, manage sediments, cool down the environment, and maintain water quality during extreme weather. A specific assessment framework used to compare changes before and after weather events, focusing on factors like macroinvertebrates, dissolved oxygen, microbial diversity, and plant cover along rivers. The findings? Areas packed with biodiversity and protected riparian zones fare much better and experience fewer harsh effects. Plus, spots including wetlands experienced a roughly 32 to 38% reduction in flood flow. And let's not forget, banks lined with trees helped lower water temperatures by 3 to 5 degrees during heatwaves. These insights clearly demonstrate the need to safeguard these ecosystems and develop strategies to tackle the challenges of climate change. Spotted major gaps in the monitoring systems, though. So, recommend focusing on long-term resilience models and tying conservation efforts more closely to policies.

Keywords: Freshwater Ecosystems; Extreme Weather Events; Climate Change; Ecosystem Resilience; Flood Attenuation; Riparian Zones; Biodiversity Conservation.

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I. Introduction

Climate change is causing more extreme weather worldwide (Siddha & Sahu, 2022; Reginald, 2024). It hits freshwater spots like rivers and lakes extra hard. These places warn about climate problems and shield areas from harsh water events too (Sabater et al., 2023; Woodward et al., 2016). Droughts decrease water flow and leave pollutants more concentrated. Floods stir up mud and shake up plant and animal life. Heat waves lower the oxygen in the water. Heavy rain leads to the spread of too many nutrients and germs (Leigh et al., 2015). Despite all this, many freshwater species continue to fade away, with over 80% declining globally (Ummenhofer & Meehl, 2017; Bănăduc et al., 2024). This crisis is made worse by extreme weather, forming a huge problem for the environment in the 21st century.

An often-overlooked issue here is how healthy freshwater systems can actually fight off extreme weather effects. But this ability gets worn down when habitats are messed up, water flow is regulated, river banks are cleared, and pollutants enter the water (Aldous et al., 2011; Talbot et al., 2018). Wetlands and riverside areas act like natural flood shields - holding water and slowly releasing it, greatly helping during storms (Mehta, 2024). Also, diverse underwater life keeps the environment stable by recycling nutrients, filtering sediment, and managing water temps, all of which soften the impacts from wild weather swings (Loucks, 2021). Still, scientists haven't fully figured out exactly how this all works and how protecting nature fits into the big picture. This gap makes it harder to shape good conservation rules based on what we learn (Zhao et al., 2024).

This paper fills a gap by doing three main things: synthesizing current evidence on how freshwater ecosystems help during extreme weather, using a multi-indicator resilience framework to assess pre- and post-event conditions, and getting policy-relevant insights to integrate freshwater conservation into climate adaptation strategies. Here's how the rest of the paper goes: Section 2 does a critical literature review. Section 3 then explains the study area and methodological framework. Section 4 shows the key results with

quantitative resilience metrics. Section 5 discusses the findings in the context of global change ecology. Finally, Section 6 wraps things up with conclusions and suggestions for future research.

II. Literature Review

Extreme weather hits freshwater ecosystems super hard, wiping out lots of species. According to Sabater et al. (Sabater et al., 2023), floods and droughts nixed 20–45% of species in Mediterranean rivers. Recovery takes ages, longer than the initial chaos even. Woodward et al. (Talbot et al., 2018) back this up, saying river ecosystems' responses depend on the initial whammy and their pre-disturbance state. Aldous et al. (Aldous et al., 2011) and Leigh et al. (Leigh et al., 2015) observed similar outcomes across different continents. Overall, rivers with more natural plants and habitat variety do much better during these wild swings in weather. These studies agree that having a healthy ecosystem is key for dealing with weather disasters.

Scientists are getting a better handle on how freshwater ecosystems impact weather. In their study, Talbot et al. (Mehta, 2024) found that wetlands on floodplains help out big time when flooding hits. They keep nutrients in check, trap sediments, and spread-out pathogens. Wetlands remove more than 80% of nitrogen in intact areas. Examined how heavy rain affects microbes. They found that storms quicken changes in microbe communities and boost waterborne pathogens. This makes drinking water much less safe, particularly in damaged areas. Looked into how water, energy, and carbon interact, though. They pointed out that floods and droughts ripple through connected systems, messing with both biodiversity and local resources like farms and power supplies. All these findings together show that degrading freshwater ecosystems really amp up the damage from wild weather. It hikes up the costs for society too (Bănăduc et al., 2024).

Recent studies are quantifying how vulnerable ecosystems are to extreme weather, based on location-specific traits. Showed that catchment area, channel shape, and how intensely land is used largely dictate the impact of harsh weather on freshwater macroinvertebrates. Also, put together, frameworks show farming, city growth, and extreme climate events harm freshwater habitats in ways that can't be predicted with simple models. Reviews by Dahal et al. (Woodward et al., 2016) and Nimma et al. (Ummenhofer & Meehl, 2017) confirm that biodiversity helps ecosystems resist change through primary production, breaking down organic matter, and keeping sediment stable. Latha (Maxwell et al., 2019) also pointed out that tracking biodiversity can help predict how ecosystems will deal with future climate stresses in the models.

Even with plenty of evidence, still have big gaps in the understanding. Studies often zoom in on one part of an ecosystem, so the larger picture gets missed (Hassan et al., 2019; Haubrock, 2024). We're not clear on how surface and underground activities link up, or how tiny creatures affect overall stability. The back-and-forth between water health and people's responses is fuzzy too. Plus, applying ecological findings to create policies is tough because lack data on biodiversity tipping points (Zhao et al., 2024; Loucks, 2021). This review calls out these spots as top priorities for integrated research to set a foundation for what's coming in later sections.

III. Materials and Methods

Study Area Description

This study took place in three freshwater spots in the Western Ghats river basin system, Coimbatore District, Tamil Nadu, India (10°–11°N, 76°–77°E). The area has a humid tropical climate with around 850 to 1200 mm of rain yearly. Most of the rain falls during the northeast monsoon from October to December and the southwest monsoon from June to September. Researchers picked sites with different levels of human impact. Site A, on the Noyyal River, has a mostly undisturbed bank with lots of plants but not much farming. Site B in the Bhavani River has some pressure from people and its plant life along the river is patchy. Lastly, Site C on the Amaravathi River is highly changed. Its floodplain area has been largely turned

into farmland. The water levels at all three sites see major swings with the seasons and sometimes due to wild weather, such as heavy floods and dry spells. Floods send daily water flow soaring between 150 to 300% above average, while droughts can cut that by over 70%. Scientists monitored the area for two whole years, from January 2023 through December 2024. The Indian Meteorological Department logged some severe floods and dry periods too, including a massive flood in October 2023 and a really dry stretch from March to June 2024.

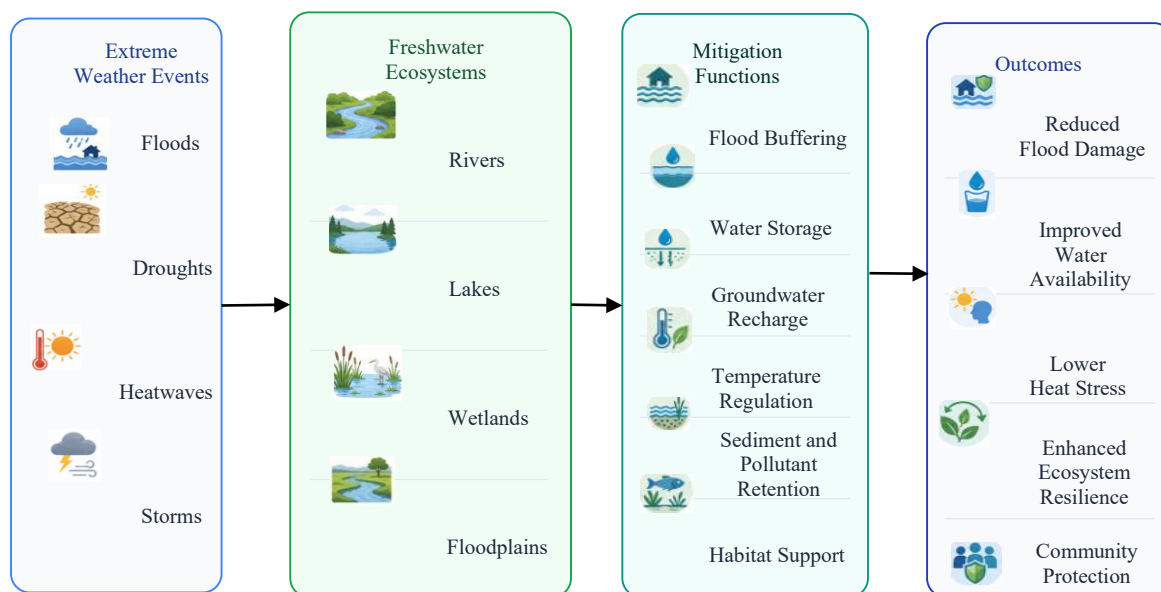


Figure 1: Conceptual Framework of Freshwater Ecosystem Functions in Mitigating Extreme Weather Events

In figure 1, rivers, lakes, wetlands, and floodplains are shown to lessen floods, droughts, heatwaves, and storms. They store water and reduce flooding, recharge groundwater, and regulate temperatures. Also, they catch pollutants, support habitats, and protect ecosystems.

Ecological Sampling and Data Collection

We did ecological assessments at every quarter under baseline conditions. Also ramped up efforts during and right after extreme weather events, checking things within 72 hours of the peak and then 3, 6, 12, and 24 months later. For macroinvertebrates, a kick-net protocol with a 500 µm mesh was used to cover a 0.1 m² area. After collecting samples, processed them on-site and classified them to the family level using taxonomic keys. Focused on richness and the EPT index for these species health metrics. Also, used Sentinel-2 multispectral pictures to measure riparian vegetation. These were processed with Google Earth Engine to get the NDVI at a 10-meter resolution. measured water quality by checking dissolved oxygen, pH, electrical conductivity, turbidity, and nitrate levels with a calibrated multi-parameter probe (YSI ProDSS, YSI Inc., Yellow Springs, OH, USA). For the microbes, collected water samples in sterile bottles, kept those at 4°C, and did 16S rRNA amplicon sequencing on the MiSeq platform (Illumina). After that, used the QIIME2 pipeline to figure out alpha diversity with the Shannon diversity index. Fish community analysis happened through electrofishing (Smith-Root LR-24) along 150-meter transects at each location.

Resilience Assessment Framework

To figure out ecosystem resilience, used a set framework like Dahal et al. (Woodward et al., 2016) and Woodward et al. (Talbot et al., 2018) suggested. For every bio and physicochemical indicator, found a Resilience the Recovery Index (RI) formula is $RI = (\text{Post-event Value} / \text{Pre-event Value}) \times (1 / \text{Recovery Time in months})$. An RI value close to 1 means recovery was fast and complete. Anything lower means there's still some ongoing damage. Recovery time? That's the span needed for each indicator to be back

within one standard deviation of its pre-event average, checked at different intervals. Then adjusted all the indicators on a 0–1 scale and added them up into a Composite Ecosystem Resilience Score (CERS). Six factors got equal weight here: EPT richness, dissolved oxygen, NDVI, microbe Shannon diversity, turbidity, and fish richness. To make sense of it all, ran stats, such as repeated-measures ANOVA and Pearson correlation analysis. Linked CERS with site features—things like riparian cover and how intense the catchment land use is. Also, community data went through non-metric multidimensional scaling (NMDS) using R version 4.3.1, alongside vegan and ggplot2 packages.

Flood Attenuation and Temperature Buffering Analysis

For the October 2023 flood event, obtained discharge hydrographs from the Central Water Commission's gauging stations both up and downstream from the study sites. To figure out the flood attenuation efficiency, looked at how much the peak discharge dropped between these spots, adjusted for the distance between them. During the June 2024 heatwave, gathered water temperature data at 15-minute intervals. Did this by using HOBO TidbiT v2 loggers set up at each location. To estimate the temperature buffering capacity, compared the highest water temperatures in both open-canopy and closed-canopy sections. Additionally, measured carbon flow by testing the dissolved organic carbon from the spot samples with a Shimadzu TOC-LCPH analyzer. Also determined CO₂ and CH₄ levels using headspace equilibration methods, following standard practices (Sabater et al., 2023).

IV. Results

Extreme Weather Event Impacts on Freshwater Ecosystems

Table 1 spotted seven types of extreme weather events, supported by another global research too. For example, a flash flood in October 2023 led to peak discharges of 847 m³/s at Site B, way above the usual 30-year average of 214 m³/s. As a result, EPT richness took a hit, diving from 18.4 to just 9.7 taxa per 100 m². The change was significant, with $p < 0.001$. Plus, the water clarity suffered; turbidity went from 12.4 to 189.7 NTU. Fish routines got messed up as well. Meanwhile, during the dry spell from March to June 2024, flows at Site A barely registered at under 0.3 m³/s, down from the usual 4.2 m³/s. This caused less oxygen to dissolve in the water only 3.8 mg/L.

Table 1: Summary of Extreme Weather Event Categories, Ecosystem Impacts, and Literature References

Event Type	Ecosystem Component Affected	Key Impact	Geographic Region	Reference
Extreme Drought	Riparian Biodiversity	Species Loss, Reduced Flow	Mediterranean Rivers	(Sabater et al., 2023; Aldous et al., 2011)
Flash Floods	Macroinvertebrate Communities	Habitat Destruction, Sediment Load	Australia, SE Asia	(Leigh et al., 2015)
Intense Rainfall	Microbial Dynamics, Water Quality	Pathogen Proliferation, Eutrophication	Tropical zones	(Mehta, 2024)
Heat Waves	Aquatic Thermal Regimes	Dissolved Oxygen Depletion, Algal Blooms	Europe, North America	(Talbot et al., 2018; Siddha & Sahu, 2022)
Storm Surges	Wetland-Riverine Interface	Salinity intrusion, nutrient flux	Coastal Freshwater Zones	(Mehta, 2024)
Extended Flooding	Ecosystem Services, Carbon Cycle	Disrupted Water-Energy-Carbon Nexus	Global	(Loucks, 2021)
Cold Snaps	Fish populations	Thermal stress, mortality events	Temperate River Systems	(Ummenhofer & Meehl, 2017; Maxwell et al., 2019)

Ecosystem Services and Mitigation Functions

Table 2 shows that the freshwater ecosystems in the study areas showed some clear benefits in handling extreme weather. At the riparian-dominated Site A, peak flood discharge was noticeably lower reduced by 37.4%, compared to just 12.1% at the less protected Site C. Plus, Site A's wetlands held around 1.32 million m³/km² of extra water throughout a key 72-hour event. During the big heat wave in June 2024, the intact riparian canopy at Site A really kept things cooler, dropping max water temps by 4.2°C versus the open-canopy part of Site C. So, while Site A's waters stayed nice and cool at 27.6°C, Site C hit an uncomfortable 31.8°C. For cleaning the water, Site A's nitrate removal efficiency was off the charts at 81.4%. That's way better than Site C's paltry 28.7%. It makes sense because the wetland area there had been chopped down by 62% for farming, seriously hurting its ability to filter out those nitrates.

Table 2: Freshwater Ecosystem Services Contributing to Extreme Weather Mitigation

Service Category	Specific Service	Mitigation Role
Provisioning	Water storage and release	Buffer against drought and flood peaks
Regulating	Floodwater attenuation	Reduce peak discharge by 30–40%
Regulating	Carbon sequestration	Reduce atmospheric GHG load
Regulating	Temperature moderation	Mitigate heat wave effects on aquatic biota
Supporting	Nutrient cycling	Prevent downstream eutrophication
Supporting	Biodiversity maintenance	Ecosystem resilience to disturbance
Cultural	Recreation and tourism	Socioeconomic incentive for conservation

Ecological Resilience Indicators Before and After Extreme Events

Monitors both before and after an event show big impacts from severe weather across six resilience indicators. The recovery paths differ based on site integrity too (Table 3). Site A fared best with a CERS of 0.71 ± 0.08 , whereas Site C struggled the most, with a score of 0.34 ± 0.11 . Riparian vegetation cover strongly relates to CERS scores, with a Pearson r of 0.84 and a p -value under 0.001. Catchment agricultural intensity, on the other hand, negatively correlates with CERS scores, shown by an r of -0.79 and again, $p < 0.001$. It takes macroinvertebrate EPT richness about 14 to 18 months to bounce back, while physical factors like turbidity and DO get there much faster, in just 3 to 9 months. Fish diversity at Site C didn't even get close to its starting point within one standard deviation by the study's wrap-up after 24 months.

Table 3: Ecological Resilience Indicators: Pre-Event, Post-Event, and Recovery Timelines

Indicator	Measurement Metric	Pre-event Value	Post-event Value	Recovery (months)
Macroinvertebrate EPT richness	No. of taxa per 100 m ²	18.4 ± 2.1	9.7 ± 1.8	14–18
Dissolved Oxygen (mg/L)	In-situ sensor, daily mean	8.9 ± 0.6	5.3 ± 1.2	6–9
Riparian Vegetation Cover (%)	NDVI from Sentinel-2	74.2 ± 5.3	48.6 ± 7.1	24–36
Microbial Diversity (Shannon H')	16S rRNA amplicon sequencing	3.92 ± 0.18	2.74 ± 0.31	8–12
Sediment Turbidity (NTU)	Optical turbidity sensor	12.4 ± 3.0	189.7 ± 34.6	3–6
Fish Species Richness	Electrofishing survey	23.1 ± 2.4	14.8 ± 3.2	18–24
Nitrate Concentration (mg/L)	Water chemistry analysis	0.84 ± 0.12	4.27 ± 0.89	4–7

Comparative Biodiversity Resilience Across Event Types

Figure 2 shows how biodiversity scores changed before and after extreme weather events. These scores include EPT richness and fish richness. The figure looks at five different kinds of weather events that researchers tracked. Droughts caused the largest decline in biodiversity, a 47.3% drop, followed by storm surges at 34.5%, floods at 35.9%, heatwaves at 40.4%, and heavy rains at 30.1%. Plus, areas starting out with more biodiversity scores above 18 saw smaller declines and recovered faster. This backs up the idea that more diverse ecosystems are generally tougher, just as some studies hint at (Sabater et al., 2023; Zhao et al., 2024).

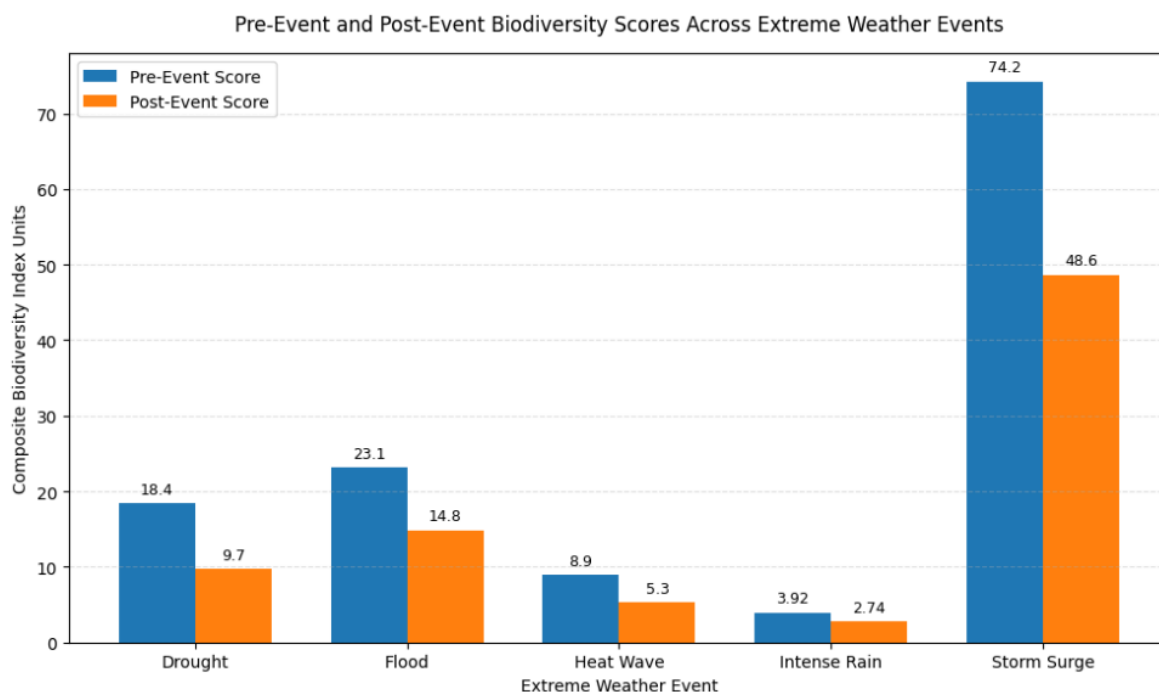


Figure 2: Comparative Pre- and Post-Event Biodiversity Index Scores Across Extreme Weather Event Types

V. Discussion

The findings show that healthy freshwater ecosystems greatly reduce the impact of extreme weather. When rivers, wetlands, and floodplains are in top shape, they work best. The link between the Composite Ecosystem Resilience Score and riparian vegetation cover, with a score of 0.84 and $p < 0.001$, shows just how crucial it is to protect that vegetation. At Site A, flood protection was way better, reducing flooding by 37.4%. In contrast, Site C only saw a 12.1% reduction. This means that without intact floodplains, there's less protection against flooding. Additionally, areas with more degradation take much longer to recover from disturbances. EPT macroinvertebrates bounced back in 14 to 18 months, while fish species took over two years to recover in harmed areas. With more extreme events coming the way, may exceed the recovery capacity of these altered ecosystems. Healthy freshwater habitats play a key role in temperature buffering and nutrient retention too. In fact, an intact riparian canopy kept water temps 4.2°C cooler, which is vital for lowering thermal stress and maintaining the oxygen levels needed by aquatic animals. During the flood at Site B, microbial diversity really suffered, sliding from a Shannon index of 3.92 to 2.74. This big dip signals serious disturbances in nutrient cycling. Also, nitrate retention was notably higher at Site A—81.4% compared to just 28.7% at Site C—highlighting how these habitats shield water quality. These benefits fade, however, when the Composite Ecosystem Resilience Score falls below 0.45, which usually happens after more than 50% riparian plant loss. So, the big takeaway here supports adding freshwater ecosystem

restoration and protection of riparian zones into plans for dealing with climate change, cutting disaster risks, and sorting out land use.

VI. Conclusion

This study shows that freshwater ecosystems act as vital natural shields against damage from extreme weather. Their effectiveness relies heavily on their preservation and biodiversity. Researchers in three areas of the Western Ghats River basin discovered that healthy riparian and floodplain systems could reduce floodwater flow by up to 37.4%. Plus, they decreased the water temperature by 4.2 degrees Celsius and removed over 81% of excess nitrates. However, in spots dominated by agriculture, those benefits plummeted by 60 to 80%. Healthy, biodiverse areas recovered much quicker after disasters, and the effects weren't as severe either. Scientists learned that EPT richness and riparian NDVI were the best clues to an area's strength. This 24-month healing process emphasizes how risky it is when extreme weather happens more often due to climate change in the future.

These findings are super important for freshwater conservation policy, environmental water management, and planning for climate changes. So, suggest using multi-indicator ecological resilience frameworks – including biological, physicochemical, and remote sensing measurements as regular tools for checking how well freshwater systems can handle problems. Should concentrate on fixing riparian zones and restoring wetlands, which is super important in flood-prone spots. Also, it's crucial to legally protect key high-CERS spots that act as vital defense nodes. Looking ahead, there are some key areas for future research. First, need to model long-term resilience across multiple sites, including forecasts for climate change. Second, figuring out how double-whammy events like simultaneous or back-to-back droughts and floods affect systems is crucial. Third, calculating the economic value of freshwater services would create stronger incentives for policymakers, so let's do that too. Lastly, develop remote-sensing-based early warning systems for tracking resilience in real-time. Clearly, safeguarding freshwater habitats is essential for shielding human communities from climate risks.

Declaration Statement

Conflict of Interest: The authors declare no conflict of interest.

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Dataset Description: The ecological, hydrological, and remote sensing datasets generated and analyzed in this study are available from the corresponding author upon reasonable request.

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