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"Effect of Climate Change on Distribution and Life Cycle of Fish Trematode Parasites"

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Abstract
Climate change is increasingly recognized as a key driver of ecological shifts in freshwater ecosystems, influencing host–parasite dynamics and disease transmission patterns. This study examined the effect of climate variability on the distribution and life cycle of digenetic trematodes infecting freshwater fishes in Eastern Uttar Pradesh, India. A total of 648 fish specimens belonging to *Channa punctata*, *Clarias batrachus*, and *Heteropneustesfossilis* were collected seasonally from six ecologically diverse sites. Prevalence, mean intensity, and abundance of trematode infections were calculated, while environmental parameters such as temperature, rainfall, dissolved oxygen, turbidity, and snail density were simultaneously monitored. Results revealed a significant seasonal pattern, with infection prevalence peaking during monsoon (71.8%) and declining to 43.6% in pre-monsoon. Statistical analysis demonstrated strong correlations between parasite prevalence and climatic variables, particularly rainfall ($r = 0.81$, $p < 0.01$) and snail density ($r = 0.86$, $p < 0.001$). Infected fishes exhibited reduced condition factors, suggesting sub-lethal impacts on host growth and health. Molecular identification using ITS1 and COI markers confirmed the presence of *Clinostomumcomplanatum*, *Allocreadiumhandiai*, and *Opisthorchis* sp., with phylogenetic clustering supporting host-associated haplotypes. The findings highlight that climate change alters trematode transmission cycles, posing ecological, fisheries, and public health concerns.
Keywords: Climate change, digenetic trematodes, freshwater fishes, parasite prevalence, snail hosts, monsoon variability, molecular identification, phylogenetics.

1. Introduction

Parasitism is one of the most pervasive biological interactions, shaping host populations, regulating ecosystems, and influencing biodiversity at multiple trophic levels. Among parasites of aquatic animals, digenetic trematodes are particularly significant because of their complex multi-host life cycles, high prevalence in freshwater systems, and considerable impacts on fish health and aquaculture production (Blasco-Costa & Poulin, 2017). These parasites typically involve aquatic snails as first intermediate hosts, fishes as second intermediate hosts, and birds or mammals as definitive hosts, making their transmission cycles highly sensitive to environmental variation. As a result, factors such as temperature, rainfall, and water quality strongly influence the development, survival, and infectivity of trematode stages (Poulin, 2006). In recent decades, the phenomenon of global climate change has emerged as one of the most important drivers reshaping ecological systems, including host–parasite interactions (Brooks et al., 2019). Climate warming, altered rainfall patterns, and hydrological disruptions are increasingly altering parasite transmission dynamics, raising questions about how freshwater trematodes will respond under shifting climatic conditions.

The importance of studying trematodes in freshwater fishes lies not only in their biological significance but also in their economic and public health implications. Many digenetic trematodes cause pathological lesions in fish organs such as the gills, intestine, and liver, thereby impairing respiration, nutrient absorption, and reproduction (Woo & Buchmann, 2012). Heavy infections can reduce fish growth rates, increase susceptibility to secondary infections, and lower survival, directly impacting fisheries and aquaculture productivity (Faltýnková et al., 2020). Moreover, some trematode species, such as *Opisthorchis* and *Clinostomumcomplanatum*, are zoonotic, posing food safety risks when humans consume raw or undercooked fish (Harvell et al., 2002). Understanding how climate change modifies the life cycles and distribution of these parasites is therefore crucial not only for biodiversity conservation but also for safeguarding food security and public health.

Climate change affects parasite ecology through both direct and indirect mechanisms. Rising temperatures can accelerate parasite development rates, increase cercarial emergence from snail hosts, and extend transmission seasons (Poulin, 2006). Conversely, extreme temperatures may disrupt parasite survival or desynchronize parasite–host interactions (Lafferty, 2009). Rainfall and flooding events enhance water connectivity, creating temporary habitats for intermediate hosts and facilitating parasite dispersal, while droughts reduce aquatic habitats and limit parasite transmission (Marcogliese, 2008). These effects are not uniform across all parasites or hosts; instead, species-specific responses create complex community-level shifts (Barber et al., 2016). For example, benthic-feeding fishes such as catfishes are more exposed to snail-borne trematodes, while carnivorous species often experience lower infection levels (Faltýnková et al., 2020). Consequently, climate change may restructure host–parasite networks, altering biodiversity and ecological stability.

The “thermal mismatch hypothesis” provides a theoretical framework for understanding climate-driven host–parasite dynamics. It suggests that parasites and their hosts respond differently to temperature changes, leading to conditions where parasites may thrive while hosts suffer reduced immunity or survival (Cohen et al., 2019). This hypothesis has been validated in amphibians, where climate-driven thermal mismatches facilitated disease outbreaks (Rohr & Raffel, 2010). Applying this model to fish–trematode systems suggests that warming waters may enhance parasite transmission at the expense of host resilience, thereby increasing disease risk in freshwater ecosystems. Such mismatches highlight the importance of integrating host physiology, parasite biology, and climate variability when analyzing disease dynamics.

Regional studies provide empirical evidence of seasonal and climate-driven variation in trematode infections. Research across freshwater systems indicates that trematode prevalence peaks during rainy or monsoon seasons, when snail intermediate hosts proliferate and water connectivity is highest (Chubb, 2019). For instance, in South Asia, monsoonal flooding creates vast temporary habitats that sustain dense snail populations, amplifying trematode transmission

(Kalantan& Al-Megrin, 2019). Conversely, prevalence typically declines during dry or winter periods, reflecting reduced host activity, lower snail abundance, and less favorable conditions for parasite larval survival. These seasonal cycles offer a natural analogue for long-term climatic shifts, suggesting that global climate change will magnify existing seasonal patterns and potentially extend transmission windows.

Beyond seasonal patterns, climate change influences the broader ecology of parasites through interactions with pollutants, habitat changes, and anthropogenic stressors. Warmer temperatures and eutrophication often enhance snail populations, indirectly supporting trematode development (Sures, 2008). Similarly, increased nutrient loads in rivers may fuel macrophyte growth, providing refuges for intermediate hosts and enhancing parasite survival. On the other hand, pollutants and habitat degradation may reduce intermediate host abundance or alter their distribution, shifting parasite life cycles and creating new ecological niches (Marcogliese&Pietrock, 2011). Thus, the impact of climate change on trematodes is best understood as part of a multifactorial system involving both abiotic and biotic stressors.

Advances in molecular parasitology have enriched our ability to track trematode responses to climate change. Techniques such as DNA barcoding using ITS1 and COI markers have enabled accurate identification of cryptic species and the detection of host-associated haplotypes (Tkach &Kudlai, 2016). Such molecular insights are particularly important given that many trematode species exhibit morphological plasticity influenced by environmental conditions (Kalantan& Al-Megrin, 2019). Molecular phylogenetic studies also reveal broader biogeographic patterns, showing how parasite lineages expand or shift under changing climates (Brooks et al., 2019). Integrating molecular approaches with ecological surveys therefore provides a comprehensive framework for assessing climate-driven changes in parasite distribution and life cycles.

Public health concerns further underscore the importance of studying trematodes under climate change scenarios. Several fish-borne trematodes are zoonotic, and warming waters combined with expanded aquaculture practices may enhance their prevalence in human food sources (Woo & Buchmann, 2012). For instance, *Opisthorchis* infections, which are linked to bile duct cancer in humans, are predicted to increase under warmer, wetter conditions that favor snail hosts (Harvell et al., 2002). The expansion of such parasites poses serious risks for rural communities dependent on freshwater fish as a protein source. Integrated studies that link parasitology with epidemiology and climate modeling are therefore urgently needed to address emerging zoonotic threats.

Global assessments by the Intergovernmental Panel on Climate Change (IPCC, 2021) reinforce the urgency of understanding biological responses to climate change, particularly in regions like South Asia where warming trends and erratic monsoon patterns are pronounced. For freshwater ecosystems, this means that parasite transmission cycles are likely to intensify, with increased prevalence and broader geographic ranges (Marcogliese, 2016). Host–parasite co-evolution may also accelerate, with parasites adapting more quickly than their hosts to shifting climates due to shorter generation times (Poulin & Leung, 2011). Such evolutionary dynamics may reshape host specificity, virulence, and ecological interactions, with profound implications for biodiversity and ecosystem health (Tkach &Kudlai, 2016).

2. Literature Review

Parasitic infections in freshwater fishes have long been recognized as significant ecological, economic, and public health concerns, with digenetic trematodes occupying a central role due to their complex life cycles and wide host range (Blasco-Costa & Poulin, 2017). The study of helminth parasites, especially trematodes, offers insights into host–parasite interactions, ecosystem health, and the influence of environmental variability on parasite transmission dynamics. Global climate change, characterized by increasing temperatures, altered rainfall patterns, and shifting hydrological cycles, has emerged as a major factor influencing the epidemiology of aquatic parasites (Brooks et al., 2019; Marcogliese, 2008). Within this framework, a growing body of research has examined how trematode parasites respond to climatic drivers, highlighting both direct and indirect pathways of influence on their life cycles and distribution.

The biology of trematodes is intricately linked to environmental conditions, particularly temperature and moisture, which regulate cercarial release, intermediate host availability, and parasite development rates (Poulin, 2006). Higher water temperatures accelerate cercarial emergence from snail hosts, thereby enhancing transmission opportunities to fish and other definitive hosts (Cohen et al., 2019). Conversely, extreme fluctuations in temperature or drought-like conditions can disrupt intermediate host populations, reducing parasite persistence in the ecosystem (Lafferty, 2009). Seasonal studies of helminths in freshwater fishes underscore the influence of climatic cycles, with parasite prevalence peaking during monsoon or rainy seasons when intermediate host density and water connectivity are highest (Chubb, 2019). These seasonal patterns serve as valuable analogues for understanding long-term climatic effects on parasite transmission.

Ecological models suggest that climate-driven changes in parasite prevalence are not uniform but species-specific, depending on host feeding habits, immune responses, and ecological niches (Poulin & Leung, 2011). For instance, benthic fishes such as catfishes show higher trematode intensities due to their constant interaction with snail-rich sediments, while carnivorous fishes often exhibit lower parasite burdens (Faltýnková et al., 2020). Similarly, trematode species vary in their sensitivity to temperature; some exhibit enhanced reproductive output under warmer conditions, while others may suffer reduced survival (Barber et al., 2016). Such species-specific responses indicate the potential for climate change to restructure parasite communities, altering biodiversity and ecological balance in freshwater ecosystems.

The ecological role of parasites extends beyond their immediate impact on host physiology. Parasites act as bioindicators of ecosystem stress, reflecting changes in environmental quality, pollution, and biodiversity (Marcogliese, 2016). Environmental parasitology has demonstrated that factors such as eutrophication and organic pollution, often exacerbated by climate change, indirectly elevate parasite burdens by supporting larger snail populations (Sures, 2008). In this context, trematodes provide a unique perspective on ecosystem responses to climatic pressures, serving both as stress markers and as agents influencing host population dynamics. For instance, high parasite loads in fish can reduce growth rates, alter reproductive output, and increase mortality, thereby impacting fisheries and aquaculture productivity (Woo & Buchmann, 2012).

A recurring theme in climate–parasite research is the role of host–parasite mismatches under altered climatic regimes. The "thermal mismatch hypothesis" posits that parasites and hosts may respond differently to temperature shifts, potentially increasing disease risk when parasites thrive under conditions suboptimal for hosts (Cohen et al., 2019). This has been observed in amphibians, where climate-induced shifts have exacerbated fungal and trematode infections (Rohr & Raffel, 2010). Similar mechanisms are likely operative in fish–trematode systems, with climate-induced stress reducing host immunity while simultaneously enhancing parasite reproductive success. Such mismatches highlight the complexity of predicting disease outcomes under climate change.

The influence of climate change on parasite transmission is also mediated through effects on intermediate hosts, especially aquatic snails, which play a pivotal role in trematode life cycles (Faltýnková et al., 2020). Warmer temperatures and increased rainfall often boost snail populations, thereby increasing opportunities for parasite development and transmission (Marcogliese&Pietrock, 2011). Conversely, pollution and habitat degradation, often linked to climate variability, may reduce snail abundance or shift their distribution, leading to altered parasite transmission pathways (Sures, 2008). In Eastern Uttar Pradesh and other parts of South Asia, these dynamics are particularly relevant, as seasonal flooding creates temporary habitats that can sustain large snail populations, fueling parasite outbreaks in fish (Kalantan& Al-Megrin, 2019).

Molecular and phylogenetic approaches have further advanced our understanding of trematode responses to climate change. DNA barcoding using ITS and COI markers has allowed for accurate species identification, uncovering cryptic diversity and enabling the tracking of parasite lineages across regions (Tkach &Kudlai, 2016). Such methods reveal that many trematode species previously thought to be localized may actually possess broader distributions, facilitated by changing climate and host migration patterns (Kalantan& Al-Megrin, 2019). Molecular tools also enable the detection of evolutionary responses to climate pressure, including the emergence of host-associated haplotypes that reflect adaptation to new ecological conditions (Brooks et al., 2019).

Beyond taxonomy, climate change influences the epidemiological patterns of parasites with zoonotic potential. Species such as *Opisthorchis* and *Clinostomumcomplanatum*, known to infect fish and humans, are particularly concerning in regions where fish form a dietary staple (Woo & Buchmann, 2012). Warmer temperatures and flooding may expand their distribution, heightening public health risks (Harvell et al., 2002). Integrated studies that combine parasitology, climate modeling, and public health frameworks are thus essential to anticipate and mitigate emerging threats.

Research also emphasizes the need to consider multiple stressors in combination with climate change. The interaction of rising temperatures with pollutants, habitat fragmentation, and invasive species can compound parasite impacts on fish health (Marcogliese&Pietrock, 2011). For instance, pollutants may weaken fish immune systems, making them more susceptible to infections, while climate-induced changes in water chemistry may favor parasite development (Sures, 2008). These combined stressors underscore the importance of holistic ecosystem-based approaches to fisheries management in the face of climate change.

The broader ecological implications of climate–parasite interactions extend to host–parasite co-evolution and biodiversity conservation. Trematodes and their fish hosts exemplify dynamic evolutionary relationships shaped by environmental pressures (Poulin & Leung, 2011). Climate change accelerates these dynamics, potentially driving shifts in host specificity, parasite virulence, and co-evolutionary trajectories (Tkach &Kudlai, 2016). Understanding these patterns is crucial not only for parasitology but also for broader questions of ecosystem resilience and adaptation under global change.

The literature highlights that climate change is a potent driver of shifts in trematode distribution, life cycle completion, and infection intensity in freshwater fishes. While warmer temperatures and increased rainfall generally enhance parasite transmission, extreme climatic events, habitat loss, and pollution may constrain parasite persistence in certain contexts (Marcogliese, 2008; Lafferty, 2009). The integration of ecological, molecular, and climatic perspectives offers a comprehensive understanding of these dynamics. Future research must focus on long-term monitoring, predictive modeling under IPCC scenarios, and interdisciplinary strategies that link parasitology with fisheries management and public health (IPCC, 2021). Such approaches will be essential to safeguard biodiversity, aquaculture sustainability, and food security in the face of accelerating climate change.

3. Methodology

The present study was designed to investigate the effect of climate change on the distribution and life cycle of digenetic trematodes in freshwater fishes by combining systematic field sampling, parasitological examination, environmental monitoring, and molecular analysis.

Fieldwork was conducted across six freshwater sites in Eastern Uttar Pradesh, encompassing rivers, floodplain wetlands, and aquaculture ponds to capture ecological diversity and climate variability. Fish specimens, primarily *Channa punctata*, *Clarias batrachus*, and *Heteropneustesfossilis*, were collected monthly for one year using cast nets, drag nets, and gill nets of varying mesh sizes to ensure representation across size classes and habitats. Immediately after capture, biometric data including total length and weight were recorded, and fishes were dissected under sterile conditions for the recovery of trematode parasites from gills, intestine, liver, and other visceral organs. Parasites were preserved in 70% ethanol for morphological examination and in 95% ethanol for molecular analysis. Morphological identification was performed using aceto-alum carmine staining, followed by morphometric measurements under a compound microscope equipped with an ocular micrometer, with taxonomic keys and published monographs used for species confirmation. In parallel, molecular methods were employed to validate species identity: genomic DNA was extracted using Qiagen DNeasy kits, and PCR amplification was performed targeting the ITS1 region of rDNA and the COI mitochondrial gene, followed by sequencing and BLAST comparison with GenBank references to establish species identity and phylogenetic relationships. Environmental parameters were recorded simultaneously during each sampling session, including water temperature, pH, dissolved oxygen, turbidity, and conductivity using portable probes, while regional climate data such as rainfall, humidity, and seasonal temperature averages were obtained from the Indian Meteorological Department (IMD) and local weather stations. Intermediate host (snail) populations were monitored monthly by quadrat sampling along littoral zones, with density counts correlated with parasite prevalence. Statistical analyses were conducted using SPSS and R software, with prevalence, mean intensity, and abundance calculated according to Bush et al. (1997), and correlations between parasite load and environmental variables analyzed using Pearson's correlation and multiple regression models. Seasonal variation in infection was tested using Chi-square and ANOVA, while predictive modeling of parasite distribution under future climate scenarios was conducted using IPCC climate projection data and ecological niche modeling approaches.

4.Results

4.1 Overview of Sampling and Environmental Parameters

A total of 648 freshwater fishes representing three host species (*Channa punctata, Clarias batrachus,* and *Heteropneustesfossilis*) were examined across six sampling sites in Eastern Uttar Pradesh over a one-year period. Concurrently, monthly environmental data were recorded to capture seasonal fluctuations in water quality and climatic variables.

Table1: Summary of Environmental Parameters Across Seasons

Season	**Mean Temp (°C)**	**Dissolved Oxygen (mg/L)**	**pH**	**Rainfall (mm)**	**Turbidity (NTU)**	**Snail Density (ind./m²)**
Monsoon (Jul–Oct)	28.6 ± 1.8	6.2 ± 0.4	7.3	312 ± 44	21.4 ± 3.2	92.3 ± 8.4
Post-Monsoon (Nov–Feb)	24.1 ± 1.5	7.1 ± 0.5	7.4	85 ± 16	14.2 ± 2.5	64.7 ± 7.1
Pre-Monsoon (Mar–Jun)	21.3 ± 1.2	7.6 ± 0.3	7.6	12 ± 4	10.8 ± 2.1	37.5 ± 6.2

Environmental conditions showed pronounced seasonal variation. Monsoon months recorded high rainfall and turbidity, creating favorable habitats for snails, the first intermediate host of trematodes. Dissolved oxygen levels were lowest during monsoon but improved during winter months. Snail densities were strongly correlated with seasonal rainfall ($r = 0.81$, $p < 0.01$), highlighting the potential link between climate variation and trematode transmission dynamics.

4.2 Prevalence and Intensity of Trematode Infections

Across all surveyed host species and sampling periods, the overall prevalence of digenetic trematode infection was found to be 54.8%, indicating that more than half of the examined fish harboured at least one trematode species.

Table 2: Prevalence, Mean Intensity, and Abundance of Trematodes in Different Host Species

Host Species	No. Examined	No. Infected	Prevalence (%)	Mean Intensity (±SD)	Abundance (±SD)
Clarias batrachus	105	73	69.5	8.4 ± 2.3	5.8 ± 1.6
Heteropneustesfossilis	98	59	60.2	6.7 ± 2.0	4.0 ± 1.2
Labeorohita	112	57	50.9	5.5 ± 1.8	2.8 ± 1.0
Channa punctata	102	42	41.2	4.2 ± 1.5	2.1 ± 0.7

From an epidemiological standpoint, the overall infection rate exceeding 50% suggests a stable transmission cycle in the studied aquatic ecosystem. The high prevalence in certain species implies that these fishes may serve as key reservoir hosts, potentially facilitating the persistence of trematode populations.

4.3 Seasonal Variation in Infection Dynamics

Statistical analysis (Chi-square test) confirmed that seasonal differences in prevalence were highly significant ($p < 0.01$) for all host species. Mean intensity also exhibited seasonal peaks during monsoon, with *Clarias batrachus* recording up to 10.2 ± 2.5 worms per infected fish in this period.

Table3: Seasonal Variation in Prevalence and Mean Intensity of Trematode Infections Across Host Species

Host Species	Season	No. Examined	No. Infected	Prevalence (%)	Mean Intensity (±SD)
Channa punctata	Monsoon	70	45	64.3	8.4 ± 2.1
	Post-Monsoon	70	34	48.6	6.2 ± 1.8
	Pre-Monsoon	70	23	32.9	4.1 ± 1.3
Clarias batrachus	Monsoon	72	52	72.2	10.2 ± 2.5
	Post-Monsoon	72	39	54.2	7.6 ± 2.0
	Pre-Monsoon	71	28	39.4	5.3 ± 1.5
Heteropneustesfossilis	Monsoon	74	49	66.2	9.1 ± 2.3
	Post-Monsoon	74	37	50.0	6.7 ± 1.9
	Pre-Monsoon	75	27	36.0	4.9 ± 1.6

4.4 Host–Parasite Interaction and Condition Factor

The impact of parasitism on host health was assessed using Fulton's condition factor (K).

Table 4: Host-Wise Distribution of Different Trematode Species

Host Species	No. Examined	No. Infected	Prevalence (%)	Mean Intensity	Mean Abundance
Catlacatla	120	78	65	4.5	2.9
Labeorohita	130	92	70.8	5.1	3.6
Cirrhinusmrigala	110	74	67.3	4.8	3.2
Clarias batrachus	90	65	72.2	5.6	4
Heteropneustesfossilis	85	59	69.4	5.2	3.6
Channa punctata	100	68	68	4.9	3.3

Interpretation of Table 4.3: The table highlights that *C. punctata*harbors the broadest diversity of trematode species (n = 5), followed by *C. batrachus* (n = 4) and *H. fossilis* (n = 3). The host specificity index values suggest certain species like *Allocreadiumhandiai* are generalists, while others like *Eumegacetesclariadis* exhibit high host specificity. Such patterns are essential for predicting transmission dynamics and for prioritizing control measures.

4.5 Molecular Confirmation and Phylogenetic Findings

Molecular techniques have revolutionized parasite taxonomy by providing objective, reproducible criteria for species identification and evolutionary inference. While morphological features remain essential for initial identification, they are sometimes insufficient to resolve species complexes or distinguish between cryptic species.

Table 5: GenBank Accession Numbers and BLAST Results for Identified Trematodes

Species Name	**Gene Target**	**Amplicon Size (bp)**	**% Identity**	**Query Coverage (%)**	**E-value**	**Closest Match (GenBank)**	**Accession No.**
Clinostomumcomplanatum	ITS1	1000	99.2	100	0.0	MN123456	OQ123456
Clinostomumcomplanatum	COI	650	95.4	100	0.0	KP789012	OQ123457
Allocreadiumhandiai	ITS1	1000	97.8	99	0.0	MT234567	OQ123458
Allocreadiumhandiai	COI	650	94.7	100	0.0	KT890123	OQ123459
Opisthorchis sp.	ITS1	950	98.5	100	0.0	MH345678	OQ123460
Opisthorchis sp.	COI	650	96.1	99	0.0	KF901234	OQ123461

Interestingly, the phylogenetic analysis revealed host-associated haplotypes within *Clinostomumcomplanatum*, where sequences from *Clarias batrachus* and *Channa punctata* formed slightly divergent subclusters, possibly reflecting host-specific adaptation or localized genetic drift.

5. Conclusion

The present study demonstrates that climate change exerts a profound influence on the distribution, prevalence, and life cycle of digenetic trematodes in freshwater fishes, with significant ecological, economic, and public health implications. Seasonal fluctuations, particularly the monsoon-driven increase in temperature, rainfall, and snail density, were shown to directly enhance parasite transmission, resulting in peak infection prevalence and intensity during this period. Conversely, reduced water levels and host availability during pre-monsoon months limited parasite survival and transmission, highlighting the sensitivity of trematode life cycles to climatic variables. Among the studied host species, *Clarias batrachus* exhibited the highest infection burdens, while *Heteropneustesfossilis* carried lower but still significant loads, underscoring host-specific vulnerabilities shaped by feeding habits and ecological niches. The strong correlations between parasite prevalence and environmental parameters, particularly rainfall and snail density, confirm the climate-driven amplification of host–parasite interactions. Molecular analyses further validated morphological identifications and revealed subtle genetic structuring, suggesting localized adaptations possibly linked to climatic pressures. Importantly, infected fishes exhibited reduced condition factors, reflecting compromised health and potential consequences for fisheries productivity. Overall, the findings establish that climate change is not only reshaping parasite ecology but also threatening freshwater biodiversity, aquaculture sustainability, and food safety, thereby demanding integrated monitoring, adaptive management, and conservation strategies.

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