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Applying the Metacoupling Framework to Multi-Scalar Conservation Planning: An Analysis for the Endangered Indiana Bat

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Abstract

The ongoing biodiversity crisis, driven by human activity, climate change, and disease spread, is reflected by the rapid decline of animal populations across all phylogenetic groups. Bats exemplify a group highly susceptible to these threats. While threats to bats are often studied locally, global interactions remain overlooked. Using a literature-based analysis and the metacoupling framework (including the telecoupling framework), which analyzes human–nature interactions across local to global scales, we take a holistic approach to understanding how conservation strategies can support both biodiversity and ecological and socioeconomic sustainability. Focusing on the Indiana bat (an endangered species with an accelerating population decline for which such a comprehensive analysis is urgently needed), we find how local, regional, and global factors contribute to the shrinking population. Results indicate that local factors include habitat disturbance, cave tourism, and public perceptions. Regional factors include inconsistent regulations and land-use change (e.g., suburban sprawl). Global factors include ecotourism, distant consumer demand (e.g., the timber market), and climate change. White-Nose Syndrome affects bats across scales. The results also suggest that conservation strategies limited to local interventions alone are insufficient. This paper advances sustainability research by applying the metacoupling framework to species conservation, demonstrating how local-to-global human–nature interactions can inform more effective and sustainable management strategies.

Keywords: metacoupling; telecoupling; endangered species; conservation planning; White-Nose Syndrome; Indiana bat; land-use change; ecosystem services

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1. Introduction

Biodiversity loss is a major global crisis [1]. Human activities, shaped by diverse social and economic contexts, are the primary drivers of biodiversity loss [2,3]. Thus, conserving biodiversity today requires a broad approach that considers not only ecological factors but also the social and economic processes that influence them [4–6]. While many conservation efforts focus on local or regional issues, the causes of species decline often extend far beyond those areas. In some cases, habitat loss is driven by human activities occurring thousands of miles away [7–9]. For example, deforestation in one region to meet global demand for timber or agricultural products can affect species that depend on those forests. These effects occur even when the species themselves are not found at the source of the demand [7,10]. These kinds of complex, long-distance interactions highlight the need for a new conservation approach that accounts for both local conditions and broader, global connections. By using frameworks that track how systems interact across space, researchers and policymakers can better identify the drivers of species decline and how to respond to them more effectively.

The metacoupling framework has become an important approach for studying connections between human and natural systems locally and across large distances [4–6]. This framework integrates the intracoupling framework (interactions within a single system), the pericoupling framework (interactions between adjacent systems), and the telecoupling framework (interactions across large distances) to provide a more comprehensive understanding of the factors influencing species conservation [4]. Within this framework, the telecoupling component helps researchers understand how flows of materials, information, people, and organisms link distant places and influence ecological processes [7,8]. For instance, the global trade in wildlife products creates telecoupled relationships that can lead to overexploitation of species and the spread of invasive organisms [11]. The metacoupling and telecoupling frameworks have been successfully applied to address a wide range of issues globally [5].

Applying these frameworks to wildlife conservation provides new ways to uncover complex and often hidden connections that affect species and their habitats. For example, bats are a group of species that experience conservation challenges worldwide. Figure 1 illustrates the global distribution of bats and the diversity of geographic locations they inhabit. Because they rely on specific roosting and hibernating sites, many bat species are vulnerable to land-use changes. Coupled with White-Nose Syndrome (WNS), a lethal fungal disease, about 15% of bat species are currently endangered [12].

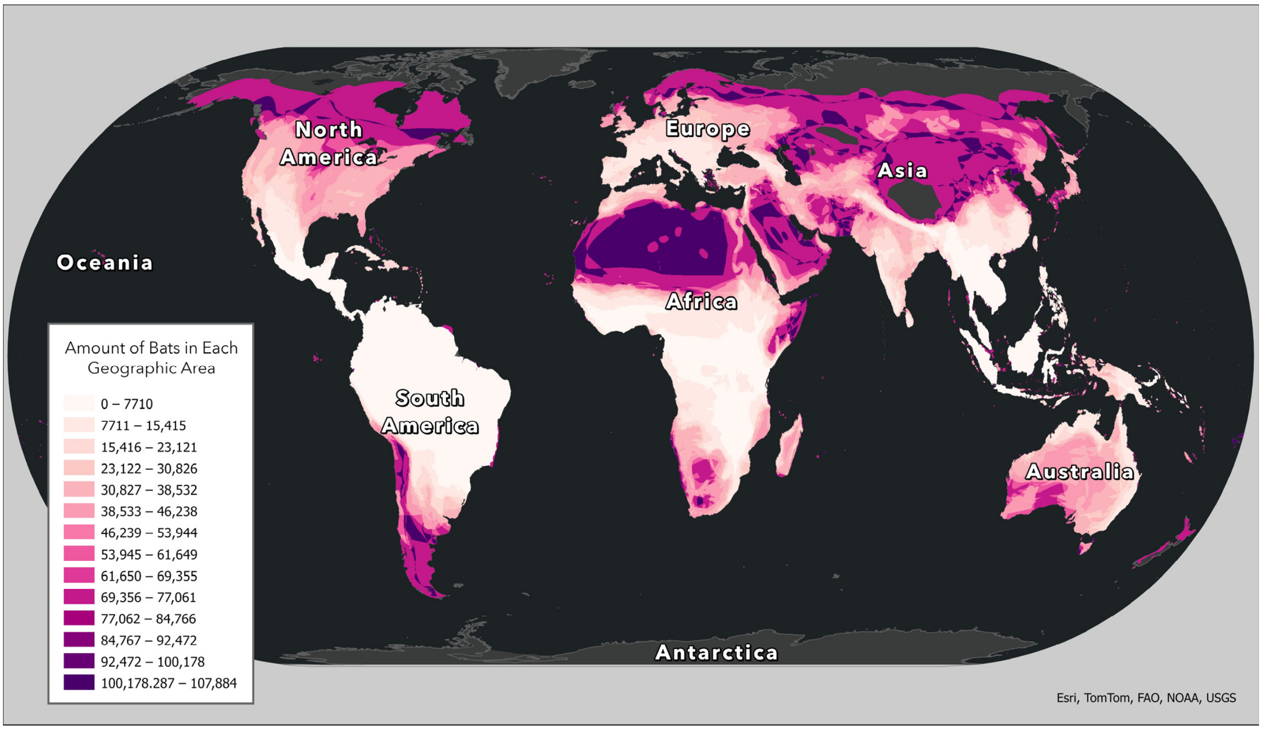

Figure 1. Global Distribution of Bats in 2018. This map depicts the global distribution of all recognized bat species in 2018, highlighting their presence across diverse regions and habitats [13]. The map was created in ArcGIS Pro 3.3.2 using data downloaded from https://biodiversitymapping.org/. Their data were obtained with ArcGIS 10 using equal area grids and species richness for bats was calculated using a 100 × 100 km grid. The WGS 1984 coordinate system was used for the projection.

The Indiana bat (*Myotis sodalis*) is a species that urgently needs such a comprehensive analysis. This species belongs to the Vespertilionidae family, the largest family of bats, currently containing 407 known species [14]. Although these bats occupy a diverse range of habitats, each species has distinct hibernating and roosting sites [14,15]. For example, the Southeast Asian club-footed bats roost in hollowed-out bamboo stalks, while banana pipistrelles roost in rolled-up leaves [14].

Since the Indiana bat was listed as endangered in 1966, the species has experienced a steady population decline for decades [16–18]. This decline has recently accelerated due to the spread of White-Nose Syndrome (WNS) [19]. Additional threats such as habitat loss and human disturbance further jeopardize the species' survival [20,21]. Despite ongoing conservation efforts, the population has continued to decline. This decline has far-reaching consequences, not only for the Indiana bat but also for the people and communities that benefit from its natural pest control services, which support agricultural sustainability [12,22]. Recognizing these ecosystem services underscores why conserving the Indiana bat is not only an ecological priority but also a step toward promoting more sustainable land-use and agricultural practices. These conservation threats occur across multiple scales, from local cave environments to regional land-use changes and global patterns of human movement and climate change.

Despite the extensive research that exists today, several knowledge gaps remain. Much of the existing work is localized, emphasizing cave ecology or summer roosting sites, but rarely connecting processes across regions or scales. Broader economic factors, such as timber markets and global ecotourism, have been underexplored. In addition, most studies have treated threats in isolation, without assessing how disease, habitat loss, and climate change impact the bats simultaneously. Finally, the integration of social research remains limited, leaving critical gaps in understanding how human decisions and attitudes towards bats, along with natural processes, all impact the conservation of this species. Understanding how these drivers operate across different scales and interact with one another is essential for creating conservation plans that tackle the underlying causes of population decline, not just the symptoms [4].

The objective of this is to conceptualize how the metacoupling framework can be applied to the conservation of the Indiana bat and sustainability. Existing knowledge of the species' ecology and threats is analyzed under the metacoupling framework to support the creation of new conservation action plans for endangered species. Ultimately, this approach offers promise for enhancing conservation outcomes, not only for the Indiana bat, but also for many other species, such as the little brown bat [23], Mexican free-tailed bat [24], and monarch butterfly [25], that face similarly complex, multi-scale threats shaped by both distant and local human activities.

The purpose of this literature review is (1) to identify the intracoupled, pericoupled, and telecoupled factors impacting the Indiana bat today, (2) to synthesize these into a conceptual management model, and (3) to derive specific management recommendations that can be applied. Information about bats and sustainability, White-Nose Syndrome, and the Indiana bat is provided in the Section 2, followed by a description of the methodology used for the literature review in the Section 3. This is followed by Section 4, which includes information from the applications of the telecoupling and metacoupling frameworks to the conservation of the Indiana bat and other similar species. The paper also presents a discussion of the results and recommendations for management and future directions in Section 5. Ultimately, this study demonstrates that addressing biodiversity loss requires recognizing and managing the interconnected social, economic, and ecological processes across local to global scales that underpin sustainable conservation outcomes.

2. Background

Understanding the ecological, economic, and social contexts of bat conservation is essential for applying the metacoupling framework to the Indiana bat. Bats contribute significantly to ecosystem stability and agricultural sustainability through their insect control services, yet many species face rapid declines due to interacting environmental and human-driven pressures. The Indiana bat serves as a focal species for examining these dynamics because its survival depends on processes that span multiple scales, from local roosting habitat conditions to regional land-use patterns and global human movements that facilitate disease spread. This section provides background on (1) the role of bats in sustainability, (2) the ecology and spread of White-Nose Syndrome and (3) the ecology and conservation challenges of the Indiana bat.

2.1. Bats and Sustainability

Bats play a vital role in maintaining ecological balance and supporting human sustainability. Globally, insectivorous bats save the agricultural industry billions of dollars each year by reducing pest populations and limiting the need for chemical pesticides [22]. These natural pest-control services protect crops, maintain soil and water quality, and promote sustainable food production. Beyond pest suppression, many bat species also serve as pollinators and seed dispersers, supporting forest regeneration and the persistence of tropical ecosystems [12].

Together, these ecological contributions directly support several United Nations Sustainable Development Goals (SDGs) [12,26]. For example, SDG 2 (“Zero Hunger”) is supported through bats’ role in controlling agricultural pests and pollinating key crops, which helps maintain sustainable agriculture and food security. SDG 12 (“Responsible Consumption and Production”) is supported by bats’ regulation of insect populations, reducing the need for chemical pesticides and promoting more efficient resource use. Their contributions to ecosystem resilience and nutrient cycling also align with SDG 13 (“Climate Action”) by enhancing carbon sequestration and stabilizing ecosystems under changing climate conditions. Finally, SDG 15 (“Life on Land”) is reinforced through bats’ essential roles in seed dispersal, forest regeneration, and maintaining terrestrial biodiversity [22,26]. Collectively, these connections highlight that conserving bats is not merely an ecological concern but a vital component of achieving global sustainability goals.

Despite these benefits, the value of bats is frequently misunderstood. In some agricultural regions, bats are mistakenly blamed for crop losses or disease transmission, even though they are key allies to farmers and forest managers [12,22]. This disconnect underscores a broader challenge in sustainability: the tendency to overlook the invisible services that wildlife provides to human systems. When bat populations decline, the consequences ripple outward, affecting pest control, crop yields, forest stability, and even economic security [22].

Indiana bats (*Myotis sodalis*) contribute directly to agricultural sustainability through natural pest control, eating up to half their weight in insects each night when they are not hibernating [16]. They feed entirely on night-flying insects [27]; they are opportunistic, but four orders of insects contribute most to their diet: Coleoptera (beetles), Diptera (flies), Lepidoptera (butterflies and moths), and Trichoptera (caddisflies). Their suppression of insect populations reduces pesticide costs for farmers and minimizes chemical runoff into waterways [12], creating benefits that extend across ecological and economic systems. This also links to human sustainability by reducing reliance on chemical pesticides, promoting healthier food systems and lower environmental toxin levels.

Because the Indiana bat is federally listed as endangered, its presence influences infrastructure, forestry, and land-use planning. For example, wind energy projects in the

U.S. must consider impacts on Indiana bat populations [28]. This aligns with sustainability goals by embedding biodiversity protection into development practices.

Indiana bats are highly sensitive to habitat disturbance, particularly in forests and cave systems. Their population trends reflect broader environmental health, serving as indicators of ecosystem health [29]. Thus, protecting their roosting and foraging habitats contributes to broader sustainability goals.

White-Nose Syndrome has devastated Indiana bat populations, highlighting the fragility of bat populations and their susceptibility to ecological disruption [19,30]. This emphasizes the need for cross-sectoral approaches (ecology, public health, land management) in sustainability efforts.

The Indiana bat exemplifies how the conservation of a single species can have broader implications for sustainability. Its population decline signals the weakening of an ecological process that benefits both natural and human systems. Efforts to conserve the Indiana bat therefore extend beyond species recovery; they contribute to maintaining ecosystem integrity, reducing pesticide dependence, and supporting resilient agricultural landscapes.

Protecting the Indiana bat also has implications for sustainable land management and policy. Forest conservation and landscape connectivity not only support bat populations but also enhance carbon storage, water regulation, and biodiversity across multiple scales [12]. These benefits align directly with sustainability frameworks that integrate ecological, economic, and social dimensions. Framing Indiana bat conservation in this way illustrates that saving this species is not an isolated goal but part of a broader strategy to sustain the coupled human–natural systems on which we all depend.

2.2. Ecology and Spread of White-Nose Syndrome

Today, one of the most serious threats to bats in North America is White-Nose Syndrome (WNS), a disease caused by the cold-loving fungus *Pseudogymnoascus destructans*, which thrives in the conditions of hibernacula (hibernation sites) where bats reside during the winter [19,31,32]. The fungus is believed to have arrived in North America from Eurasia in 2006, likely facilitated by human movement and international ecotourism [12]. Figure 2 illustrates the spread of White-Nose Syndrome across North America, from when it was first recorded in 2006 until 2023, when these data were reported.

Pseudogymnoascus destructans grows over the skin of hibernating bats, especially on the nose and wings. The fungus interferes with the physiological processes that are essential for bats during winter hibernation [19,31,32]. Bats infected with WNS wake up more often during torpor, using up the fat reserves they need to make it through the winter. In many affected populations, this has resulted in mortality rates of over 90% [19,33].

The fungus spreads rapidly within bat hibernacula, with spores persisting in the environment even when bats are absent [19,32]. This persistence makes eradication challenging and contributes to repeated reinfections. Human activities further exacerbate the spread of WNS, as recreational caving and ecotourism introduce fungal spores from cave to cave via contaminated clothing, footwear, and equipment [12,31]. This pattern of human movement and disease spread is also observed in other taxa, such as chytrid fungus in amphibians [34]. In response to this problem, management agencies have implemented cave closures and decontamination protocols, though these measures must balance conservation goals with public access and awareness.

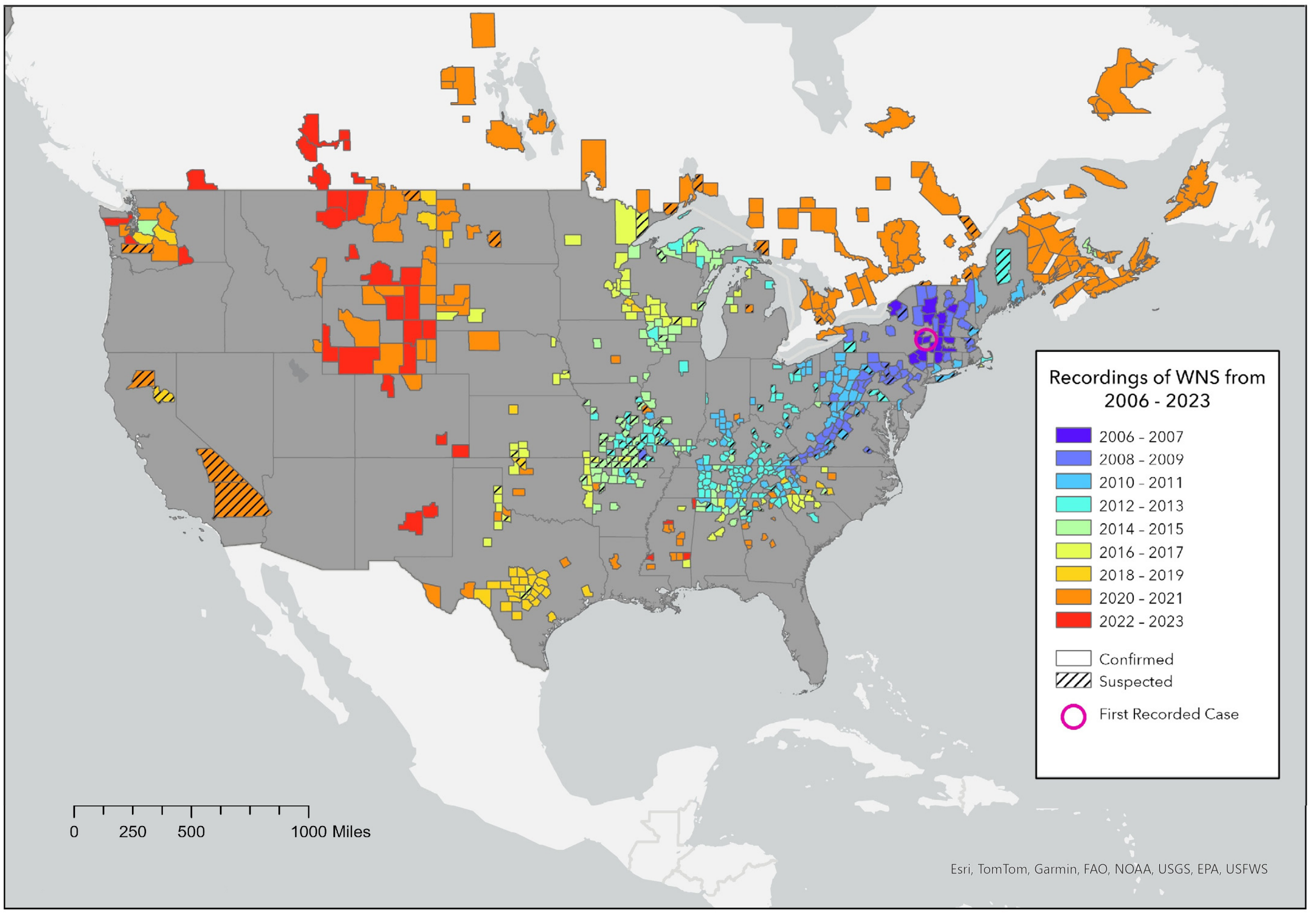

Figure 2. Spread of White-Nose Syndrome (WNS) Across the United States and Canada. This map shows the distribution of White-Nose Syndrome in the United States and Canada from its initial detection in 2006 through 2023, illustrating its continued and rapid spread across the continent. The map was created in ArcGIS Pro 3.3.2. Data were obtained in 2023 from the U.S. Fish and Wildlife Service [33], using the WGS 1984 coordinate system for projection.

2.3. Ecology and Conservation Challenges of the Indiana Bat

The Indiana bat is a small insectivorous species native to the northeastern United States [16,18]. Since the Indiana bat was first listed as endangered, scientists have diligently monitored its population; however, most research has focused primarily on its ecology and local threats [33,35]. Much of the research on this species during the 1970s focused on locating its summer habitat, as winter hibernacula were easier to find and already well documented [17]. The first summer maternity colony of the Indiana bat was documented in 1971 when a dead elm tree was bulldozed and multiple bat species, including the Indiana bat, emerged [36]. Researchers captured eight Indiana bats flying out of the summer roosting site and preserved them for further study in a museum collection.

Indiana bat winter habitat primarily consists of karst limestone caves and mines, which are between 5 °C and 10 °C, providing stable, cool, and humid conditions optimal for hibernation [15,16]. These microclimatic conditions are essential to the bats' energy conservation during winter months; the bats form large colonies in these hibernation sites, making the spread of WNS within them particularly devastating. Figure 3 illustrates the known range of the Indiana bat overlaid with the documented cases of WNS, many of which are within their known range.

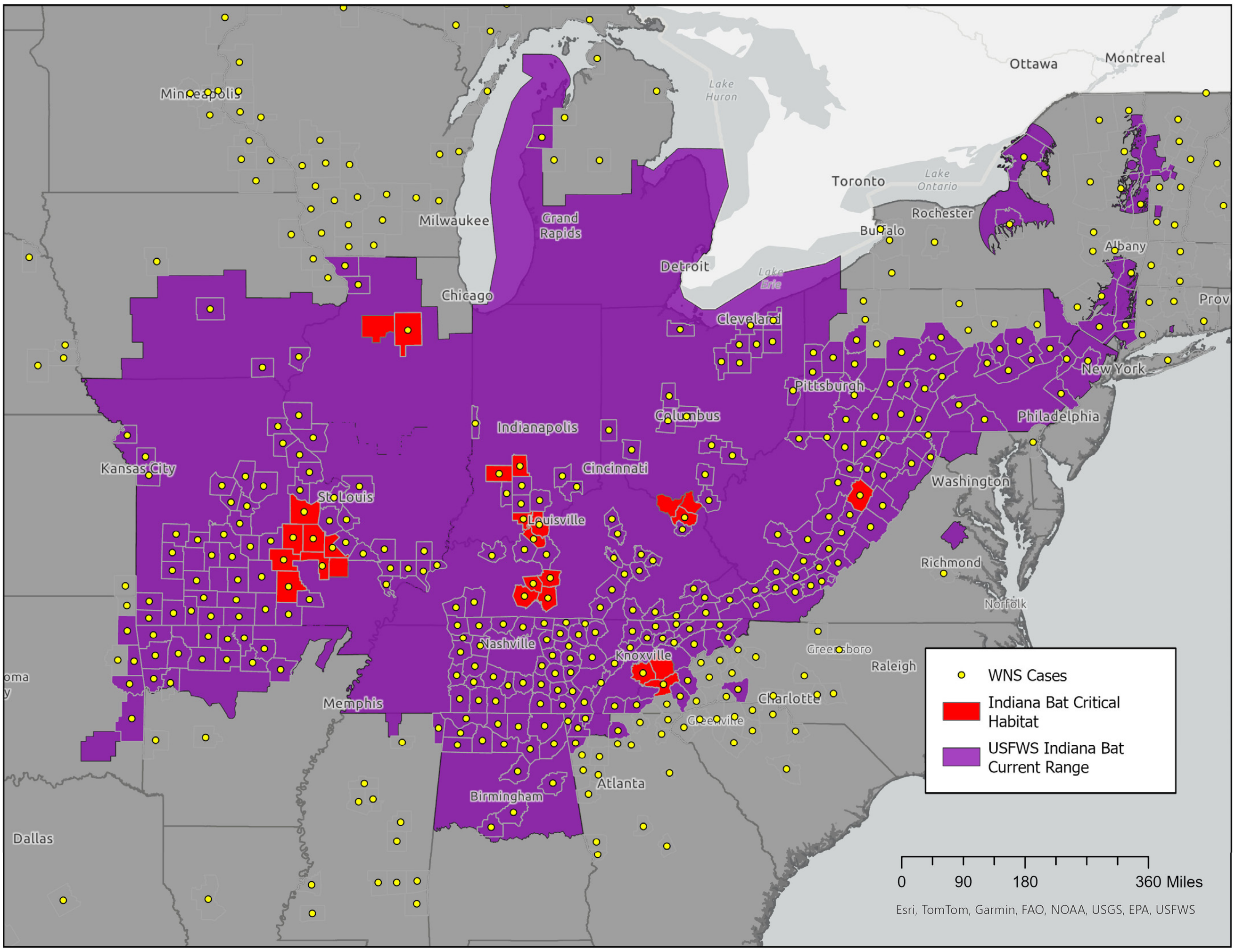

Figure 3. Indiana Bat (*Myotis Sodalis*) Range Compared to White-Nose Syndrome Spread. This map overlays the Indiana bat's geographic range with the spread of White-Nose Syndrome [33], highlighting areas of overlap between the species' distribution and disease occurrence. Red shading indicates the most critical habitat areas. The map was created in ArcGIS Pro 3.3.2 using Indiana bat habitat data from 2023 and critical habitat data from 2025, both obtained from the U.S. Fish and Wildlife Service. White-Nose Syndrome case data were reported in 2024 by the Bat Conservation Trust [37]. The WGS 1984 coordinate system was used for the projection.

During the summer, Indiana bats migrate to forested areas, where they roost individually or in small groups in the exfoliating bark of dead or dying trees, often in mature hardwood forests [16,35,36]. These roosting sites provide shelter, protection from predators, and proximity to abundant insect prey. However, the fragmentation and loss of forest habitats due to urbanization, agriculture, and timber harvesting have severely reduced the availability of suitable summer roosts [20,35,38]. Clearcutting and removal of dead trees for aesthetic or safety reasons further degrade these critical habitats [20]. Human development near roosting sites can also increase light pollution, noise, and chemical pollutants, which may interfere with bat foraging and navigation [12,35]. Additionally, forest fragmentation can isolate bat populations, reducing genetic diversity [39].

The current action plan for the Indiana bats involves protecting their most well-known hibernation sites, but less emphasis has been placed on conserving summer roosting sites [18]. Due to their summer roosting locations frequently varying, protecting their habitat has been a struggle. There is also currently limited communication among the states through which the bats migrate [38,40], leading to differences in conservation action plans between jurisdictions.

The dual pressures on both winter and summer habitats place the Indiana bat in a precarious conservation position, as disruption in either season can impact survival and reproductive success. Conservation efforts must therefore address both the protection and restoration of habitat connectivity to support bat population persistence. These multi-scale challenges underscore the need to apply the metacoupling framework to better understand the conservation challenges that the Indiana bat is facing.

3. Materials and Methods

The Indiana bat (*Myotis sodalis*) was selected for this study because it faces conservation challenges across multiple spatial scales [6,12,18]. This species exemplifies the need for applying the metacoupling framework [4–6]. The Indiana bat has been listed as endangered for decades, and its population continues to decline [12,16,18]. The introduction of White-Nose Syndrome, a metacoupled factor, has recently accelerated this decline [12,19,31]. This species not only requires an updated conservation approach but also serves as a model for other taxa experiencing multiscale conservation pressures.

To identify key challenges and opportunities for Indiana bat conservation, we first reviewed current conservation and recovery plans to assess gaps in existing management strategies [16,18]. We then synthesized literature on ecological, climatic, and anthropogenic drivers that most strongly affect the species today using a qualitative synthesis approach.

We used Google Scholar to locate peer-reviewed journal articles relevant to the Indiana bat and the metacoupling framework. Primary keywords included "Indiana bat," "*Myotis sodalis*", "White-Nose Syndrome (WNS)," "telecoupling," "metacoupling," "land-use change," "timber harvesting," and "climate change." We also obtained additional data on population trends, distribution, and conservation status from the U.S. Fish and Wildlife Service and the IUCN Red List [16,18].

Studies were included if they discussed ecological, social, or policy factors influencing Indiana bat conservation, habitat change, or human–bat interactions relevant to sustainability. Publications focused solely on physiology, genetics, or non-sustainability topics were excluded. One researcher independently reviewed the literature sources to identify the factors influencing the Indiana bat both historically and today. To enhance transparency and reduce bias, an additional researcher reviewed the sources and resolved any issues through discussion.

Using the metacoupling framework, which includes local (intracoupling), regional (pericoupling), and global (telecoupling) levels [4–6], we identified the major conservation challenges facing the Indiana bat and the areas where management gaps remain. Table 1 organizes the references used in our literature review to illustrate how each source contributed to the analysis. We categorized literature under each framework component to identify agents, flows, and effects relevant to Indiana bat conservation and management.

Table 1. Summary of references used in the literature review and their connections to the metacoupling framework as applied to Indiana bat conservation.

Framework Component	Key References	Illustrative Focus/Contribution
Intracoupling (interactions within a system)	Cope et al. (1973); Harvey & McDaniel (1986); Brack (2007); Sherwin et al. (2012); Thogmartin & McKann (2014); Roby et al. (2019); IDNR; USFWS [15–17,35,36,40–42]	Local-scale dynamics of the Indiana bat, including hibernation microclimates, migration behavior, and the effects of climate variation on grouping and survival.
Pericoupling (interactions between adjacent systems)	Sáenz-Romero et al. (2012); Pauli et al. (2015); Apeti & N'Doua (2023) [10,20,25]	Regional landscape and genetic connectivity, forest management, and spillover effects from neighboring land-use and policy changes.

Table 1. *Cont.*

Framework Component	Key References	Illustrative Focus/Contribution
Telecoupling (interactions between distant systems)	Paguntalan et al. (2004); Liu et al. (2015); Bacigalupe et al. (2017); Hulina et al. (2017); López-Hoffman et al. (2017); Giudice et al. (2019); López-Wilchis et al. (2021); Kingston et al. (2023); Montti et al. (2024); Pfenning-Butterworth et al. (2024) [1,8,9,11,24,34,39,43–45]	Long-distance drivers such as global trade, tourism, migration, and pathogen spread, with comparative cases showing how remote pressures influence biodiversity and disease dynamics.
Metacoupling Integration (synthesis across scales)	Liu (2017; 2023); Büscher & Fletcher (2020); Newig et al. (2020); Sun (2023); Cheung et al. (2024) [2–7]	Conceptual and methodological integration of intra-, peri-, and telecoupled systems, offering guidance for applying the metacoupling framework to sustainability governance and policy.
Cross-cutting Conservation Context	Dzal et al. (2010); Kunz et al. (2011); Thogmartin et al. (2013); O'Keefe (2013); Voigt & Kingston (2016); López-Hoffman et al. (2017); Cheng et al. (2021); O'Rourke et al. (2021); Valle et al. (2021); Hoyt et al. (2021); IUCN Red List (2016; 2020); Beilke & O'Keefe (2022); Newman & Surrey (2025); USFWS; U.S. Department of the Interior; ADW; UN DESA [12,14,18,19,21–23,26–33,38,46,47]	Overarching studies on sustainability, bat conservation, global biodiversity loss, and disease ecology that inform all levels of coupling analysis.

4. Results

This review synthesizes the ecological and human-related drivers influencing Indiana bat conservation across interconnected spatial scales. Using the metacoupling framework, patterns of interaction among local, regional, and global processes that collectively shape species outcomes were identified. Results show that the species' decline arises from the combined effects of habitat loss, White-Nose Syndrome, and human disturbance, all of which are influenced by broader socioeconomic and environmental systems.

Across studies, conservation challenges are consistently linked to cross-scale dynamics. Local habitat degradation is often reinforced by regional land-use policies, economic pressures, disease spread, and climate-related changes originating at distant scales. While many management efforts remain focused at the site or state level, the evidence indicates that external forces such as trade, tourism, and global climate change strongly influence local ecological conditions. These findings demonstrate that conservation cannot be fully understood through local-scale analysis alone.

The following subsections apply the telecoupling and metacoupling frameworks to organize these cross-scale patterns. The telecoupling framework describes how distant systems, linked through flows of goods, people, and information, influence ecological outcomes for the Indiana bat. The metacoupling framework extends this approach by integrating local (intracoupling), adjacent (pericoupling), and distant (telecoupling) interactions to provide a more complete picture of multi-scalar conservation dynamics. Together, these frameworks clarify the structure of the drivers identified in this review and establish a foundation for the discussion that follows.

4.1. The Telecoupling Framework and Its Relevance to Indiana Bat Conservation

The conservation challenges faced by the Indiana bat cannot be fully understood through local-scale analysis alone. While habitat degradation, disease, and human disturbance occur locally, the root causes often originate from distant social, economic, and ecological systems. The telecoupling framework helps explain how coupled human and natural systems interact across geographic distances [7–9], providing a foundation for understanding these long-distance dynamics in Indiana bat conservation.

The telecoupling framework organizes long-distance interactions into five main components: systems, flows, agents, causes, and effects [7]. Systems are the locations involved in these interactions: the sending system is where flows originate, the receiving system is where they end, and spillover systems are areas indirectly affected. Flows refer to what moves between systems, such as species, people, money, goods, or information. Agents are the people or groups driving these flows, such as government agencies, landowners, tourists, or companies. Causes are the reasons behind the flows, including economic demand, land-use decisions, or conservation goals. Effects are the intended and unintended outcomes of these interactions, influencing both ecological and human components of systems. Table 2 illustrates how the framework can be applied to Indiana bat research and conservation, comparing it to conventional approaches. The telecoupling framework goes beyond local conservation by revealing how decisions and activities in one region can generate far-reaching impacts on ecosystems and species in another [7,9]. In the case of the Indiana bat, the telecoupling framework highlights how forest loss, human disturbance, disease transmission, economic demand, and climate change are interconnected across space, often in indirect and surprising ways.

Table 2. Comparisons between conventional and telecoupling frameworks for studying and conserving bats, highlighting key components, expanded system perspectives, and resulting conservation actions.

Components	Conventional Framework for Studying and Conserving Indiana Bats	Telecoupling Framework for Studying and Conserving Indiana Bats	New Conservation Actions
Systems-Features	Natural systems (bat populations, hibernacula, summer roosts)	Coupled human and natural systems (bats linked with forestry, agriculture, urban areas, and tourism)	Incorporate human dimensions into conservation across distant places; minimize impacts and enhance mutual benefits.
Systems-Types	Known habitats (hibernacula, summer roosts, foraging locations)	Local and distant systems influencing bats (e.g., timber markets, agriculture, climate change)	Manage distant systems affecting bats; coordinate cross-scale habitat and policy management
Agents	Bats, scientists, wildlife/land managers, landowners, tourists, government agencies	All local agents plus distant actors (timber trade, agriculture, NGOs, consumers)	Engage all agents and facilitate cooperation among all types of agents across distant places. Foster cooperation among diverse agents across distant places and sectors
Flows	Bat movements and migrations, spread of White-Nose Syndrome	Environmental and socioeconomic flows (disease spread, trade, funding, knowledge)	Limit harmful flows (e.g., disease, trade-driven loss); promote beneficial flows (e.g., research, funding, education)
Causes	Environmental stressors (habitat loss, disturbance, and disease)	Environmental and socioeconomic factors (land-use policy, consumer demand for timber, global trade, public perception)	Create and use incentives (e.g., subsidies, cave access regulation, awareness campaigns) to reduce pressures across distant systems
Effects	Impacts on bat populations, health, and habitats	Impacts on both bat populations and humans (e.g., pest control, cultural values, disease risks)	Reduce ecological–socioeconomic trade-offs and enhance positive outcomes for bats and humans
Feedback	Environmental feedback (loss of roosts reduces population resilience)	Environmental and socioeconomic feedback (e.g., loss of bats increases pesticide use, driving habitat degradation and land-use change)	Manage feedback across systems; emphasize bats' ecosystem services to reinforce conservation incentives

One of the most striking examples of telecoupled dynamics affecting the Indiana bat involves the timber trade. Forests across the northeastern United States are harvested to meet both domestic and global demand for lumber and paper products [10]. These logging activities are often concentrated in the same areas where Indiana bats roost during the summer [20,21]. Although logging decisions are made by local or regional landowners and companies, they are strongly influenced by broader market forces, such as urban development in distant cities or international timber contracts [10]. As demand increases, so does the pressure to harvest forests that serve as critical bat habitats, often without consideration of the downstream ecological effects. In this case, the forest regions where bats roost act as the sending systems (providing timber), and distant cities or international markets serve as the receiving systems driving demand [4–7].

Similarly, the spread of White-Nose Syndrome illustrates how human movement, another type of telecoupled flow, contributes to ecological harm across space. Despite the best efforts by agencies to limit cave access and require decontamination, enforcement gaps and increasing demand for nature-based recreation have led to the continued spread of the fungus [12,31]. Here, the agents of telecoupling include tourists, tourism companies, and park managers whose decisions shape the flow of people between distant locations. The cause lies in the growing popularity of cave-based ecotourism, while the effects include population crashes and colony extirpations documented across North America [12,31].

In addition to this conservation problem, there are less obvious consequences, or spillover effects, that result from well-intentioned management strategies. For example, when high-profile caves are closed to protect bat colonies, tourists may redirect their activities to lesser-known, unprotected sites [12,31]. These spillover caves often lack disease management infrastructure or species monitoring, inadvertently creating new hotspots for disease transmission and human disturbance. Likewise, when conservation policies in one jurisdiction restrict logging to protect endangered species, global timber companies may shift operations to neighboring states with more lenient regulations, exporting the environmental burden elsewhere [10,38].

Another major challenge facing the Indiana bat (as well as many other species) is climate change. Climate change has an impact on the biogeography of bats, affecting their access to food, patterns of hibernation, reproduction and development, duration of torpor, and rates of energy expenditure [41,42]. Global climate processes, driven by distant emissions, alter local habitat conditions leading to warmer winters and shorter stints of hibernation. For example, Indiana bats hibernate in larger groups during severe winters and in smaller groups during warmer winters; due to climate change, Indiana bats are hibernating in smaller groups [42]. To combat rising temperatures caused by greenhouse gas emissions, many countries have adopted wind turbines as a renewable energy source; however, these have also become a source of mortality for migratory bats [12,38,41]. This issue adds another layer of telecoupled impact.

Although few published case studies have directly applied the telecoupling framework to the Indiana bat, analogous research offers valuable insights. For example, studies on wildlife trade, migratory birds, and tropical deforestation have demonstrated the framework's effectiveness in uncovering indirect drivers of species loss [4,24,43]. López-Hoffman et al. [24] applied this framework to the Mexican free-tailed bat, supporting the argument that the telecoupling framework can and should be applied to other migratory bat species. By applying the framework, researchers and practitioners can better anticipate telecoupled cascading impacts, identify key intervention points, and avoid narrow, local-only strategies that fail to address the full scope of the conservation problem. The framework can also facilitate collaboration among ecologists, economists, policymakers, and social scientists, an interdisciplinary approach that is increasingly necessary to address 21st-century conservation challenges.

The application of the telecoupling framework shows that protecting the Indiana bat and similar species involves far more than preserving roosting trees or restricting access to hibernation sites. Instead, it highlights how conservation is influenced by a complex web of factors, including distant economic pressures, human disturbance, land-use changes, and climate dynamics. These systems interact across scales, influencing local outcomes in ways that are not always obvious [7–9]. By identifying the primary factors involved, tracing the movement of people, goods, and resources, and considering both the intended and unintended impacts, conservation efforts can begin to address the broader forces affecting the bat's survival. In summary, through this literature review and synthesis under the telecoupling framework, we identified four main telecoupled dynamics influencing Indiana bat conservation: (1) global timber markets that drive local forest loss [10,20]; (2) human mobility and tourism that facilitate WNS spread [12,31]; (3) policy and management spillovers that shift rather than solve conservation pressures [10,38]; and (4) climate-driven changes that reshape habitat conditions and mortality risks [12,41,42]. Together, these results demonstrate that Indiana bat conservation is shaped by interacting global processes that extend beyond the species' immediate range. Applying the telecoupling framework reveals how distant economic and social drivers intensify local threats, emphasizing the need for cross-scale management coordination to achieve lasting conservation outcomes.

4.2. The Metacoupling Framework and Its Relevance to Indiana Bat Conservation

While the telecoupling framework provides valuable insight into how distant human and natural systems interact, it is often insufficient on its own to capture the full range of interactions affecting species like the Indiana bat. Many of the bat's conservation challenges also stem from adjacent systems, such as neighboring counties with differing land-use regulations, and/or from local, within-system interactions, such as community attitudes toward bats influencing habitat protection on private lands.

The metacoupling framework, which builds upon, encompasses, and expands the telecoupling framework by integrating both the pericoupling and intracoupling frameworks, allows for a more comprehensive understanding of the full conservation issue [4–6]. Table 3 further illustrates the metacoupling framework and highlights how it can be applied to Indiana bat conservation. By including local and neighboring pressures, the metacoupling framework offers a more complete picture of the conservation landscape. It also provides a more realistic foundation for designing effective, multi-scalar conservation strategies for the Indiana bat and other species facing similar challenges.

Intracouplings play a critical role in Indiana bat conservation at the local level. For example, within a single county, decisions made by private landowners, local forestry services, and planning departments collectively shape the availability and quality of summer roosting habitats [16,18,20]. Local ordinances that incentivize the preservation of dead or dying trees, essential for Indiana bat roosting, can help sustain populations [20], while other counties may permit widespread clear-cutting, even during sensitive breeding seasons. These internal dynamics also influence how communities respond to bat conservation, with public attitudes toward bats affecting support for conservation initiatives, compliance with cave closures, and participation in habitat restoration programs [21].

Pericoupling dynamics become apparent when examining how neighboring regions with differing policies, economic strategies, or land-use regulations influence one an-other. For instance, when one state tightens timber harvest restrictions to protect endangered species, logging operations may shift across state or county lines to areas with less strict regulations, displacing environmental pressure instead of alleviating it [10,20]. Additionally, like other species, bats do not recognize jurisdictional boundaries. Summer foraging ranges and winter hibernacula often span multiple counties or states, requiring cross-boundary cooperation [16,38,39]. A protected roosting site in one county may be rendered ineffective if adjacent regions allow for high levels of disturbance or deforestation, disrupting bat movement and reducing overall habitat connectivity [20]. Pericoupling analysis highlights how coordination, or lack thereof, between adjacent systems can amplify or undermine conservation outcomes [7].

Table 3. Results from the application of the metacoupling framework to Indiana bat conservation at local, regional, and global scales, with examples and recommended management actions.

Coupling Type	Definition (Conservation Context)	Indiana Bat Example	Conservation Actions
Intracoupling (within-system interactions)	Interactions within a single local system (e.g., community, county)	Local land-use decisions, cave closures, community attitudes	Promote habitat stewardship, protect roost trees, strengthen ordinances, community outreach
Pericoupling (adjacent-system interactions)	Interactions between neighboring systems (e.g., counties, states)	Logging displaced across borders; bats migrating across jurisdictions	Coordinate migration corridors, align land-use policies, develop regional timber standards
Telecoupling (distant-system interactions)	Interactions between distant systems linked through ecological or socioeconomic flows	Spread of White-Nose Syndrome, global timber trade, ecotourism, climate change	Enforce global cave hygiene protocols, regulate global timber trade, promote global awareness/funding, monitor climate impacts
Metacoupling (integration of all three types of coupling)	Combined framework using intracoupling, pericoupling, and telecoupling simultaneously	Regional development altering local land use (intracoupling), shifting logging to adjacent forests (pericoupling), and increasing distant ecotourism flows into caves (telecoupling)	Design multi-scalar strategies addressing local, regional, and global pressures together

By integrating all three coupling types, the metacoupling framework enables researchers and conservation practitioners to map how local, regional, and distant systems interact simultaneously, revealing feedback loops and compounding pressures that a narrower analysis might overlook [4–6]. For example, regulations restricting land-use change in one county can protect local bat habitat (intracoupling), displace logging operations into neighboring forests and counties with fewer regulations (pericoupling), and influence the global economy by reducing timber supply (telecoupling) [7–9]. The cumulative effect of these interactions may significantly degrade habitat or accelerate disease spread, even if each individual driver appears benign when considered in isolation [3,20,32].

In summary, through the literature review and synthesis under the metacoupling framework, we identified four main metacoupled dynamics influencing Indiana bat conservation: (1) Local intracouplings, such as land-use decisions, roost tree protection, and community attitudes toward bats, which directly determine habitat quality and support for conservation initiatives [16,18,21]; (2) Regional pericouplings, where differences in adjacent land-use policies and economic pressures displace habitat loss or disturbance across borders, highlighting the need for coordinated management among counties and states [20,38]; (3) Global telecouplings, including the spread of White-Nose Syndrome, international timber markets, and climate-driven habitat change, which create distant but powerful feedbacks on local bat populations [8,10,12,41]; and (4) Cross-scale feedbacks, where local, regional, and global processes interact to either reinforce or undermine conservation outcomes, demonstrating the importance of integrated, multi-level policy implementation [4–6]. Together, these results indicate that Indiana bat conservation is shaped by interacting ecological and socioeconomic forces across multiple scales.

4.3. Lessons from Applying the Metacoupling Framework to Other Bat Species

The conservation crisis facing the Indiana bat is not unique. Across the globe, multiple bat species have suffered dramatic population declines or even extinction due to the same interconnected threats of habitat loss, disease spread, human disturbance, and climate change [12]. In 2008, the IUCN officially declared five species of bats extinct during the Anthropocene, including: the giant vampire bat (*Desmodus draculae*), the dusky flying fox (*Pteropus brunneus*), the large Pelew flying fox (*P. pilosus*), the dark flying fox (*P. subniger*), and the Guam flying fox (*P. tokudae*). Additionally, about 15% of bat species are currently listed as threatened by the IUCN, classified as critically endangered, endangered, or vulnerable. Another 18% lack sufficient data for assessment, though many may be in the same critical state. Studying these cases highlights the urgency of conservation action and shows how the metacoupling framework can reveal patterns and drivers often missed by conventional approaches.

The dusky flying fox (*P. brunneus*), once native to Australia [44], was one of the five species declared extinct in 2008 [12]. Believed to have gone extinct in the mid-20th century, this species suffered from land clearing, persecution due to perceived threats to fruit crops, and increasing human pressure on roosting sites [44]. In this case, pericoupling dynamics were likely at play; neighboring agricultural systems, landowners, and regional governments implemented inconsistent policies, resulting in fragmented habitat protection and variable enforcement [4]. In hindsight, a metacoupling analysis might have revealed how adjacent land-use decisions and regional economic interests created reinforcing feedback loops that led to species collapse [4–6].

The Philippine bare-backed fruit bat (*Dobsonia chapmani*) is another species in need of radical conservation management changes. Having been declared extinct in 1996 due to a combination of extensive deforestation, agricultural expansion, and hunting pressure [45], it was rediscovered in 2001 and is considered in critical condition today [46]. Global demand for tropical timber and farmland commodities contributed to the loss of native forest habitat, while local communities, often operating under economic hardship, engaged in bat hunting for food and traditional medicine [45]. Although this species is in an entirely different geographic location, the threats it is facing mirror those threatening the Indiana bat: habitat loss driven by regional logging and urbanization, coupled with local stressors and distant economic drivers [12,32,35].

Although the application of the telecoupling framework to bat conservation is still emerging, research in other taxa provides useful precedents. For example, studies of migratory birds have demonstrated how changes in one part of a species' range, such as habitat destruction in wintering grounds or changes in food availability due to agricultural intensification, can lead to population declines at breeding sites thousands of kilometers away [24,43]. These studies highlight the importance of understanding cross-system flows.

Additionally, applications of the telecoupling framework to zoonotic disease ecology have illustrated how human movement, tourism, and global trade networks facilitate the spread of wildlife pathogens, such as White-Nose Syndrome in bats or chytrid fungus in amphibians [32,34]. These analyses emphasize that conservation must consider not only where a species lives, but how human behavior in distant regions may influence species health and survival through invisible or indirect pathways [4–6].

5. Discussion

This study demonstrates how the metacoupling framework can be applied to Indiana bat (*Myotis sodalis*) conservation, highlighting the influence of local, regional, and global interactions on population trends, management actions, and conservation outcomes. Indiana bat conservation is shaped by multiple, interacting factors rather than by isolated local processes [4–7,12]. The results of this synthesis show that the framework effectively connects ecological and social perspectives, emphasizing that conservation outcomes are shaped by cross-scale interactions rather than single drivers. The following discussion explores these findings in greater depth, examining their implications for management, policy, and sustainability, while also addressing key limitations and future research directions.

5.1. Cross-Scale Conservation Insights and Sustainability Implications

Across all three scales, the persistence of WNS and ongoing habitat degradation emphasize the need to maintain and restore critical roosting and hibernation areas for Indiana bats. However, without regional cooperation and global awareness, local management actions remain vulnerable to external pressures. Regional disparities in forestry practices and land-use planning illustrate how inconsistent policies weaken landscape connectivity and migration corridors that are essential for population recovery. At the global level, trade, tourism, and climate change demonstrate how distant human behaviors drive local ecological outcomes, revealing the importance of aligning species conservation with global sustainability goals.

Viewing the Indiana bat through a metacoupled lens emphasizes the species' broader ecological and economic importance. As natural pest controllers, bats contribute to agricultural productivity and reduce the need for chemical pesticides, providing a sustainable ecosystem service that benefits both people and the environment [12,22]. These ecosystem services directly link Indiana bat protection to human sustainability, aligning with the United Nations Sustainable Development Goals [26]. By connecting local conservation actions to regional policy and global sustainability initiatives, bat protection contributes to biodiversity conservation, ecosystem resilience, and socioeconomic sustainability simultaneously [12,22,26].

Overall, this synthesis reinforces that the metacoupling framework offers a practical foundation for connecting ecological processes with human decision-making across scales. Rather than treating the species' decline as a purely ecological issue, it situates Indiana bat conservation within global systems of production, consumption, and environmental change, helping to identify where interventions can most effectively strengthen both biodiversity and sustainability outcomes.

Incorporating the metacoupling framework into global bat-conservation management provides more than a new theoretical framework; it offers a practical tool for navigating a rapidly changing world [4]. Figure 4 illustrates how conservation and management measures at different scales influence bat dynamics and conservation actions. If conservation planning is to keep pace with the scale and complexity of contemporary threats, we must embrace these broader, more holistic perspectives.

5.2. Conservation Implications and Management Recommendations

Addressing the decline of the Indiana bat and other endangered bat species requires a rethinking of conservation strategies that have traditionally focused on localized threats in isolation. While protecting roosting and hibernating sites is essential, it is not enough to address the broader forces negatively impacting these species, such as market dynamics, regional development, and human movement, that drive habitat loss and disease spread [4,12,20]. The metacoupling framework offers a more comprehensive view, revealing how distant and nearby systems interact in ways that either support or undermine conservation goals [4]. Applying this framework allows for a more integrated, responsive, and effective approach to managing the complex range of threats faced by bats today.

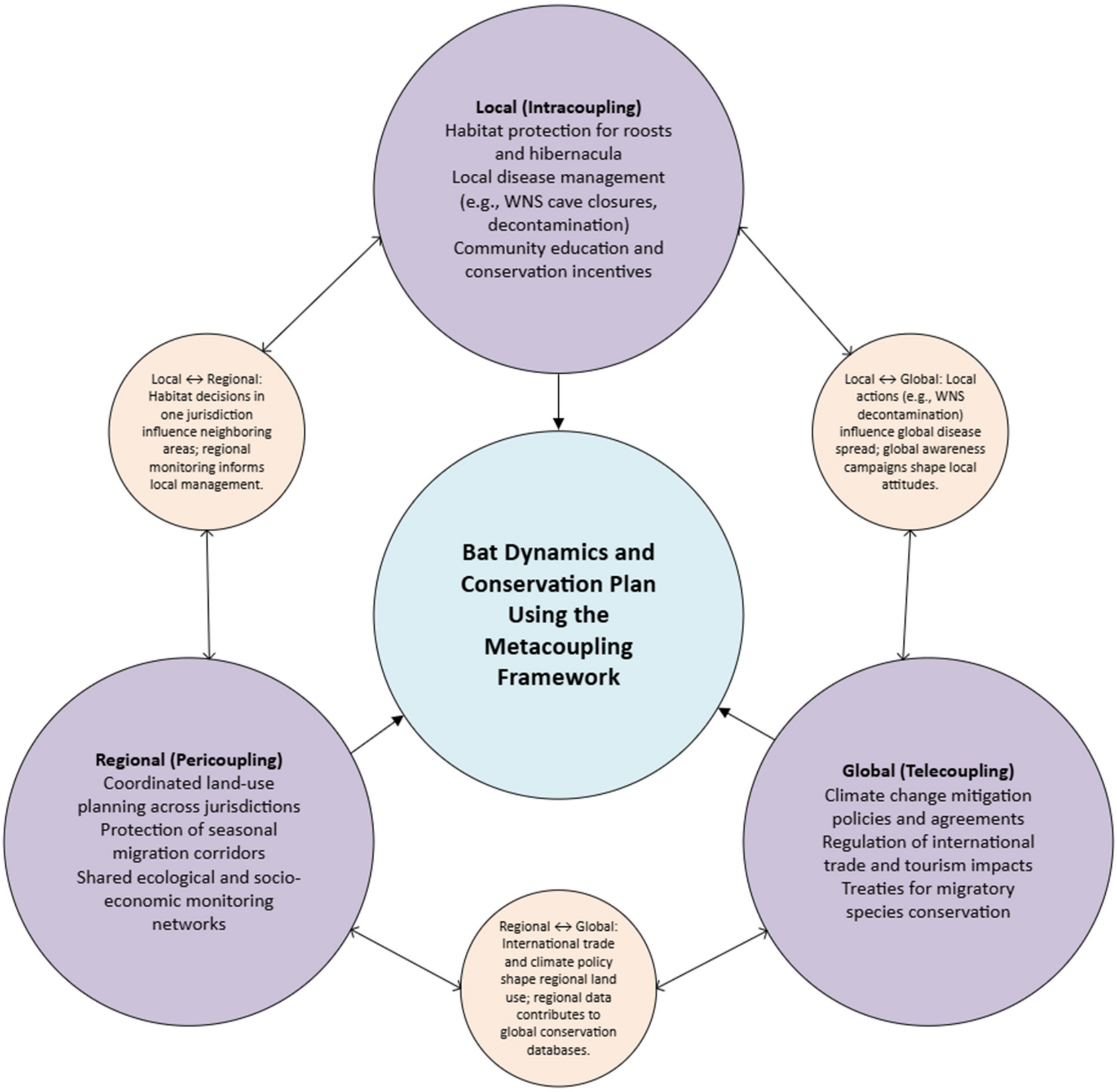

Figure 4. Bat Dynamics Under Influences across Multiple Scales. Conceptual diagram showing how conservation and management measures at different scales influence bat dynamics. The arrows represent the relationships between local, regional, and global scales, illustrating how each level influences bat dynamics within the metacoupling framework.

One clear implication of the telecoupling framework is the need to incorporate distant economic and policy drivers into conservation planning. Decisions made in urban centers, for instance, often have cascading effects on the rural landscapes where bats live. Housing development driven by rising demand in metropolitan areas frequently leads to suburban sprawl that encroaches on bat habitats, even if the species itself is not immediately present in those urban cores [10]. Similarly, distant consumer demand for timber products may influence where and how forests are harvested in bat-inhabited regions [10,20]. These insights suggest the importance of aligning policies across sectors, not just environmental regulations, but also housing, transportation, and trade policies that shape land use from afar.

The telecoupling framework can also be used to address the role of tourism and recreation in species conservation. Ecotourism in caves may appear to be a localized activity, but the movement of people between sites, and between regions and countries, contributes to the spread of WNS [12,31]. Management plans often address human disturbance but rarely consider how global ecotourism contributes to WNS spread, such as the initial spread of White-Nose Syndrome from Eurasia to North America [12]. Rather than focusing only on cave closures, conservation strategies could include broader awareness campaigns, decontamination infrastructure, and partnerships with tourism agencies to distribute information and promote responsible behavior [12,21].

Locally, landowners, forestry managers, and planning boards determine whether critical habitat is preserved or destroyed [7,21]. Conservation incentives, such as financial support for retaining roosting habitat, or community education programs that promote coexistence with bats, can help shift these local dynamics toward outcomes that favor species persistence [12,21]. In places where bats are misunderstood or feared, improving public perception could be just as important as habitat protection [12,21].

Additionally, a protected habitat in one area may be undermined if a neighboring jurisdiction permits clear-cutting or industrial development [10,20]. Coordinated land-use planning, inter-county conservation agreements, and shared ecological monitoring could help ensure that protective measures are spatially and temporally aligned [7]. This regional approach would also support seasonal migration and dispersal, ensuring that bats can move safely between summer and winter habitats [40]. This is particularly applicable to species that do not hibernate during the winter, as Indiana bats do, but instead migrate to warmer climates to follow their insect food source. For example, hoary bats from across the U.S. and Mexican free-tailed bats from the Carlsbad Caverns both migrate to Mexico in the winter [47]. These bats migrate across many different political boundaries each year; without cohesive conservation plans along their migration path, they will be negatively impacted, even if one jurisdiction is working diligently to conserve their habitat.

Conservation efforts should be adaptive; ongoing monitoring is not only necessary to track bat populations, but also to observe how the human systems that affect them evolve over time [6,7]. Changes in land-use patterns, economic incentives, or public attitudes could all negatively impact these sensitive animals [12]. Networks that bridge federal and state agencies, non-governmental organizations, and academic institutions will be essential for creating region-wide strategies that anticipate unintended consequences and avoid policy gaps. By tracking both ecological indicators and socio-economic trends, managers can refine their strategies and remain responsive to emerging challenges. This adaptive approach is something that static, one-size-fits-all plans often fail to do [4–6].

The metacoupling framework aligns with a growing consensus in conservation science that biodiversity in the Anthropocene requires recognizing and managing the full complexity of human–environment interactions [12,24,43]. For species like the Indiana bat, whose life cycles span multiple landscapes and whose threats originate from both near and far, this integrative perspective is not merely helpful, it is essential for the successful conservation of the species.

5.3. Future Directions

Because this study synthesizes existing literature rather than presenting new field data, its conclusions are constrained by the quality and consistency of available sources. Addressing these limitations will require more quantitative, data-driven analyses to measure the relative influence of different drivers and to test the framework's predictive capacity. Empirical research linking bat ecosystem services to sustainability indicators could also clarify how species protection contributes to agricultural stability, climate resilience, and broader sustainability outcomes.

Looking to the future, empirical studies that quantify these frameworks with real-world data are urgently needed. Spatial analyses that map land-use change, disease spread, and socio-economic activity altogether could help identify priority areas for intervention. Integrating ecological monitoring with data on tourism flows, timber exports, and housing trends would enable the development of multi-scale conservation models that address the challenges bats face today [10,12,20]. Emerging tools, such as artificial intelligence, machine learning, digital twins, remote sensing, agent-based modeling, and social network analysis, can also be used to capture the multi-scalar dynamics that shape bat conservation [4,48]. These methods could be used to model how changes in one system cascade through others, leading to targeted, timely, and effective conservation responses.

In addition to further research, future policy and management efforts should emphasize cross-sector and cross-boundary coordination. For the Indiana bat, conservation strategies guided by the metacoupling framework can help identify multi-scalar problem areas and promote collaboration across local, regional, and global levels. At the local scale, strategies might include developing community education programs or incentivizing forest stewardship practices on private land [12,21]. At the regional scale, strategies could involve creating inter-county or interstate habitat corridors, coordinating land-use policies, or implementing regional timber certification programs that account for bat conservation [10,20]. At the global scale, strategies may include adopting standardized ecotourism hygiene protocols, regulating international trade practices that influence domestic land use, and continuously monitoring the effects of climate change [10,12,24,41].

There is a pressing need (1) to implement standardized international cave decontamination protocols to prevent the spread of White-Nose Syndrome and (2) to develop aligned timber certification standards across counties, states, and countries. Conservation strategies must also engage stakeholders across disciplines and sectors, including economists, urban planners, tourism managers, and local communities, who may not traditionally be part of wildlife conservation efforts but whose decisions deeply affect ecological outcomes [4,6]. By integrating these efforts, conservation can move beyond isolated interventions toward a truly systems-based approach that is both ecologically grounded and socially responsible [4].

6. Conclusions

Sustainable conservation management depends on understanding metacoupled human–nature systems. Protecting the Indiana bat helps maintain ecosystem stability and supports sustainable agriculture by reducing pest populations, thereby contributing to both ecological and social sustainability. Time is of the essence for endangered species like the Indiana bat. Its population continues to decline under pressures that are accelerating rather than stabilizing. However, by expanding the conservation plan under the metacoupling framework, we can better match the complexity of the problem with an equally sophisticated set of tools. If adopted broadly, this approach can improve outcomes for the Indiana bat and transform how we approach conservation for other species caught in the web of global environmental change. By examining Indiana bat conservation through applying the metacoupling framework, this study offers a new lens for understanding multi-scale threats to wildlife. It highlights the importance of integrated, multi-scale approaches for sustaining biodiversity in an interconnected world.

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