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Review

Define–Investigate–Estimate–Map (DIEM) Framework for Modeling Habitat Threats

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Abstract: As the human population increases, the landscape is altered to provide housing, food, and industry. Human activity poses a risk to the health of natural habitats that, in turn, affect biodiversity. Biodiversity is necessary for a functioning ecosystem, as species work synergistically to create a livable environment. It is, therefore, important to know how human practices and natural events threaten these habitats and the species living in them. A universal method of modeling habitat threats does not exist. This paper details the use of a literature review to formulate a new framework called Define–Investigate–Estimate–Map (DIEM). This framework is a process of defining threats, investigating an area to discover what threats are present, estimating the severity of those threats, and mapping the threats. Analysis of 62 studies was conducted to determine how different authors define and characterize threats in various contexts. The results of this analysis were then applied to a case study to evaluate the Choctawhatchee River and Bay Watershed. Results suggest that the most abundant threat in the watershed is agricultural development, and the most destructive threat is urban development. These two threats have the greatest impact on the total threat level of the watershed. Applying the DIEM framework demonstrates its helpfulness in regional analysis, watershed modeling, and land development planning.

Keywords: GIS; habitat; threat; ecology; land use/cover; watershed

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1. Introduction

In general, various events and activities put habitats at risk of being degraded. These stressors are referred to as habitat threats. Habitats are at risk of degradation due to human and/or environmental pressure such as land use, climate change [1], increasing population, urbanization, agriculture, and running-water diversions [2]. Habitats are also threatened because of side effects of human development, which include habitat loss, land fragmentation, deforestation, conversion to intensive agriculture, pollution (by synthetic pesticides and fertilizers), biological factors (pathogens and introduced species) [3], and constructed dams for water consumption and energy production [4]. Globally, the terrestrial landscape has a 7.56 million km network of streams, and river channels with a surface area of approximately 773,000 km^2 [5] are impacted. Increasing population demands for water and land resources and increased food production add to the stresses on these terrestrial resources. Of the world population, 50% lives within 3 km of freshwater; more than 50% of the historical expanse of floodplains is constricted, and more than 600,000 km of inland waterways globally are altered for navigation [2]. Paukert et al. [4] observed that this pressure endangers freshwater biodiversity more than it does terrestrial and marine systems. They stated and estimated that 68% of all mussel species, 51% of crayfish species, 40% of amphibian species, and 46% of fish species in United States freshwater are considered to be vulnerable or thought to be extinct. Globally, 10% to 50% of species are threatened with extinction; in the United States, at least one-third of native species are considered to be imperiled [6]. Of the world's insect species, 40% may become extinct over the next few decades [3]. Therefore, it is necessary to understand threats that impact natural habitats and biodiversity [7].

Although "habitat threat" is broadly described as all stressors that put habitats at risk, it is a mercurial concept that is multidisciplinary in nature. Generally, mercurial concepts adapt to the context, geography, and spatial and temporal scale at which they are applied [8], and the multidisciplinary nature of concepts involves many aspects and principles from both the ecological and social perspectives [9]. To the best knowledge of the authors, the term "habitat threat" is not well defined in the literature, as shown in our literature review of habitat-threat definitions in Table 1. This creates a need to define it.

Table 1. Definitions and examples of habitat threats found in the literature.

Definition/Description	Examples	Context/Objective	References
Economic development activities that cause a risk of species extinction	Urban development	Ecological conservation	[10]
Events causing disturbances to habitat structure	Wildfires	Fire and habitat management	[11]
Pressure imposed on landscapes through human activity	Urbanization, agriculture	Sustainable land-use evaluation	[12]
Things that hinder biodiversity	Threats in order: habitat destruction, invasive species, climate change, pollution, overexploitation, habitat fragmentation, and disease	Preserving biodiversity	[6]
Activities that pose a risk to species richness and endemism	Agricultural activity, forestry, animal husbandry, fishery, invasive species	Species conservation	[13]
Stressors that cause habitat degradation	Urbanization	Pool-breeding amphibian habitat assessment	[14]
Anthropogenic disturbances	Agriculture, urbanization, road and railroad density, pollution sites, canals, and dams	Freshwater ecosystem assessment	[4]
Practices that transform the ecosystem	Urbanization, cultivation (i.e., forestry plantation), grazing, mining, introduction of invasive species	Ecosystem risk assessment	[15]
Stresses on the ecosystem	Agriculture, industry, domestic activity, water extraction, introduction of exotic species, dams and reservoirs, and pollution	Freshwater species conservation	[16]
Human activities	Agriculture, urban, point-source pollution, infrastructure, and nonagricultural threats	Conservation of lotic systems	[17]
Anthropogenic activities that alter the natural state of the habitat	Pollution, agricultural expansion, removal of soil for various purposes, removal of vegetation (extraction of consumable products), expansion of vegetation (spread of weeds), land encroachment, fishing, siltation	Indian Sarus Crane habitat conservation	[18]
Negative human and environmental impacts	Sea-level rise	Coastal archaeological site preservation	[19]
Human-related impact.	Mining and agriculture	Freshwater conservation	[20]
Habitat conversion due to development	Urbanization, agriculture, fossil fuel energy, renewable energy, mining	Global habitat	[21]
Human activities that drive species loss and ecosystem change	Open-cut mining, grazing, oil-palm production, and coastal urban development	Conservation planning	[22]

Table 1. *Cont.*

Definition/Description	Examples	Context/Objective	References
Factors that put biodiversity at risk	Natural threats: erosion, floods, droughts, disease, pests; human-induced threats: population pressure, overexploitation of biological resources, uncontrolled introduction of exotic species, poaching, fire, war; political threats	Rangeland resources/biodiversity	[23]
Things that put the health and condition of ecosystems at risk	Unconventional natural-gas development	Watershed	[24]
Things that pose a risk to species richness and endemism	Human activities	Mexican freshwater crayfish conservation	[25]
Things that change species diversity, distribution, and conservation status. Activities that pose a risk to species richness and endemism	None listed	Freshwater biodiversity	[26]
Human activities that impact water resources	Increasing population, land cover changes in watersheds, urban expansion, and intensive use of freshwater resources	Water-resource management and security	[27]
Something that poses a risk to a habitat	Thermal stress, cyclone damage, land-based pollutants, and predation. Main threat is climate change	Risk to coral-reef habitats	[28]
Human activities	Agriculture, urbanization, river regulations (channelization, dams, flood control by levees)	Large floodplain river conservation	[2]
Anthropogenic factors that impact ecosystem services	Urbanization, construction, agriculture, and invasive species	Forage production	[29]
A human-modified land-use/cover type that causes habitat fragmentation, edge, and degradation in neighboring habitats	Agriculture and urbanization	Habitat quality	[30]

A proper understanding of habitat threats is important for the following reasons:

(1) Habitat threats impact biodiversity, which is connected to the production of ecosystem services.

(2) Understanding of habitat threats plays an important role in scheduling conservation action, designing regional conservation plans, and improving biodiversity [7].

(3) Knowledge of habitat threats is required to ensure better habitat quality and suitability.

(4) Conservation planning primarily focuses on conserving species and ecosystems of interest, but threats may alter management objectives [20].

(5) Scientists agree that restoring ecological processes and reducing anthropological threats are both crucial for successful conservation [31]. Since financial resources for conservation are limited, identifying priority areas for conservation to achieve the greatest impact is important [16].

(6) Proactively identifying threats and habitats at risk is critical to achieving sustainable development [21].

Habitat threats are classified in a number of ways, most commonly as natural or anthropogenic by several studies [2,6,23,27,28]. The mercurial and multidisciplinary nature of habitat threats has resulted in various classifications, provided in supplementary material. This has created the need to develop a synthesized classification tree for habitat threats.

The mercurial and multidisciplinary nature of habitat threats gives them a complex character. In general, this character leads to multiple ways of perceiving and quantifying them, and depends on the threat's characteristics and the technique on which it focuses [9]. Studies have characterized existing perceived threats by using weights, the range of the threat, and the manner of impact (Table S1 in the Supplementary Materials). In the literature, habitat threats are measured using several indices to model how threats affect habitats [4,6,19,25,32]. Threat level is frequently cited as one of the major indices for explaining diversity patterns [13]. However, to the best knowledge of the authors, a synthesis of habitat-threat indices and a framework to estimate them are not available in the literature.

Conceptual frameworks are often an excellent way through which to understand a system and can involve mental or physical images [33]. Therefore, conceptual models are needed to collate, visualize, understand, and explain situations (actual or predicted) and how they might be solved [34]. These frameworks can be an important first step in developing a quantified model [33] when they are considered as organizational diagrams that bring together and summarize information in a standard, logical, and hierarchical way [34]. To the best knowledge of the authors, there is no clear framework to estimate and map habitat threats.

The two objectives of this study address this need by (1) developing a framework that could be used in defining, classifying, characterizing, and estimating habitat threats in any given area by synthesizing the existing literature on habitat threats; and (2) empirically operationalizing the framework in case-study contexts, advancing it beyond desk-based feasibility testing through its application to real-world settings by assessing habitat threats in the Choctawhatchee River watershed basin in the southeastern USA.

2. Materials and Methods

The process used in this study consisted of three methodologies: one for conducting the meta-analysis, one for developing a habitat-threat estimation framework, and one for applying the framework to a watershed. Figure 1 was created by visualizing the process of mapping habitat threats (going from concept to practice). Figure 2 is a map of the Choctawhatchee River Watershed which was created using ArcMap 10.4.1, a GIS software manufactured by the Environmental Systems Research Institute (Esri) based in Redlands, California, USA. Figure 3 is a summary of the methods.

2.1. Meta-Analysis

1. A document search was performed using Google Scholar on 26 November 2019. The keywords “threat index” and “habitat threat” were used, which gave 3370 results and 406 results, respectively, for a total of 3776 articles. The search range of years was set as 2000–2019 to capture the past two decades. Out of the 3776 retrieved articles, 401 were identified as being related to habitat threats. The selection criteria for determining whether an article was relevant were accessibility and context. Full-text articles available for viewing and downloading were included. Articles pertaining to threat indices such as political, sports, personal health, and vehicular threats were excluded.
2. The article pool was then further narrowed by selecting articles that fit the criteria of describing environmental, ecological, biodiversity, and habitat threats. We retrieved 34 references that had been published between 2003 and 2019.
3. Forward and backward snowball sampling was utilized in these 34 papers. These processes involve analyzing papers that cite a previously retrieved paper (forwards) and reviewing papers that the retrieved paper cited (backwards). An additional 28 relevant papers were found that were not in the initial set of search results. The total number of papers increased to 62. These papers were published between 1997 and 2019.
4. These 62 papers were analyzed by gathering information pertaining to the definitions, types, and characteristics of habitat threats. Of the 62 papers, 24 articles were used to define habitat threat, 44 articles were used to synthesize the types of threat, 11 articles were used to synthesize threat characteristics, and 14 articles were used to understand threat index calculations. Several articles provided information on multiple subjects.

5. Analytical results were then summarized in six tables and nine figures. Definitions and descriptions from the literature are shown in Table 1. Most studies did not give a direct definition of "habitat threat". A definition was derived from what was understood from those studies. Multiple tables were made that list the types of threats, their category based on specificity, and the references that cite each one as well as the sources of available data that were either used in the literature or found by searching the Internet, the variables used to standardize the equations, and a list of threat index estimation equations. Index equations that had directly been found in the literature or had been produced on the basis of the calculation methodology from the literature were compiled. Equations were grouped according to specificity (broad, region-specific, and habitat-specific) and then changed to be more uniform. Similar variables are represented by the same symbol. A bar graph that displays the number of articles per year was created. Figures displaying the meta-analysis results were created by classifying articles used in the analysis by threat type and country of origin. A figure was made to display a tree diagram grouping similar threats and then categorizing them on the basis of how broad or specific the threat is. Another figure displays the country, types of threats, and the number of articles that mention each threat are displayed by using the Layout 5 design of a bar graph in Microsoft Excel 2010. A study distribution map was created by overlaying the number of articles in each country using a photo-editing software called Paint.NET 3.6 developed by dotPDN, LLC at Washington State University in Pullman, Washington, USA. Two histograms were created for the threat characteristics of distance and weight and combined into one figure. The data used to create the figure came from threat-characteristic data found in 11 studies. Finally, a selection tool to aid with choosing the equation that best fits on the basis of obtainable data was made. Equations were first grouped by an identifying variable. The used variables were threat frequency (f), threat severity (α), landscape factor score (L), number of species (S), and threat factor score (F). One equation had nothing in common with the other equations and was placed in its unique group identified by the conversion potential (CP) variable. Equations were then listed in order of complexity.

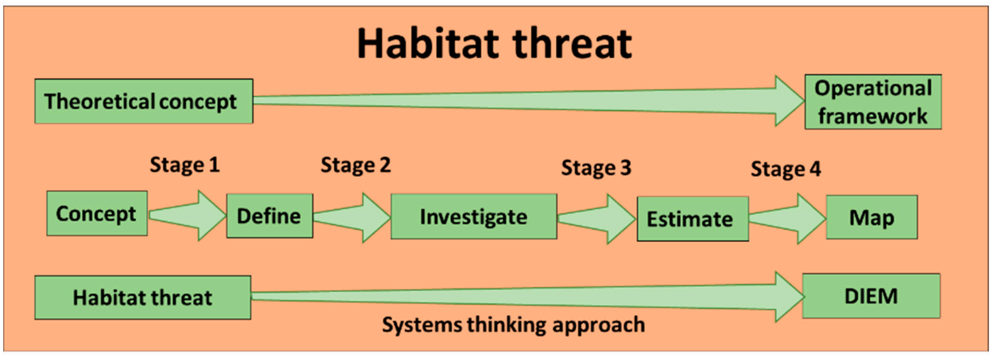


Figure 1. Concept to creation of DIEM framework starting from a mental to an operational model.

2.2. Habitat Threat Framework Development

Analytical results were used to formulate the Define–Investigate–Estimate–Map (DIEM) framework for assessing habitat threats. The DIEM framework illustrates a method of defining threats on the basis of the derived definition, investigating an area using available spatial data, estimating threat severity using the principles used in existing equations, and mapping threats using spatial analysis methods. The theoretical concept is that the resulting framework should be able to serve as a decision support tool. The framework is divided into four stages.

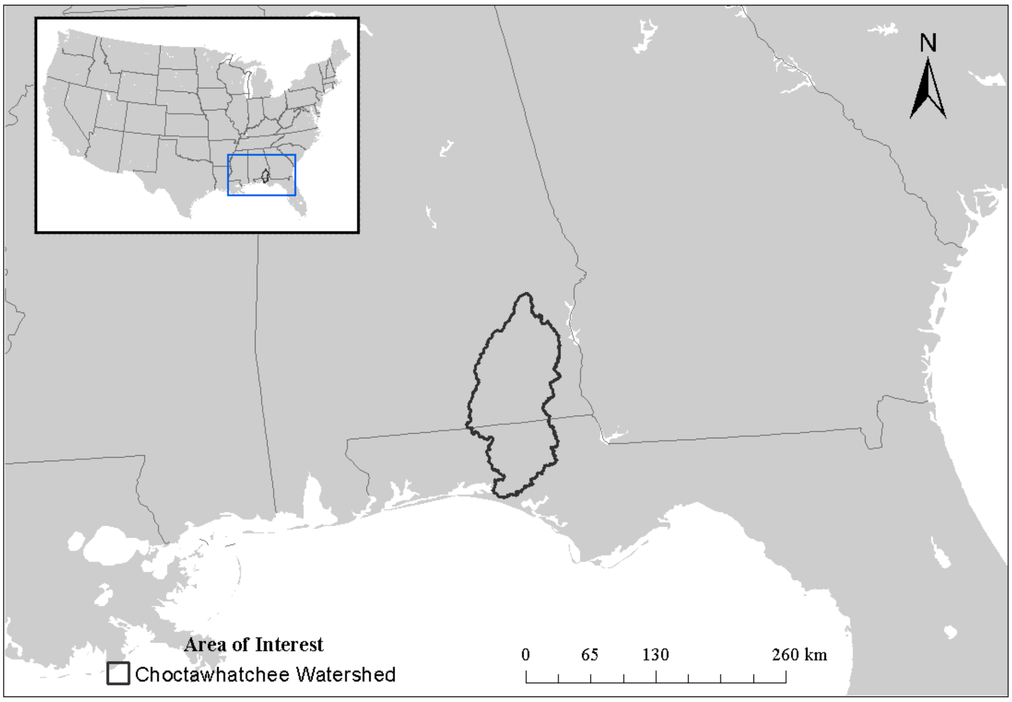


Figure 2. Location of Choctawhatchee Watershed in southeastern USA.

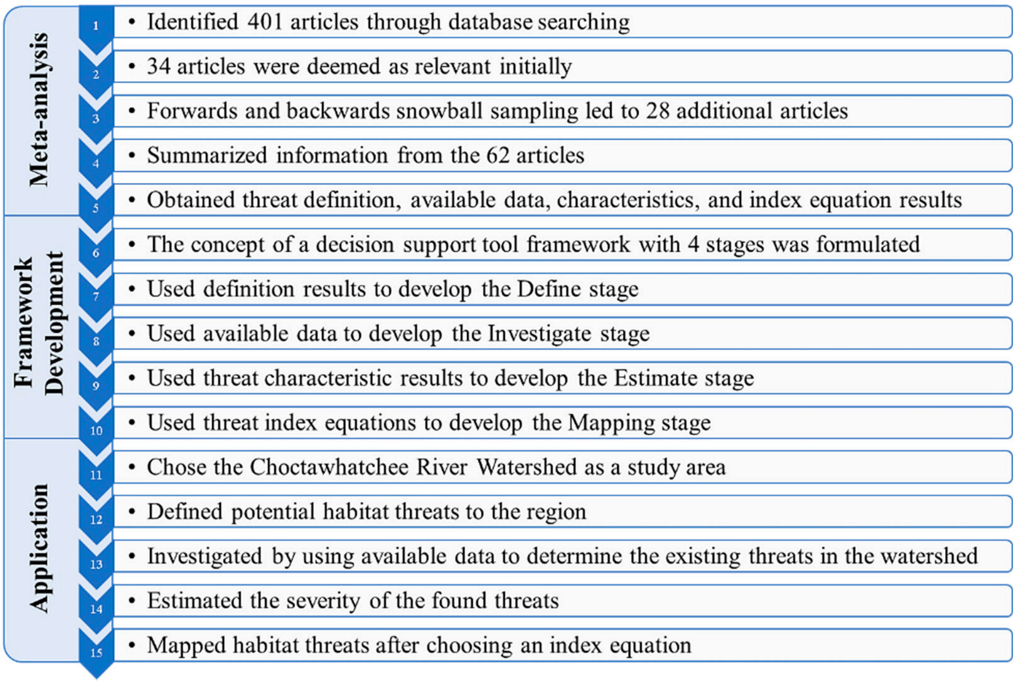


Figure 3. Flowchart of the methodology process.

Stage 1: The definition of habitat threat and the compilation of the types of threats from the meta-analysis are utilized to formulate the Define stage of the DIEM framework. The definition and examples of what is considered to be a habitat threat are used in this stage to determine what constitutes a threat in a particular area.

Stage 2: The list of available data is used in the Investigate stage. This stage involves analyzing spatial datasets to determine if the previously defined habitat threats occur within the area of interest. Methods of analysis involve importing the data into GIS software such as ArcMap, ArcGIS Pro, ArcGIS Online, and QGIS. It is also possible to use online data viewers.

Stage 3: Threat characteristics are estimated in the Estimate stage. Meta-analysis results are used to estimate the maximal area that a threat can impact and the weight or destructive capacity of that threat. A table of the distance and weight values of many different threats can be found in the Supplementary Materials. Alternatively, threat characteristics can be estimated on the basis of opinions from experts in the field.

Stage 4: Habitat threat maps are created with GIS software. Alternatively, Python can be used to create maps. Threat index equations chosen by using the equation selection tool are used to calculate the relative threat that each grid cell presents. Multiple maps for each threat can also be produced as an alternative. Choosing a threat index equation is not required in that case. The final framework was then developed. A visualization of how the initial theoretical concept was turned into an operational framework is shown in Figure 1. Different results of the meta-analysis were used in conjunction with one another as components in a systems thinking approach to formulate the DIEM framework.

2.3. Habitat Threat Framework Application

The framework was applied to a case study to investigate habitat threats in the Choctawhatchee River and Bay Watershed. The Choctawhatchee River originates in Alabama and drains into Choctawhatchee Bay in Florida's panhandle. It is the third largest river system in Florida in terms of discharge [35]. The location of the watershed is displayed in Figure 2. The watershed is a biodiversity hotspot, as it is home to more species of trees than any other forest in temperate North America, according to the Choctawhatchee, Pea, and Yellow Rivers Watershed Management Authority [36]. The goal is to keep track of the threats in that area as a step towards modeling the ecological system in the watershed. Habitat threats for the area were defined as anthropogenic disturbances that include urbanization, agriculture, power plants and dams, mining, and population pressure. Natural threats such as wildfires and invasive species were also considered. A Google search and literature review were conducted to gather spatial datasets to be used for the investigation. The source of these data and their descriptions were then compiled in a table. These datasets were analyzed using ArcMap 10.4.1 to determine if any of the defined threats existed within the watershed. Threat maps were then created for each threat found in the watershed. Python programming, and specifically the Geospatial Data Abstraction Library (GDAL) 3.2.0 developed by the Open Source Geospatial Foundation in Chicago, USA in conjunction with NumPy 1.19.2 created by Travis Oliphant in Provo, USA and Pandas 1.2.1 created by Wes McKinney in New York City, USA, was used to produce the maps. Map results are displayed in Section 3.7 of the Results.

The methodology process is visualized in Figure 3. This figure serves as a summary of the process for quick reference. The meta-analysis, framework development, and application methodologies are each composed of five major steps.

3. Results

The distribution of studies per year is shown in Figure 4. These various papers were used to synthesize the types, definitions, and characteristics of threats, and the different ways to develop threat indices. Most articles are recent, with nearly 60% of the articles published after 2014. A timeline showing the cited threats for each five-year period is shown in Figure S15 in the Supplementary Materials. Different authors use different definitions for habitat threats, and these definitions evolve over time. More processes are recognized as threats as time goes on. Fossil fuel production was not mentioned in any paper in the results prior to 2015, for example.

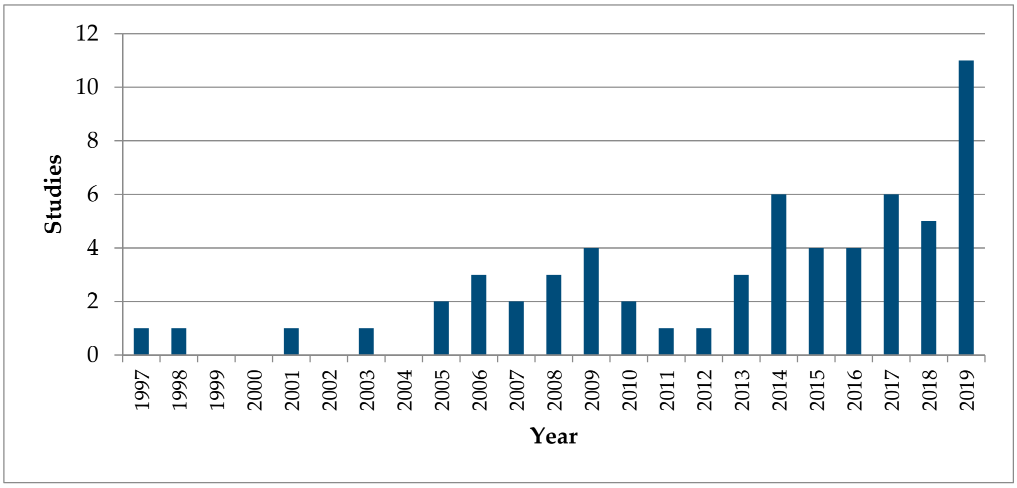


Figure 4. Number of studies per year for the 62 articles used in analysis.

3.1. Defining Habitat Threat

The idea of habitat threats is a concept that is known but not explicitly defined in the literature. This study seeks to create a general definition for the term. The definition and description inferred from the literature are shown in Table 1. Most studies did not give a direct definition of habitat threat; its definition was derived from what was understood from those studies. Out of the 23 articles used to create the table, seven provided direct definitions of habitat threat [10–12,18,19,22,26].

Habitat is defined as "the resources and conditions present in an area that produce occupancy by a given organism" [37]. The distribution of species and the resources that they require should be considered when defining "habitat" for conservation purposes. If one wanted to conserve a specific species, it would be most effective to look at the species range (the area where a particular species can be found during its lifetime) and the resources that it needs. Additionally, a subhabitat can be defined within the general forest habitat [38]. Threat is defined as "an indication or warning of probable trouble" [39].

In this study, the definition of a habitat threat was developed (Figure 4) from the documented definitions listed in Table 1 and the dictionary meaning. These definitions are made up of two broad components, "habitat" and "threat", and several subcomponents. The threat component can include threat description and type subcomponents, while the habitat component includes present organisms, its environmental description, and ecological concepts and processes studied as subcomponents. Some of the categories to choose in the subcomponents are bulleted. In a few studies, the habitat threat definition emphasizes just one component, namely, the threat component (e.g., human activities).

A narrow definition of habitat threat includes one or two categories in the subcomponents. A broader definition can include multiple or all categories. The detailed broader definition specifies and/or describes the types of pressure, factors, impact, stresses, stressors, developmental activities, things, disturbances, practices, events, risks, and activities that indicate or warn of one or more probable types of difficulty faced by the habitat. The threat source can be anthropogenic or natural. The habitat component in the detailed definition of habitat threat refers to a place or environment for a species (plant, animal) and/or resource (e.g., water), with several ecological concepts and processes. Single or multiple (e.g., biodiversity) species and resources can be used to describe this component. Further, the environment for the habitat can be described using ecological concepts and processes such as species richness, endemism, biodiversity, extinction, and species loss. More information on the types of threats is provided in the next section. The process of going from a concept to developing a definition for habitat threats and a list of threat characteristics to investigate is shown in Figure 5.

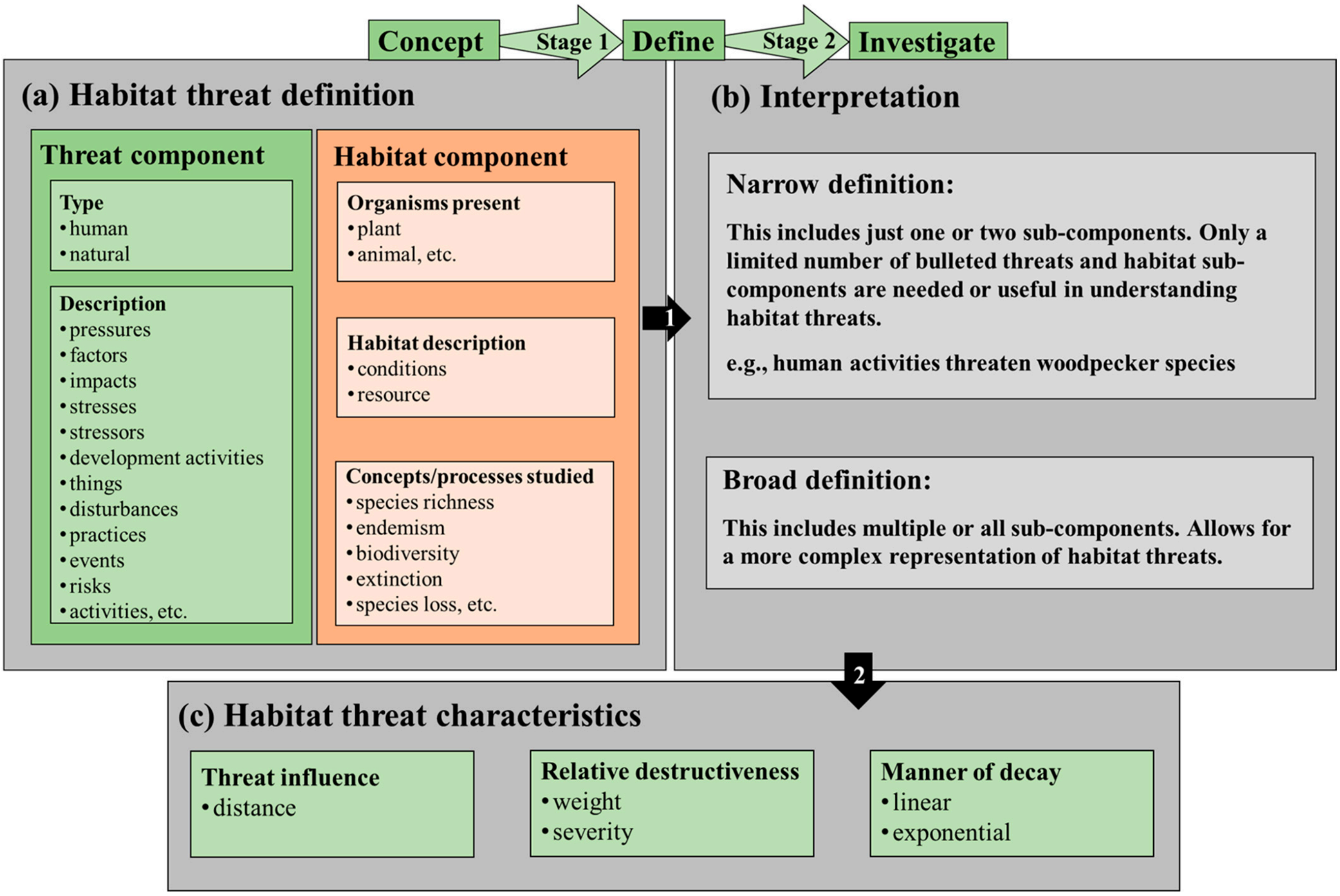


Figure 5. Definition of habitat threat developed in this study. (**a**) Components, subcomponents (lighter boxes) and categories (bullets) in definition; (**b**) interpretation of the definition; (**c**) characteristics of habitat threats.

3.2. Types of Threats

Habitat threats were classified in several ways in the literature. Figure 6 is a tree diagram developed by combining tree diagrams created from each of the studies (provided in Supplementary Materials). The developed synthesized tree diagram in this study has multiple levels. Habitat threats are generally on the first level, which is then separated into natural and anthropogenic categories and then further separated into more specific classifications. Natural threats can include climate change, disease, predation, pests, and wildfires. Climate change can also be considered an anthropogenic threat [40–43]. Specific effects of climate change considered threats are extreme weather, erosion, floods, droughts, and sea-level rise. Anthropogenic threats can include resource use, pollution, development and industry, fires, war, LULC change, and invasive species. Resource use involves the use or removal of living and nonliving habitat components, such as water, soil, plant and animal species, and raw material. More specific threats that fall under resource use are overexploitation, water use, poaching, and fishing. Water use can be further broken down into river regulations, canal, dams, and reservoirs. Pollution is any substance introduced into the environment that has a harmful effect. Specific types of pollution include land-based pollutants and thermal stress. Land-based pollutants are threats to aquatic and coastal habitats that originate from land-based activities. Sources of these pollutants include wastewater, urban runoff, chemical waste, and pesticides. Thermal stress or pollution degrades the quality of water by raising its temperature. Sources of thermal pollution include coal and nuclear power plants, steel and paper mills, and urban runoff. Development and industry describe activities associated with land development and raw-material processing. As land and raw materials are resources, some types of development threats can also fall under resource use. Specific types of development and industrial threats are agriculture, urbanization, forestry, infrastructure, population pressure, fossil fuel energy, renewable energy, mining, and bioenergy. LULC change is broad and can be further broken down into habit destruction and fragmentation. Habitat destruction is a process in which a habitat loses its ability to support native species. Climate change and invasive species can also be causes of habitat destruction [44]. Habitat fragmentation is when a habitat loses its connectivity due to land-use change.

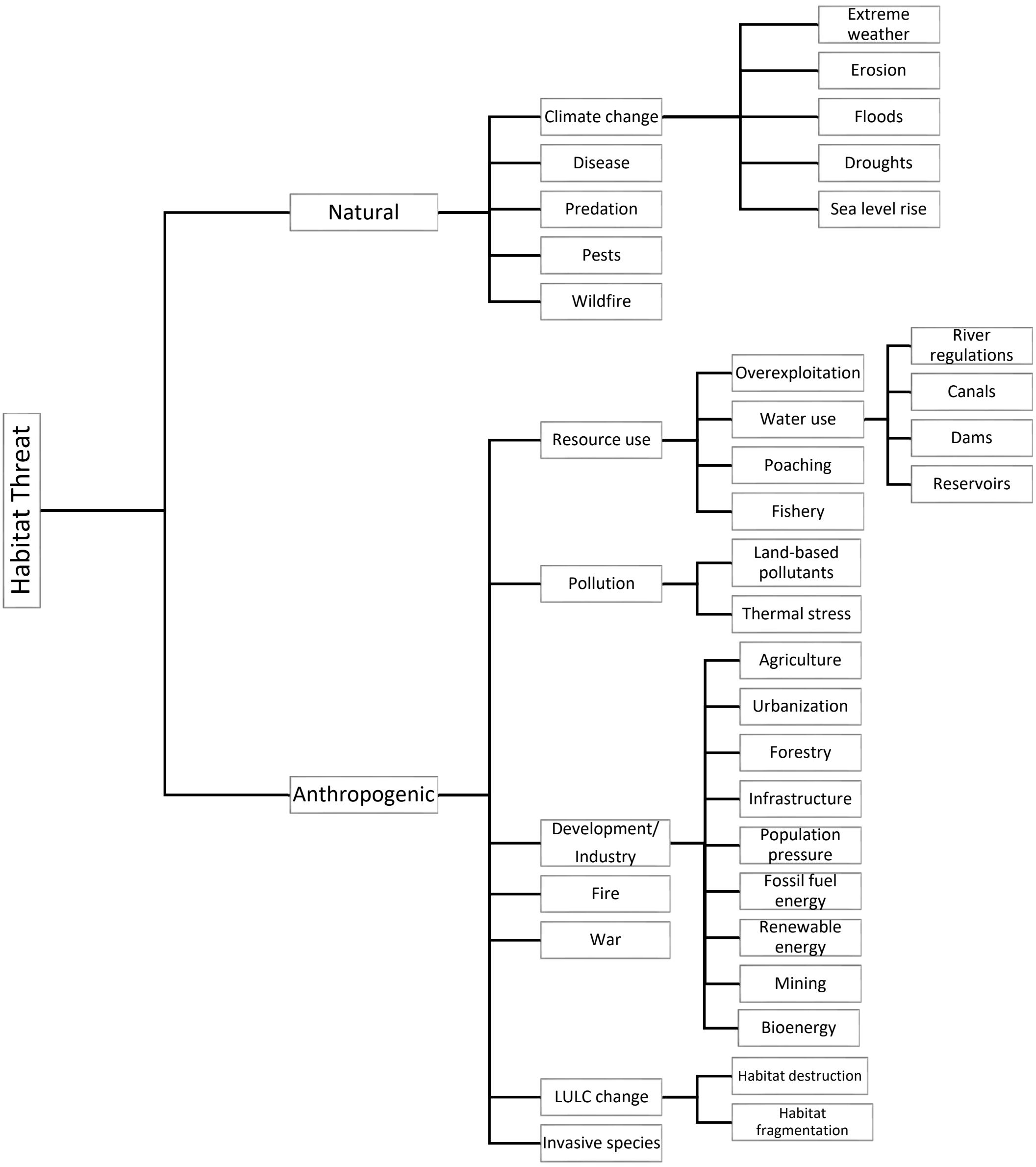


Figure 6. Habitat threat types found in the literature.

Tables 2 and 3 list studies that note each threat. Table 2 lists natural threats, and Table 3 lists anthropogenic threats. Both tables are broken down by classification (level). Level I denotes a broad level of classification (natural or artificial). As the level increases, the threats become more specific. The hierarchy was developed by first grouping threats on the basis of commonalities. Urbanization and agriculture are both anthropogenic threats. The two can also be considered to fall under development and industry.

Table 2. Studies that consider natural threats.

Level	Threat (Number)	References
I	Natural (9)	[6,9,11,19,23,27,28,45,46]
II	Climate change (5)	[6,9,19,27,28]
	Disease (3)	[6,23,46]
	Predation (1)	[28]
	Pests (1)	[23]
	Wildfire (2)	[11,45]
III	Extreme weather (1)	[28]
	Erosion (1)	[23]
	Floods (1)	[23]
	Droughts (1)	[23]
	Sea-level rise (1)	[19]

Table 3. Studies that consider anthropogenic threats.

Level	Threat (Number)	References
I	Anthropogenic (43)	[2,4,6,9,10,12–18,20–29,37,46–65]
II	Resource use (6)	[2,4,6,13,16,27]
	Pollution (4)	[4,16,18,28]
	Development/industry (4)	[16,56,61,64]
	Fire (1)	[23]
	War (1)	[23]
	LULC change (7)	[9,20,27,49–52]
	Invasive species (9)	[6,9,13,15,29,46,51,58,59]
III	Habitat destruction (4)	[6,18,46,47]
	Habitat fragmentation (1)	[6]
	Overexploitation (4)	[6,9,23,46]
	Water use (4)	[16,27,58,63]
	Poaching (1)	[23]
	Fishery (2)	[13,59]
	Land-based pollutants (1)	[28]
	Thermal stress (1)	[28]
	Agriculture (18)	[2,4,12,13,16–18,21,29,53,55–58,60–63]
	Urbanization (20)	[2,4,10,12,14,15,17,21,22,27,29,48,49,53,55,57,58,61,62,65]
	Forestry (1)	[13]
	Infrastructure (1)	[17]
	Population pressure (3)	[23,27,53]
	Fossil-fuel energy (3)	[21,24,47]
	Mining (8)	[15,21,22,52,58,61–63]
	Bioenergy (1)	[45]
IV	River regulations (1)	[2]
	Canals (2)	[4,58]
	Dams (4)	[4,16,58,60]
	Reservoirs (1)	[16]

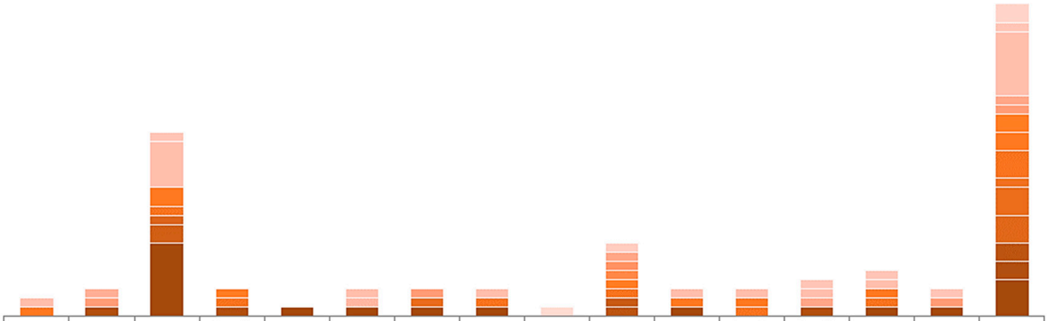
Anthropogenic threats were noted by 43 references, and nine references noted natural threats (Tables 2 and 3, and Figure 6). Eight of the nine references that recognized natural threats also recognized anthropogenic threats. More artificial threats than natural threats were considered. Anthropogenic threats can be broken down into four tiers. Natural threats, on the other hand, are broken down into three tiers. The most cited natural threat is climate change, which was cited in five different studies. Disease and wildfires were the next most frequent threats with three and two studies recognizing them, respectively.

Half of the natural threat types were mentioned by Khobe et al. [23]. They listed disease as a habitat threat and are also the only ones to note pests, erosion, floods, and droughts. The paper also listed human-induced fire, war, and poaching as habitat threats. The authors listed eight habitat threats in total, which is the highest number of any article referenced in this meta-analysis. Strauss et al. [6] listed the second-highest number of habitat threats with seven. It is also the only paper to recognize habitat fragmentation as a threat. Both papers listed both natural and anthropogenic threats and viewed threats in the context of preserving biodiversity.

Figure 7 shows which threats were mentioned the most and in which regions they were mentioned. The two most mentioned threats were agriculture and urbanization. Agriculture was mentioned more in China, and urbanization was mentioned more in the United States. There were 19 papers that noted agriculture and urbanization as threats. A threat that is important to study in one region may not be relevant in another. The results suggest that threats such as poaching are relevant in Nigeria but may not be relevant in Belgium, while a threat such as land-based pollution is relevant in Belgium and may not be relevant in Nigeria. Threats might also only affect certain habitats in a country. The study by Khobe et al. [23] focused on rangelands in Nigeria. These authors revealed that poaching posed a threat to rangelands, but may not pose a threat to coastal habitats. The United States has a wide range of habitats from mountains to plains and from tundra to tropical climate zones. Even though urbanization is the threat most often cited as an issue, it may not be a threat in every U.S. region.

Mexico is the only country from the results for which no specific threat was listed. Not every study listed specific threats. Of the 61 analyzed studies, 21 did not list specific threats. These 21 articles included 16 from the United States, two from Australia, one from Belgium, one from South Korea, and one from Mexico. It is also likely that studies that list specific threats did not list every threat in the region but only those relevant to the context of the study. A study by van Rensselaer [19] that focused on coastal environments cited sea-level rise as a threat but did not mention urbanization, while a study by Root et al. [10] that focused on overall species conservation cited urbanization as a threat but did not mention sea-level rise, even though both studies evaluated California, USA.

Figure 8 shows the country of origin of the articles. Many articles used in this study originated in the United States and China. One article from Ecuador was the only study that originated in South America. The continent of Africa had the next least number of studies, with two. Not counting Antarctica, South America and Africa were the least-represented continents in this meta-analysis. There were also no articles originating in the Arctic region. The distribution of articles for this study was primarily shaped by the language of the articles. Articles without an English version or a way to accurately translate them, such as articles from Brazil or Russia, were not used.



	Australia	Belgium	China	Czech Republic	Ecuador	Hungary	India	Iran	Mexico	Nigeria	Portugal	South Africa	South Korea	Spain	UK	USA
Unspecified									1							
Wildfire																2
War										1						
Water Use			1										1	1	1	1
Urbanization	1		5			1		1			1	1	1	1		7
Resource Use						1										
Predation		1														
Population Pressure										1			1			1
Pollution		1					1								1	1
Poaching										1						
Pests										1						
Overexploitation				1						1						2
Mining	1		2								1	1		1		2
Invasive Species			1	1				1		1		1		1		3
Habitat Fragmentation																1
Habitat Destruction							1									3
Fossil Fuel Energy																3
Forestry			1													
Fishery			2													
Fire										1						
Disease										1						2
Climate Change		1		1									1			2
Agriculture			8		1	1	1	1			1			1	1	4

Figure 7. Distribution of papers listing major threats by country (Levels II and III).

Figure 8. Distribution of works used in the literature review by country. The numbers represent the number of studies found in each country. Countries of origin are highlighted.

3.3. Available Data

A list of available spatial datasets that can be used to identify threats in an area is found in Table 4. The table provides sources for land-cover datasets, vegetation change data, cropland data layers, wildfire data, maps of energy-related processes, mine-related features maps, and invasive species maps. LANDFIRE's Vegetation Change Tracker (VCT) and Monitoring Trends in Burn Severity (MTBS) data go as far back as 1970. Most of the available data are recent. These datasets were used to determine whether a threat exists in the area of interest. The threats of agricultural expansion, urbanization, and other forms of land use change could be identified by using NLCD maps. The NLCD Land Cover Change Index was used to determine where land cover changes occurred between 2001 and 2016. VCT and WELD data were used to identify where forest cover has changed. This can also be accomplished by using the NLCD to see where forest cover or any other landscape has changed over the years. The MTBS, U.S. Energy Information Administration (USEIA), mine-related features, and nonindigenous aquatic species maps were used to determine if the area of interest is threatened by wildfire, energy-related threats, mining, and invasive species, respectively. An alternative to MTBS data is the Wildland Fire Interagency Geospatial Services (WFIGS) Wildland Fire Location dataset, which shows the location of fires. If the location of the fires is the only concern, either dataset can be used. If the project requires severity in order to rank the fires occurring in the watershed to determine which areas are more susceptible to fires, the MTBS should be used. Homeland Infrastructure Foundation Layer Data (HIFLD) are an alternative to USEIA data. Both sources provide data from 2019 to 2020, and either dataset can be used. If monitoring a specific invasive species, the Early Detection and Distribution Mapping System (EDDMapS) is a viable alternative to Nonindigenous Aquatic Species maps. EDDMapS also focuses more on terrestrial species. WorldPop population count maps represent population per square kilometer. These maps are useful for modeling population pressure.

Table 4. Sources and descriptions of available spatial datasets.

Dataset	Date (s)	Description	Scale/Resolution	References
National Land Cover Dataset (NLCD)	1992, 2001, 2006, 2011, 2016, 2019	Land-cover data	30 m	[66–68]
NLCD Land Cover Change Index	2001, 2004, 2006, 2008, 2011, 2013, 2016, 2019	Land cover change data	30 m	[67]
NLCD Retro Product	1992, 2001	Retrofitted 1992–2001 land-cover change data	30 m	[69]
LANDFIRE's Vegetation Change Tracker (VCT)	1984–2016	Annual forest disturbance	30 m	[70]
Web-enabled Landsat Data (WELD)	2006–2014	Forest decline data	30 m	[71]
Cropland Data Layer (CDL)	1997–2019	Crop cover history	30 to 56 m	[72]
Monitoring Trends in Burn Severity (MTBS)	1984–2019	Burn severity and wildfire data	30 m	[73]
Wildland Fire Interagency Geospatial Services (WFIGS)	1970–2020	Point location for reported fires in the US	N/A	[74]
Homeland Infrastructure Foundation Layer Data (HIFLD)	2019–2020	National foundation-level geospatial data within the open public domain such as mining, energy, and natural hazards	N/A	[75]

Table 4. *Cont.*

Dataset	Date (s)	Description	Scale/Resolution	References
U.S. Energy Information Administration (USEIA) maps	2019–2020	Map layers for various energy-related things such as biofuel and power plants	≥50 m	[76]
Prospect- and mine-related features map	2019	Mining-related features digitized from historical USGS topographic maps	1:24,000 scale to 1:62,500 scale	[77]
Nonindigenous Aquatic Species (NAS) data	Real-time	Map of invasive-species sightings	1:100,000 scale	[78]
Early Detection and Distribution Mapping System (EDDMapS)	Real-time	Web-based maps of invasive-species distribution	N/A	[79]
National Forest Type Dataset	2004	141 forest types across the US	250 m	[80]
National Hydrography Dataset (NHD)	2018	Map of surface water networks, including canals and dams	10 m	[81]
WorldPop population data	2000–2020	Population counts and density datasets	30 arc-seconds ~1 km	[82]

3.4. Characteristics

There were three characteristics described in the literature. Threats were characterized by how far their influence could reach (D_{max}), their relative destructiveness (weight), and their decay as one travels away from the threat source, which can be either linear or exponential. Threat weight was assigned values from 0 to 1. For example, if an urban area has a threat weight of 1, and the threat weight of roads is set to be 0.5, then the urban area causes twice the disturbance to all habitat types. Weight characteristics were based on its general destructiveness [30]. For example, urbanization may affect a habitat more than agricultural development or forestry does [83]. The potential range of a threat describes how far away from its source a threat can cause disturbance. The manner in which the impact of the threat lessens as one moves away from the source can be classified as linear or exponential [30,57,59]. The level of threat referred to the number of threatened species in an area divided by the total number of species in that same area [13]. Figure 9 displays the distribution of maximal distance and weight. The x axis represents the range of values, and the y axis denotes how many data points fall within each range. A total of 65 data points were used to create the maximal distance histogram, and 62 data points were used to create the weight histogram. Six studies originated in China and account for 32 data points [49,56,59,62,63,84]. Two studies originated in Portugal and account for 11 distance data points and eight weight data points [61,65]. Nine data points come from a study in Spain [58], seven from South Korea [64], and six from Ecuador [60]. The maximal influence distance generally tends to be less than 10 km. Threat weights are anywhere between 0.02 and 1, with many being above 0.8.

The impact of a threat r coming from grid cell y on habitat x is differently calculated on the basis of the type of decay rate:

$$\text{Linear}:\ i_{rxy} = 1 - \left(\frac{D_{xy}}{D_{\ max}}\right) \tag{1}$$

$$\text{Exponential}:\ i_{rxy} = \exp\left(-\left(\frac{2.99}{D_{\ max}}\right)D_{xy}\right) \tag{2}$$

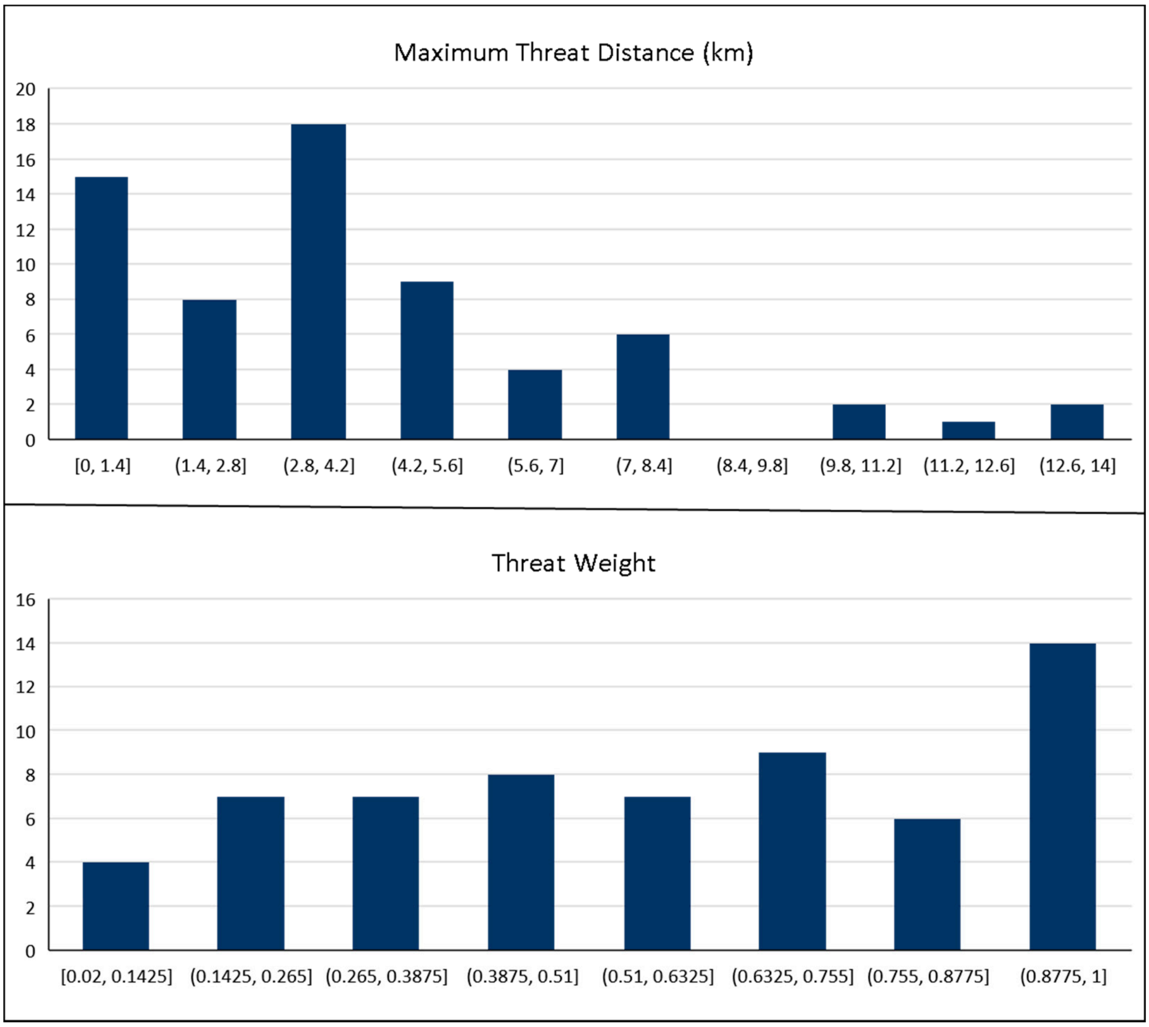


Figure 9. Histograms of threat distance and weight to show value distribution.

The linear distance between grid cell and habitat is D_{xy} [30]. Paukert et al. [4] used different criteria for evaluating threat severity. They used ecological integrity values for water quality, habitat quality, biotic interactions, flow regime, and energy source. These values were then added together to obtain a total threat severity score. Khobe et al. [23] characterized threats on the basis of their prevalence. The higher the rate of occurrence, the more severe the threat is likely to be.

3.5. Threat Index

Determining the threats that pose the greatest risk to an area requires an understanding of that area. This area can be a specific habitat, an entire region, or global. Habitat threat index equations were divided into broad, region-specific, or habitat-specific categories. Broad equations are used in global and multiregional analyses. Region-specific equations are used for specific regions such as mountain ranges, ecoregions, or watersheds. Habitat-specific equations are used to assess the threat level of habitats such as coral reefs, deserts, or rangelands. Variables are described in Table 5, and Index equations are listed in Table 6.

Table 5. List of variables used in standardized threat index equations.

Symbol	Description
HTI	Habitat threat index
HTI_c	Habitat threat index at target grid cell
HTI_j	Habitat threat index for land use j
HTI_{se}	Habitat threat index for stream segment s in ecoregion e
C	Number of grid cells
C_c	Number of grid cells with score less than target cell
CPc^P	Conversion potential—likelihood of land conversion projected for each grid cell
DT^{PA}	Distance to protected area
F	Threat factor index/ranking/score
H	Habitat value or suitability—ability of a habitat to support life
L	Landscape factor index/ranking/score
$LULCc$	Land-use/land-cover change
N	Number of grid cells
Nc	Number of grid cells for land use type
Nl	Number of land uses
PL	Protection level
Ps	Projected scenario
S	Number of species
X	Probability of extinction
e	Ecoregion
f	Threat frequency—how often a threat occurs (grid cells)
j	Land use type
k	Threat metric
n	Total number of threat factors or landscape factors
ns	Number of stream segments
s	Stream segments
y	Year
α	Threat impact or severity
β	Coefficient for linear regression
γ_{ji}	Contribution of land use j on the viability of species i
σ	Standard deviation

A total of 14 equations are shown in Table 6. Similar index equations found in the literature were modified to be uniform. These equations include risk-based multispecies conservation value [10], threat score [21], ecological indicator ranking [6], ecological risk index [4,85], threat index [17,27,84], threat value [14], coastal vulnerability index [19], conversion threat index [32], relative threat factor severity index [23], endemism index [25], and habitat quality index [28]. Each of these index equations can be understood as habitat threat index equations on the basis of the broad definition of habitat threat. Most of the equations involve the summation of values in terms of the number of threats, landscapes, or species. Two equations are the product of values [19,28]; two equations incorporate mean values for landscape factor [6] or threat factor scores [23], and two equations are simple index equations [14,21].

Commonly used variables are threat frequency (f), threat severity (α), landscape factor score (L), number of species (S), and threat factor score (F). One equation had nothing in common with the other equations and was placed in its unique group identified by the conversion potential (CP) variable. Figure 10 shows an equation selection tool, based on which data are obtainable through datasets, calculations, a literature review, and/or expert knowledge. Equations are then ordered in terms of simplicity. The simplest equations appear at the top of the list, and equations become more complex further down the list. There are two equations wherein the threat index is calculated on the basis of multiple common variables. The figure was designed to account for these overlaps.

Table 6. Threat index equations derived from the literature.

Specificity	Region/Habitat	Equation	References
Broad	Various regions	$HTI_j = \frac{\sum_{i=1}^{S}(H_{ij} \times X_i \times \gamma_{ji})}{\sum_{i=1}^{S} X_i}$	[10]
	Global	$HTI_c = \frac{C_c + 0.5f_i}{N} \times 100$	[21]
Region-specific	Mountain range	$HTI = \frac{L - L_{mean}}{\sigma}$	[6]
	Lower Colorado River Basin	$HTI = \sum_{i=1}^{n} f_i \alpha_i$	[4]
	Watershed	$HTI = \beta_0 + \sum_{i=1}^{n} \beta_i F_i$	[27]
Habitat-specific	Wetlands	$HTI = \frac{F \times H}{PL}$	[14]
	Prairie, desert, steppe	$HTI_{se} = \left[\frac{\sum_{k=1}^{ns} F_{sek}}{\max(\sum_{k=1}^{ns} F_{sek})}\right] \times 100$	[17]
	Coastal	$HTI = \left(\frac{\prod_{i=1}^{n} L_i}{n}\right)^{0.5}$	[19]
	Coast, lowlands, cascades	$CPc_{y1-yn}^{P} = \sum LULCc\Delta_{y1\ldots yn}^{Ps1\ldots n}$ $HTI_c = CPc_{y1-yn}^{P} \times DT^{PA}$	[32]
	Rangelands	$HTI = \frac{F_{mean}}{F_{max}}$	[23]
	Aquatic habitats	$HTI = \frac{1}{Nc \times Nl} \sum_{i=1}^{Nl} \sum_{j=1}^{Nc} \alpha_{ij}$	[84]
	Freshwater	$HTI = \frac{\sum_{i=1}^{S} \frac{1}{C_i}}{S}$	[25]
	River ecosystems	$HTI = \sum_{i=1}^{n} f_i \alpha_i$	[85]
	Great Barrier Reef	$HTI = \prod_{i=1}^{n} F_i^{\alpha}$	[28]

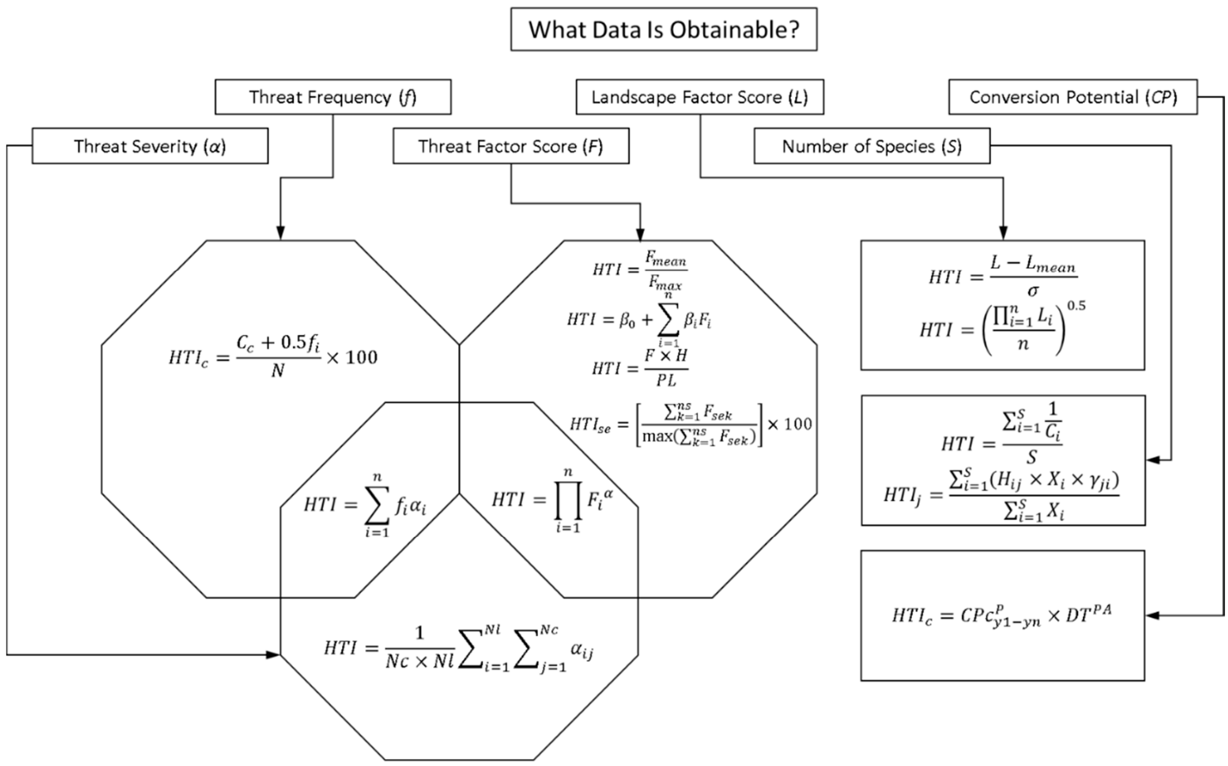


Figure 10. Equation selection tool framework used to determine appropriate index equations on the basis of obtainable data.

3.6. DIEM Framework

The Define–Investigate–Estimate–Map (DIEM) framework translates habitat threats, a mercurial concept, into an operational framework that can be applied to a given area, through undergoing a series of steps (Figure 11). These steps are divided into investigation and mapping phases. The first step of the investigation is to decide if the goal is to analyze a specific habitat within a region or the entire region. If analyzing a specific habitat, the location of the habitat within the area of interest needs to be identified. The next step is to define habitats threats for the area and then obtain spatial datasets.

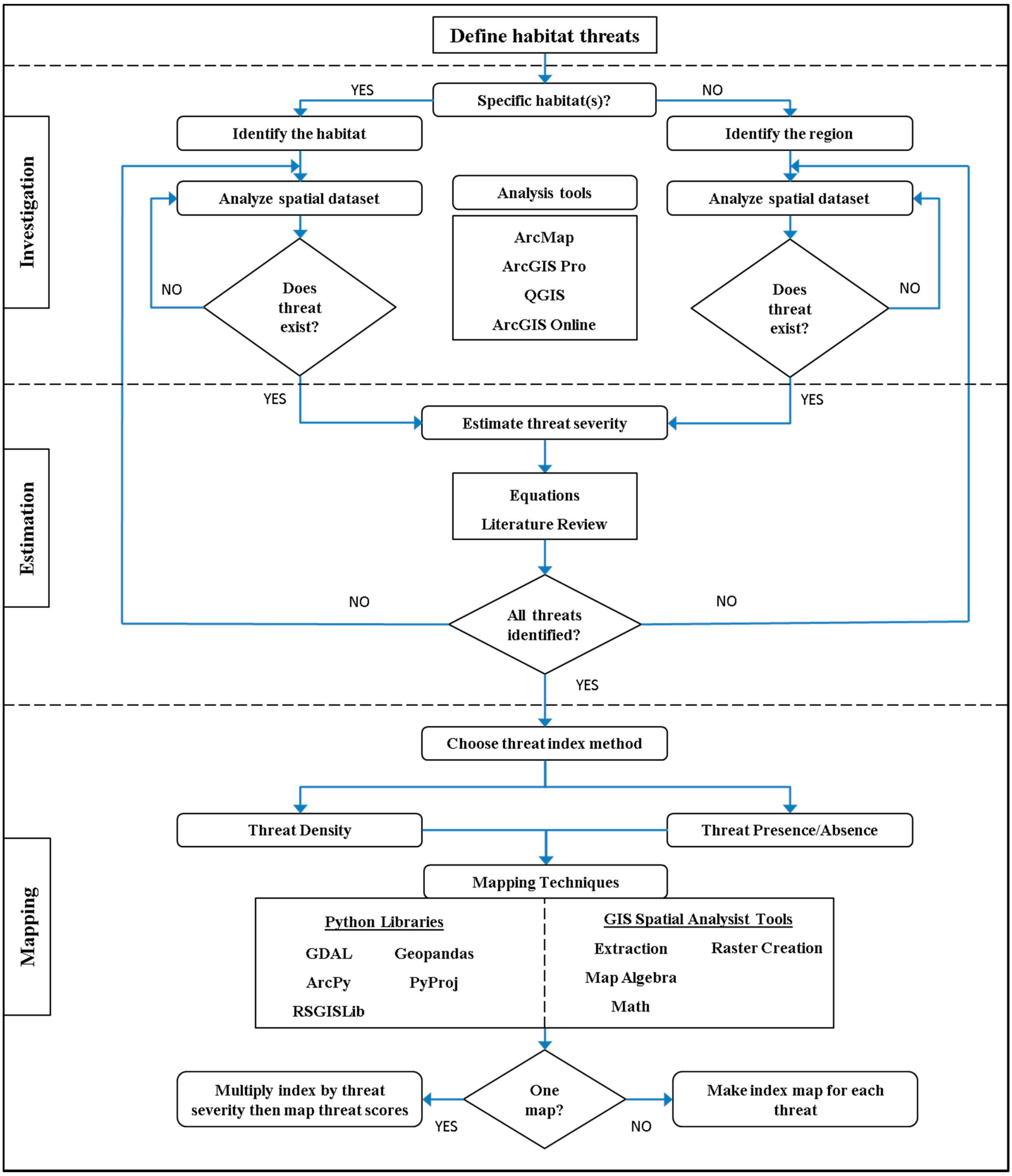


Figure 11. DIEM framework for assessing habitat threats.

After obtaining the data, each dataset is analyzed. If no threat is found in one dataset, the next dataset is analyzed until all are. Analytical methods include using GIS programs such as online map viewers, ArcMap, ArcGIS Pro, or QGIS to select features within an area to highlight where threats occur. When threats are found, the threat severity or weight of each threat is estimated. Severity can be estimated from values found in the literature. A table of threat weight is included in the Supplementary Materials. Once all threats are identified, and their severity scores are estimated, the next step is the mapping phase.

The first step of the mapping phase involves determining which threat index method is to be used. The threat density method is performed by dividing the number of pixels where a threat exists by the total number of pixels in the area of interest. All density values are then divided by the highest value, so that the highest density value is set to 1, and every other value is proportionally determined so that the values fall between 0 and 1. The presence/absence method is conducted by assigning 1 as the value for every pixel where a threat is present and 0 for pixels where a threat is absent. Other threat index methods, such as the ones found in Table 6, can also be used. The next step is to choose a mapping method. The framework in Figure 11 divides mapping tools into Python libraries or GIS spatial analysist tools categories. Python programming is used to transform spatial data into arrays of values. The matrix coordinates of values that correspond to the pixels of interest are then identified and changed to threat index values. Examples of GIS libraries with spatial data analysis and manipulation functions are the Geospatial Data Abstraction Library (GDAL), ArcPy, Geopandas, the Remote Sensing and GIS Software Library (RSGISLib), and PyProj. There are also NumPy, Pandas, and Re, which are used to filter and alter data. Spatial analysis tools in GIS software such as Map Algebra and Raster Creation in ArcMap 10.4.1 are alternative map-making tools. If the goal is to produce a single map, index scores are multiplied by threat severity scores to calculate the threat scores. All threat scores for each pixel are summed and mapped. Alternatively, an individual map can be produced for each threat. A framework of this process is shown in Figure 11. This method is useful for conservationists seeking to measure the impact of threats on the habitat they seek to conserve. Understanding how LULC changes affect proximal ecosystems is important to someone who, for instance, wants to preserve a natural forest. A land developer can also benefit from threat measurements, as they can estimate how urban expansion impacts the surrounding environment, which may prompt them to incorporate mitigation strategies.

3.7. Application of Framework—Case Study in Choctawhatchee River and Bay Watershed

The Choctawhatchee River and Bay Watershed was assessed, which has the six-digit hydrologic unit code HUC-031402. This watershed has an area of 12,051.24 km^2 and spans from Alabama to Florida, where it discharges into the Gulf of Mexico. The area has a sizable agricultural component and diverse forest habitats. Threats were defined as anything that posed a risk to habitats, so every threat listed in Figure 6 was considered. A regional analysis approach was taken. Analysis began with identifying the threats by analyzing each available spatial dataset. The identified threats were urbanization, agriculture, mining, power plants, and population pressure.

The habitats affected by the threats were identified in order to estimate where the threats were likely to spread. The NLCD Land Cover Change Index was used to determine what type of land cover was most affected by urbanization and agriculture. Python programming was used to examine where potential land use changes occurred. The used libraries were Geospatial Data Abstraction Library (GDAL), NumPy, and Pandas. Raster files were imported as arrays, which made it possible to individually analyze each LULC. Urbanization affected both woody and herbaceous wetlands. These areas tended to be near bodies of water. Agriculture affected barren land, deciduous, coniferous, and mixed forests, shrub land, and herbaceous cover. These areas had varying levels of biodiversity. Identifying habitats affected by mining and power plants was accomplished by clipping the LULC raster in a GIS program such as ArcMap or ArcGIS Pro, using shape files obtained online [76,77]. Mining was present in every type of land use and land cover in the watershed. Power plants were located in urban and agricultural areas. Lastly, the threat of population pressure usually occurred in developed landscapes.

Threat severity was estimated by using the average value of threat weight found in the literature. Average values are listed in Table 7. Values used to estimate threat weight and their sources are listed. The threat with the most data points was agriculture, with seven values, followed by urbanization, with six; mining, with four; and power plants and population pressure, both with two.

Table 7. Estimated threat weights for discovered threats in Choctawhatchee watershed.

References	Weight				
	Urbanization	Agriculture	Mining	Power Plants	Population Pressure
[84]	0.7	0.4			
[58]	1	0.68	0.8	0.92	
[55]		0.2			
[63]	0.3	0.1	0.15		
[49]	0.24				0.28
[60]		0.29		0.3	0.34
[61]	1	0.68	1		
[62]	1	0.6	0.5		
Average:	0.71	0.42	0.61	0.61	0.31

The final steps involved choosing an index equation and calculating and mapping the index. The presence/absence method described in the InVEST model handbook was used in this case [30]. Grid cells where the threats were located were given a value of 1; otherwise, they had a value of 0. Grid cells with a value of "NoData" were converted into 0. Individual maps were produced for each threat to be larger than the area of the watershed to account for the distance that the threats could affect. Threats outside the watershed could influence habitats in the watershed. This usually took place on the edge of the watershed, where the distance between threat and watershed was less than the D_{max} value of the threat. Figure 12 shows the resulting maps. The used pixel resolution was 30 by 30 m.

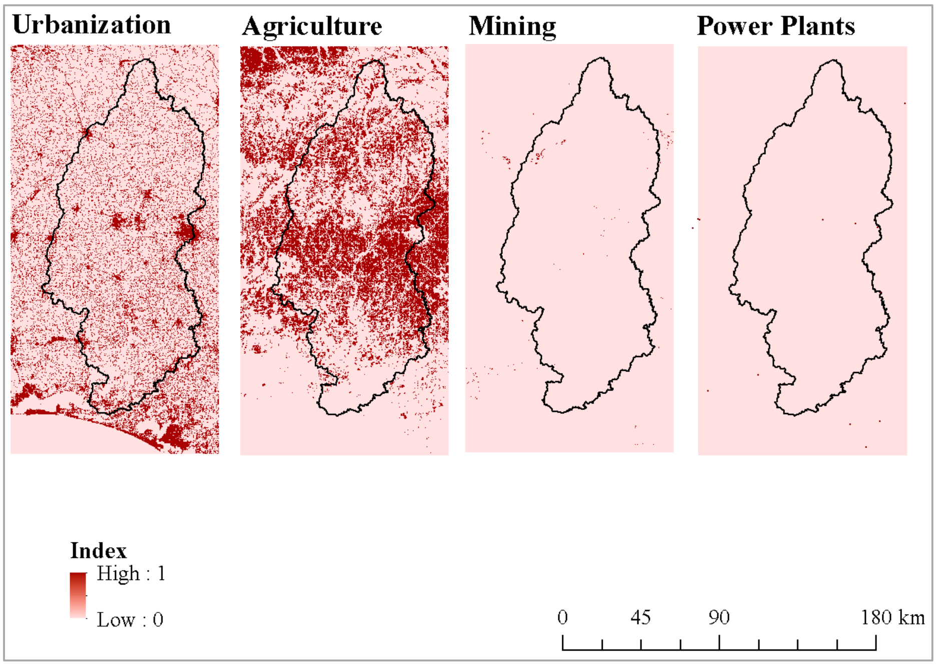


Figure 12. Threat index maps of urbanization, agriculture, mining, and power plants.

A population-pressure threat map was also created. The presence/absence method was not appropriate to map this threat, so an index was created on the basis of population density. Each population-density value was simply divided by the highest population-density value displayed in the watershed to create a relative population-pressure index map. The result is shown in Figure 13. Pixel resolution is approximately 1 by 1 km.

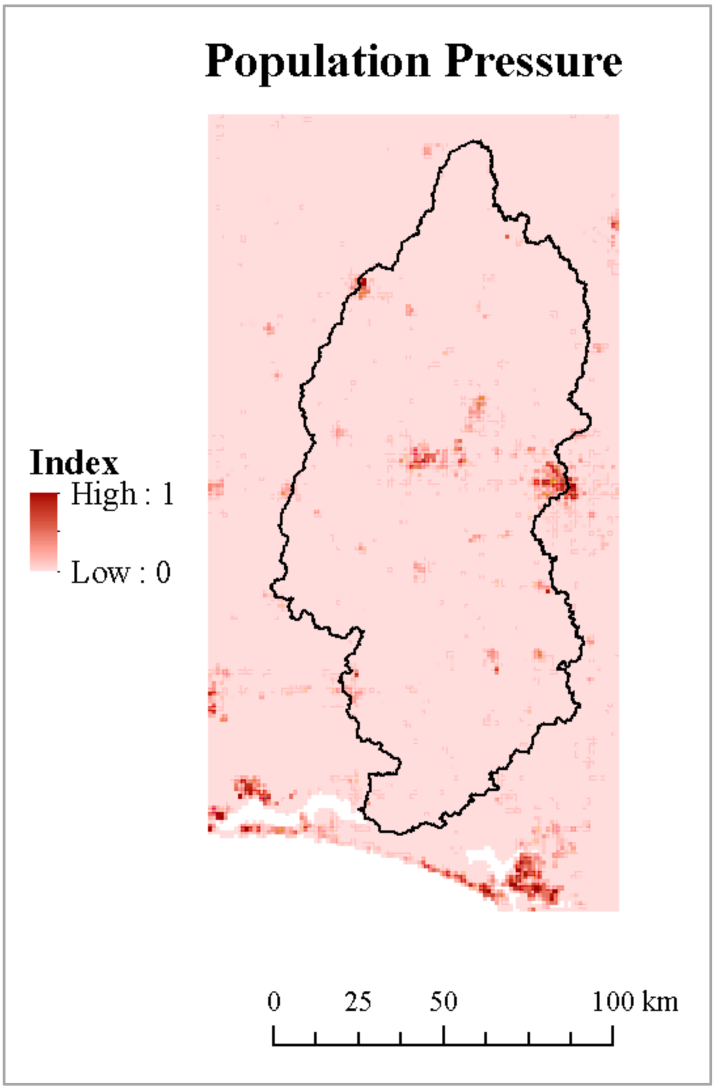


Figure 13. Threat index map of population pressure.

Alternatively, a combined map could be created by first multiplying the index values of each threat map by their corresponding weights listed in Table 7. A summation of the resulting maps was created using the raster calculator from the Spatial Analysist Toolbox in ArcMap. Since population data were of a coarser resolution than that of the other maps, all maps were automatically resampled to a resolution of 30 arc-seconds (~1078.74 m). Another total threat map was created with the population-pressure data omitted. The resulting map maintained its 30 m resolution. Both maps are shown in Figure 14 for comparison.

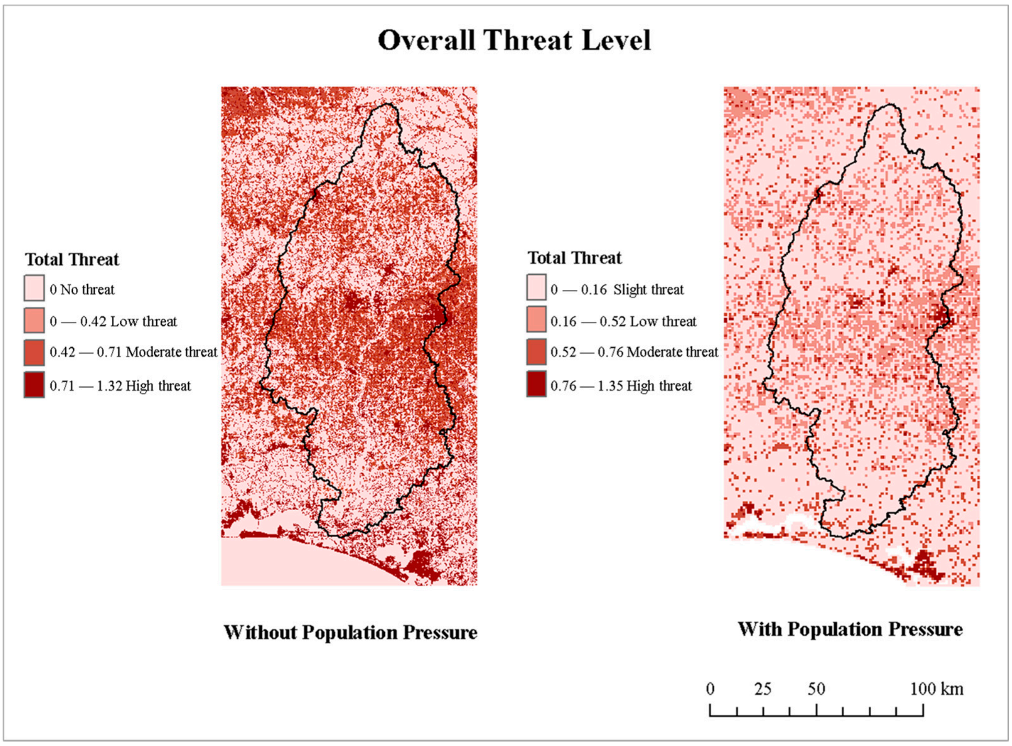


Figure 14. Estimated total threat with and without population pressure.

4. Discussion

4.1. Literature-Review Implications

The destruction of habitats usually leads to a loss of genetic resources that have ecological, medical, industrial, and cultural value [23]. The results of this paper are integral to understanding what puts habitats at risk. Biodiversity is connected to the production of ecosystem services. Protecting biodiversity is a primary goal of habitat conservation [30]. Habitats depend on biodiversity because different species play unique roles that are vital in supporting the function of the ecosystem. Vegetation, for example, holds soil in place. Different species of plants hold soil in place at different soil depths; therefore, having plant diversity benefits the overall soil stability of the ecosystem. This decreases the amount of erosion that occurs. Sediments can be transported to nearby bodies of water, which decreases the depth of the water bodies. Animals such as fish living in water, and animals that rely on them for food, benefit from plants holding soil in place [6]. A decrease in biodiversity leads to a decrease in habitat quality, which is defined as the ability of the ecosystem to provide conditions appropriate for population persistence [37]. Biodiversity also has economic value. Diverse ecosystems provide goods and services to human society. For example, coral reefs benefit both the ecosystem and the economy, as they provide shelter and food for many species, which promotes nurseries for commercial fishing. Reefs also encourage tourist activities, such as diving and snorkeling [28]. The results of this paper are integral to understanding what puts habitats at risk.

Deciding on a threat index depends on the region and goal of the study. The threat index can be calculated using the density of each threat. This involves taking the number of cells wherein a threat occurs, divided by the total number of cells. That value is then multiplied by a threat severity factor. This method can be used to map multiple threats at once. The threat index can also be determined by the presence/absence method, wherein 1 denotes the presence of a threat, and 0 denotes the absence. This method can only be used to map one threat at a time, as the severity of each threat is different. There are also equations to calculate the threat index for specific habitats and specific species. The equations were made uniform to simplify understanding of the differences between each equation. This also simplifies the equations, makes them more readily comparable, and makes it easier to select an equation. The tradeoff is that the equations lose specificity, as the complexity of the equations is not apparent. The advantage is that the broad nature of the equations makes them easier to use for a wider range of scenarios.

4.2. Local Threats and Habitats

Within the Choctawhatchee River Watershed, the natural habitats are open water, barren land, deciduous, coniferous and mixed forests, shrub lands, grasslands, and both wooded and herbaceous wetlands. Agriculture was the threat that occurs most often, but it had a relatively low average threat weight. Urbanization was the second-most frequent threat, and it had the highest average weight. Mining was the next most frequent, followed by power plants, and both had the same average weight. Population pressure had the lowest average weight and generally occurred where there was development. The greatest threats occurred in the same general areas between maps. Areas with the highest threat value were developed, with the highest values being where urbanization and mining or power plants overlapped. There were a few pixels on the map that included population pressure where agriculture, population, and mining or power plants overlapped, which yielded a high threat value, but these pixels were not numerous enough to be recognized by eye.

Since agriculture and urbanization contributed to the overall threat level the most, management strategies to mitigate the impact of these practices should be considered. These management strategies include agricultural best management practices such as reducing water use and diversion, environmental functional zoning to protect vulnerable habitats from urban growth, and formal mechanisms such as policies created in response to landscape threat assessment models [46,49].

4.3. Using the DIEM Framework to Produce Threat Maps

The DIEM framework was demonstrated through the case study. In this study, spatial data with the finest resolution and the most recent data were used. Identifying the types of threats in an area requires spatial data for each potential threat. These data are difficult to find at times. There are also threats that are not straightforward, such as climate change, war, and population pressure. Threats such as these require extensive research. The characteristics of these threats can vary on the basis of region. The D_{max} value can be, for instance, as low as 0.5 km in Portugal [65] and as high as 10 km in China [62]. Using an average of every value may not be accurate. Using values from regions that are most like the area of interest is advised. The ideal approach is to thoroughly study the chosen region if resources are available.

Weights were used to create overall threat level maps. The method for creating the maps was similar to the equation derived from the literature [4,85], which is as follows:

$$HTI = \sum_{i=1}^{n} f_i \alpha_i \tag{3}$$

where f_i is the threat frequency of each threat, and α_i is the threat severity or weight of each threat. The equation has f_i as the threat index value of individual threats. This does not change the results for the four threats where the index was modeled on the basis of presence or absence. Frequency is 1 for each pixel where the threat occurs, and 0 otherwise. The population-pressure index map had values in the range between 0 and 1, so frequency in this map was a fraction in some cases and did not represent the actual population, but rather a relative value. An alternative to this method is to use the equation derived from Deffense [28], which is as follows:

$$HTI = \prod_{i=1}^{n} F_i^{\alpha} \tag{4}$$

where F_i is the threat factor score, which is understood as the threat index of individual threats. The rationale for not using this method was that there were pixels in each threat map that had a value of 0. When maps are multiplied together, the resulting map would be 0. The habitat threat index equation derived from Nie, Yang, and Huang [84] could also be used. It is as follows:

$$HTI = \frac{1}{Nc \times Nl} \sum_{i=1}^{Nl} \sum_{j=1}^{Nc} \alpha_{ij} \quad (5)$$

where N_c is the number of grid cells in a land use type; N_l is the number of land uses in the area, and α_{ij} is the threat severity of each threat for each land-use type. This equation is used to calculate the HTI for each land use. The threat severity in this equation also needs to account for the sensitivity of land uses to each threat. The advantage of using this equation is that it is not affected by differences in spatial data resolution. The equation can be used with tabular results, and the only spatial data needed are the land use/cover dataset. However, this method requires many more steps than those in Equations (3) and (4) when it comes to general watershed analysis, so it was not used here.

Two overall threat maps were created due to the map resolution being changed when using population data that were coarser than those of other datasets. This caused some data to be lost after resampling. Therefore, a threat map was created where population pressure was not used. The two maps were similar when it came to modeling the distribution of threats.

4.4. Potential Uses of Threat Maps

Spatial imaging is effective in understanding patterns in biodiversity. Mapping processes that threaten biodiversity helps in identifying locations that are at risk of degradation. Decision-makers use threat maps to decide what locations should be prioritized in conservation efforts. The goal of conservation is also to protect species, habitats, and ecosystems within a region. Mapping the occurrence of species, habitats, and ecosystems, and the activities that threaten them, is required to design an appropriate plan for conservation. There are various approaches to how maps can be used to identify priority areas for conservation. Threat maps can be used for understanding how threats affect land cover, reduce the number of species in an area, disrupt patterns in endemism, or impact ecological processes [30].

In addition to conservation planning, threat maps can be used to study the effects that those threats have on the environment. Historic LULC and threat maps allow for researchers to see how the existence of threats affects habitats over time. It also gives insight into the growing number of threats in an area. Urbanization may have not been a threat to a region historically but may be now. This is often the case in developing countries. Other threats, such as droughts or floods, may become more frequent due to the changing climate. Understanding how threats affect the environment over time is important when attempting to predict how an environment may change due to threats. It can also be used to determine how similar environments would be affected if certain threats ever occur. If it is known how a hydroelectric dam impacts a river and the surrounding habitats, for example, decision-makers can plan mitigation strategies if a hydroelectric dam is planned to be built on another river. Decision-makers could even decide to use an alternative energy-production method if a dam proves to be too destructive to proximal habitats.

4.5. Advantages of the Framework

The DIEM framework is flexible and can be used in a variety of situations. It is general enough to be used in any region whether the focus is on habitats or threats. It is also a method that can be used with any regional analysis model. The flexible nature of the framework makes it easy to follow. It is also possible to modify the framework for a specific situation while maintaining the idea behind it.

Being able to produce threat maps is advantageous as well. Available threat maps may not be useful in every case. They could be produced using a method that is too broad.

They could also have too coarse a resolution to use on small-scale projects. It is also likely that not every threat in a given area is mapped. In cases such as these, it is important to be able to produce maps wherein index calculation and resolution can be controlled.

4.6. Potential Limitations of the Framework and Future Work

Due to the framework requiring spatial data to work, it is limited by the quality and availability of data. Finding national LULC data at a 30 m resolution for the United States is not difficult. Other regions may only have global LULC data available, which are coarser than NLCD. Data other than LULC are not always available, especially when searching for very specific threats such as population pressure. Natural-threat maps such as wind and flood maps are hard to come by. In addition, threat characteristics are not easily estimated. The average threat characteristic values from meta-analysis were used in the case study. These values may not be as accurate, as data could be limited. Accurately estimating the characteristics may require additional steps that are not part of the framework. Some of these steps may include different statistical methods or specialized research to accurately assess the severity of threats in an area.

Future work includes quantifying how habitats react to different threats. This is referred to as habitat sensitivity. Habitat suitability, the measure of how livable a habitat is, will also be assessed. Habitat sensitivity to each threat, along with habitat suitability, will be used in conjunction with habitat threat maps to model habitat quality. Quantitative management strategies to mitigate the impact of land development will then be proposed. This endeavor is currently beyond the scope of this project and is deferred for future work.

5. Conclusions

This study employed three interconnected methodologies. Meta-analysis led to the development and application of a habitat threat framework. It is possible to follow the methodology for a different case while skipping the meta-analytical steps, as these were already conducted in this study. The framework development steps can also be skipped if it is preferred to use the already developed DIEM framework. It is recommended to replicate the entire process to add onto what is presented here or formulate a new framework that suits the desired region and research goals.

The literature review results give insight on the definition, types, and characteristics of habitat threats, and various methods to quantify their impact on the natural environment. Though the definitions of "habitat threat" differ from paper to paper, the literature agrees that a habitat threat is something natural or human-induced that poses a risk to natural ecosystems. This understanding leads to the ability to determine existing threats in any given area and estimate how destructive the threats are.

The DIEM framework method requires available data. High-quality historical spatial data are not always accessible. Coarse-resolution maps based on global maps might be the only available data. This method also only takes existing threats into account. There is no sure way to predict future threats. The DIEM method can still be used to spatially display a rough estimate of the relative severity of the present threats.

The information provided by this study can be used to modify existing threat index equations to fit specific cases by understanding principles used in other studies. Modified threat mapping frameworks can also be created on the basis of the general framework presented here. Data context and availability can affect how one approaches habitat threat analyses.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132011259/s1, Figure S1: Tree diagram based on Strauss et al. [6]; Figure S2: Tree diagram based on Deffense, [28]; Figure S3: Tree diagram based on Eros et al. [2]; Figure S4: Tree diagram based on Fore et al. [17]; Figure S5: Tree diagram based on Khobe et al. [23], Figure S6: Tree diagram based on Oakleaf et al. [21]; Figure S7: Tree diagram based on Paukert et al. [4]; Figure S8: Tree diagram based on Tulloch et al. [22]; Figure S9: Tree diagram based on Xu et al. [13]; Figure S10: Tree diagram based on Collen et al. [16]; Figure S11: Tree diagram based on Payet et al. [15]; Figure S12:

Tree diagram based on Mashizi and Sharafatmandrad, [29]; Figure S13: Tree diagram based on Kim et al. [27]; Figure S14: Tree diagram based on Jha and McKinley [18]; Figure S15: Timeline of habitat threats; Table S1: Threat characteristics; Table S2: Threat index equations from the literature.

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References

1. Kuemmerlen, M.; Schmalz, B.; Cai, Q.; Haase, P.; Fohrer, N.; Jähnig, S.C. An attack on two fronts: Predicting how changes in land use and climate affect the distribution of stream macroinvertebrates. *Freshw. Biol.* **2015**, *60*, 1443–1458. [CrossRef]
2. Eros, T.; Kuehne, L.; Dolezsai, A.; Sommerwerk, N.; Wolter, C. A systematic review of assessment and conservation management in large floodplain rivers—Actions postponed. *Ecol. Indic.* **2019**, *98*, 453–461. [CrossRef]
3. Sánchez-Bayo, F.; Wyckhuys, K.A. Worldwide decline of the entomofauna: A review of its drivers. *Biol. Conserv.* **2019**, *232*, 8–27.
4. Paukert, C.P.; Pitts, K.L.; Whittier, J.B.; Olden, J.D. Development and assessment of a landscape-scale ecological threat index for the Lower Colorado River Basin. *Ecol. Indic.* **2011**, *11*, 304–310. [CrossRef]
5. Thoms, M.; Sheldon, F. Large rivers as complex adaptive ecosystems. *River Res. Appl.* **2019**, *35*, 451–458. [CrossRef]
6. Strauss, A.; Hurlbutt, B.; O'Brady, C. Preserving Biodiversity. In *Colorado College State of the Rockies Report Card*; Colorado College: Colorado Springs, CO, USA, 2006; p. 61.
7. Mehri, A.; Salmanmahiny, A.; Mikaeili Tabrizi, A.R.; Mirkarimi, S.H.; Sadoddin, A. Integration of anthropogenic threats and biodiversity value to identify critical sites for biodiversity conservation. *Geocarto Int.* **2019**, *34*, 1202–1217. [CrossRef]
8. Bell, A.; Matthews, N.; Zhang, W. Opportunities for improved promotion of ecosystem services in agriculture under the Water-Energy-Food Nexus. *J. Environ. Stud. Sci.* **2016**, *6*, 183–191. [CrossRef]
9. Prokopova, M.; Salvati, L.; Egidi, G.; Cudlin, O.; Vcelakova, R.; Plch, R.; Cudlin, P. Envisioning Present and Future Land-Use Change under Varying Ecological Regimes and Their Influence on Landscape Stability. *Sustainability* **2019**, *11*, 4654. [CrossRef]
10. Root, K.V.; Akcakaya, H.R.; Ginzburg, L. A multispecies approach to ecological valuation and conservation. *Conserv. Biol.* **2003**, *17*, 196–206. [CrossRef]
11. Hummel, S.; Calkin, D.E. Costs of landscape silviculture for fire and habitat management. *For. Ecol. Manag.* **2005**, *207*, 385–404. [CrossRef]
12. Peng, F.; Wang, Y.L.; Li, W.F.; Yue, J.; Wu, J.S.; Zhang, Y. Evaluation for sustainable land use in coastal areas: A landscape ecological prospect. *Int. J. Sustain. Dev. World Ecol.* **2006**, *13*, 25–36. [CrossRef]
13. Xu, H.G.; Wu, J.; Liu, Y.; Ding, H.; Zhang, M.; Wu, Y.; Xi, Q.; Wang, L.L. Biodiversity congruence and conservation strategies: A national test. *Bioscience* **2008**, *58*, 632–639. [CrossRef]
14. Baldwin, R.F.; Demaynadier, P.G. Assessing threats to pool-breeding amphibian habitat in an urbanizing landscape. *Biol. Conserv.* **2009**, *142*, 1628–1638. [CrossRef]
15. Payet, K.; Rouget, M.; Esler, K.J.; Reyers, B.; Rebelo, T.; Thompson, M.W.; Vlok, J.H.J. Effect of Land Cover and Ecosystem Mapping on Ecosystem-Risk Assessment in the Little Karoo, South Africa. *Conserv. Biol.* **2013**, *27*, 531–541. [CrossRef] [PubMed]
16. Collen, B.; Whitton, F.; Dyer, E.E.; Baillie, J.E.M.; Cumberlidge, N.; Darwall, W.R.T.; Pollock, C.; Richman, N.I.; Soulsby, A.M.; Bohm, M. Global patterns of freshwater species diversity, threat and endemism. *Glob. Ecol. Biogeogr.* **2014**, *23*, 40–51. [CrossRef]

17. Fore, J.; Sowa, S.; Galat, D.; Annis, G.; Diamond, D.; Rewa, C. Riverine Threat Indices to Assess Watershed Condition and Identify Primary Management Capacity of Agriculture Natural Resource Management Agencies. *Environ. Manag.* **2014**, *53*, 567–582. [CrossRef]
18. Jha, K.K.; McKinley, C.R. Demography and Ecology of Indian Sarus Crane (*Grus antigone antigone*) in Uttar Pradesh, Northern India. *Asian J. Conserv. Biol.* **2014**, *3*, 8–18.
19. Van Rensselaer, M. A GIS Analysis of Environmental and Anthropogenic Threats to Coastal Archaeological Sites in Southern Monterey County, California. *Proc. Soc. Calif. Archaeol.* **2014**, *28*, 373–380.
20. Mattson, M.K. Modeling Ecological Risks at a Landscape Scale: Threat Assessment in the Upper Tennessee River Basin. 2015. Available online: https://vtechworks.lib.vt.edu/bitstream/handle/10919/78611/Mattson-Hansen_KM_D_2016.pdf?isAllowed=y&sequence=1 (accessed on 7 October 2021).
21. Oakleaf, J.R.; Kennedy, C.M.; Baruch-Mordo, S.; West, P.C.; Gerber, J.S.; Jarvis, L.; Kiesecker, J. A World at Risk: Aggregating Development Trends to Forecast Global Habitat Conversion. *PLoS ONE* **2015**, *10*, e0138334. [CrossRef] [PubMed]
22. Tulloch, V.J.D.; Tulloch, A.I.; Visconti, P.; Halpern, B.S.; Watson, J.E.; Evans, M.C.; Auerbach, N.A.; Barnes, M.; Beger, M.; Chadès, I.; et al. Why do we map threats? Linking threat mapping with actions to make better conservation decisions. *Front. Ecol. Environ.* **2015**, *13*, 91–99. [CrossRef]
23. Khobe, D.; Akosim, C.; Kwaga, B.T. Susceptibility to Threats and Threat Severity of Adamawa Rangelands, Nigeria. *J. Adv. Agric.* **2016**, *5*, 698–705.
24. Verkamp, H.J. Stream benthic algal relationships with multimetric indices of sensitivity, exposure, and vulnerability to watershed land use change, with an emphasis on unconventional natural gas development. *Biol. Sci.* **2016**. Available online: https://scholarworks.uark.edu/cgi/viewcontent.cgi?article=1011&context=biscuht (accessed on 7 October 2021).
25. Armendariz, G.; Quiroz-Martinez, B.; Alvarez, F. Risk assessment for the Mexican freshwater crayfish: The roles of diversity, endemism and conservation status. *Aquat. Conserv.-Mar. Freshw. Ecosyst.* **2017**, *27*, 78–89. [CrossRef]
26. Turak, E.; Harrison, I.; Dudgeon, D.; Abell, R.; Bush, A.; Darwall, W.; Finlayson, C.M.; Ferrier, S.; Freyhof, J.; Hermoso, V.; et al. Essential Biodiversity Variables for measuring change in global freshwater biodiversity. *Biol. Conserv.* **2017**, *213*, 272–279. [CrossRef]
27. Kim, Y.; Kong, I.; Park, H.; Kim, H.J.; Kim, I.J.; Um, M.J.; Green, P.A.; Vorosmarty, C.J. Assessment of regional threats to human water security adopting the global framework: A case study in South Korea. *Sci. Total Environ.* **2018**, *637*, 1413–1422. [CrossRef] [PubMed]
28. Deffense, N. Deriving a habitat quality index to inform reef conservation in the Great Barrier Reef. In *Faculté des Bioingénieurs*; Université Catholique de Louvain: Louvain-la-Neuve, Belgium, 2019; p. 78.
29. Mashizi, A.K.; Sharafatmadrid, M. Assessing Impact of Anthropogenic Disturbances on Forage Production in Arid and Semiarid Rangelands. *J. Rangel. Sci.* **2019**, *9*, 234–245.
30. Nelson, E.; Ennaanay, D.; Wolny, S.; Olwero, N.; Vigerstol, K.; Pennington, D.; Mendoza, G.; Aukema, J.; Foster, J.; Forrest, J.; et al. InVEST 3.8.0. User's Guide. Sharp, R., Chaplin-Kramer, R., Wood, S., Guerry, A., Tallis, H., Ricketts, T., Eds.; 2020. Available online: https://invest-userguide.readthedocs.io/_/downloads/en/3.8.3/pdf/ (accessed on 7 October 2021).
31. Groves, C. *Drafting a Conservation Blueprint: A Practitioner's Guide to Planning for Biodiversity*; Island Press: Washington, DC, USA, 2003; p. 458.
32. Wilson, T.S.; Sleeter, B.M.; Sleeter, R.R.; Soulard, C.E. Land-Use Threats and Protected Areas: A Scenario-Based, Landscape Level Approach. *Land* **2014**, *3*, 362–389. [CrossRef]
33. Blair, P.; Buytaert, W. Socio-hydrological modelling: A review asking" why, what and how?". *Hydrol. Earth Syst. Sci.* **2016**, *20*, 443–478. [CrossRef]
34. Patrício, J.; Elliott, M.; Mazik, K.; Papadopoulou, K.-N.; Smith, C.J. DPSIR—Two Decades of Trying to Develop a Unifying Framework for Marine Environmental Management? *Front. Mar. Sci.* **2016**, *3*, 177. [CrossRef]
35. Livingston, R.; Epler, J.; Jordan, F.; Karsteter, W.; Koenig, C.; Prasad, A.; Ray, G. *Ecology of the Choctawhatchee River System*; Springer: New York, NY, USA, 1991; pp. 247–274.
36. CPYRWMA. Choctawhatchee River. 2017. Available online: https://cpyrwma.alabama.gov/about-the-watersheds-choctawhatchee-river/ (accessed on 28 March 2021).
37. Hall, L.S.; Krausman, P.R.; Morrison, M.L. The habitat concept and a plea for standard terminology. *Wildl. Soc. Bull.* **1997**, *25*, 173–182.
38. Turlure, C.; Van Dyck, H.; Schtickzelle, N.; Baguette, M. Resource-based habitat definition, niche overlap and conservation of two sympatric glacial relict butterflies. *Oikos* **2009**, *118*, 950–960. [CrossRef]
39. Amorim, J.; Hendrix, M.; Andler, S.; Gustavsson, P. Gamified Training for Cyber Defence: Methods and Automated Tools for Situation and Threat Assessment in Nato Modelling & Simulation Group (NMSG) Multi-Workshop, MSG-111. 2013. Available online: File:///C:/Users/Admin/Downloads/2013-P055-010-54-SYDNEY2-paper18_NATO-Cyber.pdf (accessed on 7 October 2021).
40. Barnett, T.P.; Pierce, D.W.; Schnur, R. Detection of Anthropogenic Climate Change in the World's Oceans. *Science* **2001**, *292*, 270–274. [CrossRef]
41. Cook, J.; Oreskes, N.; Doran, P.; Anderegg, W.R.L.; Verheggen, B.; Maibach, E.W.; Carlton, S.; Lewandowsky, S.; Skuce, A.G.; Green, S.A. Consensus on consensus: A synthesis of consensus estimates on human-caused global warming. *Environ. Res. Lett.* **2016**, *11*, 048002. [CrossRef]

42. Hook, M.; Tang, X. Depletion of fossil fuels and anthropogenic climate change—A review. *Energy Policy* **2012**, *52*, 797–809. [CrossRef]
43. Travis, J.M.J. Climate change and habitat destruction: A deadly anthropogenic cocktail. *R. Soc.* **2003**, *270*. [CrossRef]
44. Calizza, E.; Costantini, M.L.; Careddu, G.; Rossi, L. Effect of habitat degradation on competition, carrying capacity, and species assemblage stability. *Ecol. Evol.* **2017**, *7*, 5784–5796. [CrossRef]
45. Fargione, J.E.; Cooper, T.R.; Flaspohler, D.J.; Hill, J.; Lehman, C.; McCoy, T.; McLeod, S.; Nelson, E.J.; Oberhauser, K.S.; Tilman, D. Bioenergy and Wildlife: Threats and Opportunities for Grassland Conservation. *Bioscience* **2009**, *59*, 767–777. [CrossRef]
46. Wilcove, D.S.; Rothstein, D.; Dubow, J.; Phillips, A.; Losos, E. Quantifying threats to imperiled species in the United States. *Bioscience* **1998**, *48*, 607–615. [CrossRef]
47. Entrekin, S.A.; Maloney, K.O.; Kapo, K.E.; Walters, A.W.; Evans-White, M.A.; Klemow, K.M. Stream Vulnerability to Widespread and Emergent Stressors: A Focus on Unconventional Oil and Gas. *PLoS ONE* **2015**, *10*, e0137416. [CrossRef] [PubMed]
48. Gibson, D.M.; Quinn, J.E. Application of Anthromes to Frame Scenario Planning for Landscape-Scale Conservation Decision Making. *Land* **2017**, *6*, 33. [CrossRef]
49. Li, F.X.; Wang, L.Y.; Chen, Z.J.; Clarke, K.C.; Li, M.C.; Jiang, P.H. Extending the SLEUTH model to integrate habitat quality into urban growth simulation. *J. Environ. Manag.* **2018**, *217*, 486–498. [CrossRef]
50. Polasky, S.; Nelson, E.; Lonsdorf, E.; Fackler, P.; Starfield, A. Conserving species in a working landscape: Land use with biological and economic objectives. *Ecol. Appl.* **2005**, *15*, 1387–1401. [CrossRef]
51. Radeloff, V.C.; Nelson, E.; Plantinga, A.G.; Lewis, D.J.; Helmers, D.; Lawler, J.J.; Withey, J.C.; Beaudry, F.; Martinuzzi, S.; Butsic, V.; et al. Economic-based projections of future land use in the conterminous United States under alternative policy scenarios. *Ecol. Appl.* **2012**, *22*, 1036–1049. [CrossRef]
52. Sleeter, B.M.; Sohl, T.L.; Loveland, T.R.; Auch, R.F.; Acevedo, W.; Drummond, M.A.; Sayler, K.L.; Stehman, S.V. Land-cover change in the conterminous United States from 1973 to 2000. *Glob. Environ. Chang.-Hum. Policy Dimens.* **2013**, *23*, 733–748. [CrossRef]
53. Sowa, S.; Annis, G.; Morey, M.; Diamond, D. A gap analysis and comprehensive conservation strategy for riverine ecosystems of Missouri. *Ecol. Monogr.* **2007**, *77*, 301–334. [CrossRef]
54. Wang, L.; Brenden, T.; Seelbach, P.; Cooper, A.; Allan, D.; Clark, R.; Wiley, M. Landscape Based Identification of Human Disturbance Gradients and Reference Conditions for Michigan Streams. *Environ. Monit. Assess.* **2008**, *141*, 1–17. [CrossRef] [PubMed]
55. Chengxin, W.; Changbo, Q.; Hongdi, L.; Yan, S. Exploration of Ecological Space Identification and Ecological Impact Assessment in Planning Environmental Impact Assessment —A Case Study of Changchun New District Development Planning. *Chin. J. Environ. Manag.* **2017**, *9*, 88–94. [CrossRef]
56. Wang, R.; Jiang, Y.; Su, P.; Wang, J.A. Global Spatial Distributions of and Trends in Rice Exposure to High Temperature. *Sustainability* **2019**, *11*, 6271. [CrossRef]
57. Yunzhe, D.; Jiangfeng, L.; Jianxin, Y. SpatiotemporalresponsesofhabitatqualitytourbansprawlintheChangsha metropolitanarea. *Prog. Geogr.* **2018**, *37*, 11. [CrossRef]
58. Terrado, M.; Sabater, S.; Chaplin-Kramer, B.; Mandle, L.; Ziv, G.; Acuna, V. Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning. *Sci. Total Environ.* **2016**, *540*, 63–70. [CrossRef]
59. Zhang, H.B.; Wu, F.E.; Zhang, Y.N.; Hans, S.; Liu, Y.Q. Spatial and temporal changes of habitat quality in Jiangsu Yancheng wetland national nature reserve—Rare birds of China. *Appl. Ecol. Environ. Res.* **2019**, *17*, 4807–4821. [CrossRef]
60. Galarraga, K.S.R. Evaluación del Servicio Ecosistémico de Calidad del Habitat Presente en la Cuenca Alta y Media del Río Coca Mediante el Uso del Paquete Computacional Invest 3.3.1, in Facultad De Ingeniería Civil y Ambiental. 2019. Available online: file:///C:/Users/Admin/Downloads/CD-9446.pdf (accessed on 5 October 2021).
61. Meyer, J.M. Modeling the Impact of Gold Mining on Ecosystem Services in Ghana´s Southern Water Basins in Geospatial Technologies. 2019. Available online: https://run.unl.pt/bitstream/10362/63813/1/TGEO0214.pdf (accessed on 5 October 2021).
62. Xu, L.T.; Chen, S.S.; Xu, Y.; Li, G.Y.; Su, W.Z. Impacts of Land-Use Change on Habitat Quality during 1985–2015 in the Taihu Lake Basin. *Sustainability* **2019**, *11*, 3513. [CrossRef]
63. Lina, Z.; Jun, W. Evaluation on effect of land consolidation on habitat quality based on InVEST model. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 250–255. [CrossRef]
64. Ryu, J.-E.; Choi, Y.-y.; Jeon, S.-W.; Sung, H.-C. Evaluation of Habitat Function of National Park Based on Biodiversity and Habitat Value. *Korean Environ. Res. Technol.* **2018**, *21*, 39–60. [CrossRef]
65. Lemos, A.B. Evaluating Ecosystem Services Trade-Offs Due to Land Use Changes: Transition to an Irrigated Agriculture Landscape in Departamento de Biologia Animal. 2017. Available online: https://repositorio.ul.pt/bitstream/10451/27672/1/ulfc120781_tm_Ana_Lemos.pdf (accessed on 5 October 2021).
66. Vogelmann, J.E.; Howard, S.M.; Yang, L.; Larson, C.R.; Wylie, B.K.; Van Driel, J.N. Completion of the 1990s National Land Cover Data set for the conterminous United States from Landsat Thematic Mapper data and ancillary data sources. *Photogramm. Eng. Remote Sens.* **2001**, *67*, 650–662.
67. Yang, L.; Jin, S.; Danielson, P.; Homer, C.; Gass, L.; Bender, S.M.; Case, A.; Costello, C.; Dewitz, J.; Fry, J.; et al. A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. *ISPRS J. Photogramm. Remote Sens.* **2018**, *146*, 108–123. [CrossRef]

68. Jin, S.; Homer, C.; Yang, L.; Danielson, P.; Dewitz, J.; Li, C.; Zhu, Z.; Xian, G.; Howard, D. Overall Methodology Design for the United States National Land Cover Database 2016 Products. *Remote Sens.* **2019**, *11*, 2971. [CrossRef]
69. Fry, J.A.; Coan, M.; Homer, C.G.; Meyer, D.K.; Wickham, J.D. Completion of the National Land Cover Database (NLCD) 1992–2001 Land Cover Change Retrofit Product, in Open-File Report. 2009. Available online: https://pubs.usgs.gov/of/2008/1379/pdf/ofr2008-1379.pdf (accessed on 7 October 2021).
70. Huang, C.; Goward, S.N.; Masek, J.G.; Thomas, N.; Zhu, Z.; Vogelmann, J.E. An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. *Remote Sens. Environ.* **2010**, *114*, 183–198. [CrossRef]
71. Roy, D.P.; Ju, J.; Kline, K.L.; Scaramuzza, P.L.; Kovalskyy, V.; Hansen, M.; Loveland, T.; Vermote, E.; Zhang, C. Web-enabled Landsat Data (WELD): Landsat ETM+ composited mosaics of the conterminous United States. *Remote Sens. Environ.* **2010**, *114*, 35–49. [CrossRef]
72. Johnson, D.M. Using the Landsat archive to map crop cover history across the United States. *Remote Sens. Environ.* **2019**, *232*. [CrossRef]
73. Eidenshink, J.C.; Schwind, B.; Brewer, K.; Zhu, Z.; Quayle, B.; Howard, S. A Project for Monitoring Trends in Burn Severity. *Fire Ecol.* **2007**, *3*, 3–21. [CrossRef]
74. WFIGS, W.F.I.G.S. WFIGS-2021 Wildland Fire Locations to Date. 2021. Available online: https://data-nifc.opendata.arcgis.com/datasets/nifc::wfigs-2021-wildland-fire-locations-to-date/about (accessed on 1 July 2021).
75. DHS, D.o.H.S. HIFLD Open Data. 2020. Available online: https://hifld-geoplatform.opendata.arcgis.com/ (accessed on 1 July 2021).
76. USEIA. Layer Information for Interactive State Maps. 2020. Available online: https://www.eia.gov/maps/layer_info-m.php (accessed on 13 June 2020).
77. Prospect- and Mine-Related Features from U.S. Geological Survey 7.5- and 15-Minute Topo-graphic Quadrangle Maps of the United States. Available online: https://www.sciencebase.gov/catalog/item/5a1492c3e4b09fc93dcfd574 (accessed on 5 October 2021).
78. USGS. NAS—Nonindigenous Aquatic Species. 2020. Available online: https://nas.er.usgs.gov/viewer/omap.aspx (accessed on 13 June 2020).
79. Bargeron, C.; LaForest, J.; Bush, B.; Carroll, R.; Daniel, J.; Dasari, S.; Wallace, R. Distribution Maps. 2021. Available online: https://www.eddmaps.org/distribution/ (accessed on 1 July 2021).
80. Ruefenacht, B.; Finco, M.V.; Nelson, M.D.; Czaplewski, R.; Helmer, E.H.; Blackard, J.A.; Holden, G.R.; Lister, A.J.; Salajanu, D.; Weyermann, D.; et al. Conterminous U.S. and Alaska Forest Type Mapping Using Forest Inventory and Analysis Data. *Photogramm. Eng. Remote Sens.* **2008**, *74*, 1379–1388. [CrossRef]
81. National Geospatial Program, U. National Hydrography. 2020. Available online: https://www.usgs.gov/core-science-systems/ngp/national-hydrography (accessed on 12 July 2020).
82. WorldPop. Population Density. 2021. Available online: https://www.worldpop.org/project/categories?id=18 (accessed on 1 July 2021).
83. Czech, B.; Krausman, P.R.; Devers, P.K. Economic Associations among Causes of Species Endangerment in the United States. *Bioscience* **2000**, *50*, 593–601. [CrossRef]
84. Nie, C.; Yang, J.; Huang, C.H. Assessing the Habitat Quality of Aquatic Environments in Urban Beijing. *Procedia Environ. Sci.* **2016**, *36*, 162–168. [CrossRef]
85. Shen, Y.; Cao, H.; Tang, M.; Deng, H. The Human Threat to River Ecosystems at the Watershed Scale: An Ecological Security Assessment of the Songhua River Basin, Northeast China. *Water* **2017**, *9*, 219. [CrossRef]