Technical Report on Assembling Indicators to Monitor Climate-Driven Change in Northeastern Forests

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Technical Report on Assembling Indicators to Monitor Climate-Driven Change in Northeastern Forests (Version 1.0)

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Executive Summary

Forest ecosystems are experiencing the impacts of climate change in many forms, however, comprehensive monitoring efforts are not always available to identify changing baselines. In order to improve our understanding of the impacts of climate change on ecosystem processes, the FEMC developed the *Forest Impacts of Climate Change: Monitoring Indicators* tool (Version 1.0). The *Forest Impacts of Climate Change: Monitoring Indicators* tool was developed for use by researchers and professionals to be able to easily access protocols used to monitor high priority indicators of the impacts of climate change in New England and New York. The monitoring protocols provide information for landowners and managers to implement their own monitoring programs that will be comparable to other studies being conducted across the region. By centralizing information about this network of monitoring sites, more data will become available to the community to help discern how forest ecosystems are changing. This report describes the methods and implementation used to build this tool.

To develop the *Forest Impacts of Climate Change: Monitoring Indicators* tool, FEMC formed a committee of partners to select indicators and provide guidance about the literature review and eventual tool. The committee identified four ecological categories as important for monitoring climate change in the Northeast: Wildlife, Forest Systems, Trees, and Aquatic Systems. FEMC identified who is currently conducting monitoring efforts, what monitoring protocols are available for replication, gaps in monitoring data, and how we can make data and monitoring information easily available so that land managers can have the most up-to -date information possible. The developed tool compiles over 350 studies across 24 different indicators of the impacts of climate change. Through a filterable webtool users can find these studies, as well as 168 replicable protocols to direct implementation. The tool helps to identify gaps in monitoring efforts and provides a platform for users to contribute to regionally cohesive datasets.

Monitoring of indicators across systems is critical for tracking and understanding climate change impacts. The *Forest Impacts of Climate Change: Monitoring Indicators* tool, developed for use by researchers, professionals, and land managers across the region, lets users find methods and protocols for monitoring climate change impacts and see where these monitoring efforts are already being conducted in our region. In addition, you can quickly visualize where there are gaps in our monitoring. As contributors in the Cooperative region share more information about their own monitoring efforts, this will become available to the community through this tool, increasing our ability to track and identify change in our forested ecosystems.

Introduction

Globally, unpredictable shifts in climate patterns are increasing, negatively impacting ecosystem function. As the effects of climate change accelerate, abiotic disturbances such as extreme weather, drought, and fire will subject forested systems to increased stress. Under normal circumstances, forests are resilient to regular disturbance and external change, however, the impacts of climate change may push certain systems beyond their threshold. These negative impacts have the potential to cause widespread loss of biodiversity, natural resources and ecosystem services.

Being able to anticipate when and to what extent ecosystems are being impacted by climate change is critical for proactive, adaptive forest management practices. In order to predict patterns in ecosystem response, it is necessary to establish accurate baseline conditions and reference systems. Structured, long-term monitoring allows us to see changes to baselines over time and increases the chances of implementing effective management strategies before a threshold is passed or systems transitions occur.

Why this Tool is Needed in the Northeast

The northeastern region of the United States is comprised of many different forest types that provide habitat for critical flora and fauna. Across the region, numerous efforts are already conducted to track forest health and condition, however, it can be difficult to exchange data across administrative boundaries. Natural resource managers and researchers are constrained by permitting and funding sources as well as the structure of data collection. There are also large tracts of privately owned lands that are not actively managed that hold critical information about forest health trends. Considering the ongoing and growing implications of climate change on northeastern forests, the Forest Ecosystem Monitoring Cooperative (FEMC) was asked to identify key ecosystem metrics to monitor and pinpoint what to look for in monitoring data in order to improve the ability of resource managers and planners to identify possible impacts of climate change within forested ecosystems.

Objectives

The objective of this project is to identify key ecosystem processes that can be monitored to track changes in the impacts of climate change across the Northeast, and document where and how those processes are being monitoring. The project determined where monitoring efforts are being conducted, who is carrying out efforts, and which monitoring protocols are available for replication by stakeholders. This project also identified where there are gaps in monitoring data and made protocol information easily available for use by future monitoring programs. This project is meant to be a consolidated platform for information about indicator monitoring and will hopefully continue to grow as data is added. This project does not attempt to analyze trends in any changes or impacts to indicators, as that work is beyond the scope of what could be accomplished during this phase of the effort.

OUTCOMES

Based on input from FEMC cooperators, the desired outcomes from this project were:

- Through a visual tool, users will be able to easily determine **where** monitoring efforts are happening in their region and read about the methodologies of related studies;
- Users will be able to quickly find replicable, standardized protocols that detail **how to monitor** for key indicators of climate change impacts; and
- A gap analysis will show users where monitoring is **not yet happening** or is not current and allow a platform for users to add studies or monitoring efforts as they become available.

KEY PRODUCTS

The key products of this effort are listed below:

- Completed aggregation of dozens of monitoring protocols, studies and datasets representing sensitive aspects of forest ecosystems in the Northeast;
- Interactive information portal showcasing the locations of existing monitoring of climate-sensitive ecosystem processes and metrics; and
- White paper summarizing current extent of key indicator monitoring in the region and model monitoring methods.

Project Development

Cooperative Engagement

Advisory Committee

An advisory committee of regional experts from across disciplines was formed to advise the FEMC project team throughout the development of this webtool (Table A-1). Their purpose was to provide direction on project objectives, supplement the resource identification process, and support the justification of included data.

The Advisory Committee convened three times over the course of the project. The first Advisory Committee meeting happened at the onset of the project during which the broader scope of the project was determined and preliminary goals for development were set. In this meeting, the Advisory Committee identified the target audience of the project (primarily land managers, landowners, and researchers) as well as the constraints of the final project outcomes. The second and third Advisory Committee meetings were held to provide a structured review of the webtool and data criteria at milestone points in the project; once at the halfway point and again when the beta version of the tool was largely completed. The work of the Advisory Committee was supplemented with a separate, more specialized working group.

Working Group

A working group of regional experts, including participating advisory committee members and external cooperators (Table A-2), was convened in Fall 2020. With facilitation by FEMC staff, the working group reviewed the survey results of the Advisory Committee and helped to identify a subset of key indicators of the impacts of climate change on northeastern forests. Selected indicators were constrained at the ecosystem process level and were divided into four major ecological categories: Aquatic Systems, Forest Systems, Trees, and Wildlife (Appendix 1). Each ecological category was further divided into climate indicator categories and climate indicator subcategories.

To select the indicators to include, an initial list of species and ecosystem processes were compiled through conversations with working group members and parsed down to a smaller critical list via a voting process. Selected indicators are deemed high priority because of their sensitivity to climatic shifts or because of their role in ecosystem dynamics. These indicators were selected because of their relative importance as well as their ability to be monitored for signs of impact. Through this process, the working group selected four ecological categories, 13 climate indicator categories and 24 indicator subcategories (Table 1). All initial indicator categories were included in the first release of the tool except for “Subcategory: Range Shifts” and “Indicator: Elevation” which were removed after the literature review process due to contradicting evidence of relevance.

Table 1. Selected indicators of the impacts of climate change. Indicators are divided into hierarchical categories: Category, Subcategory, and Indicator (Left to right). Indicators with asterisks were removed from inclusion after the literature review process.

Category	**Subcategory**	**Indicator**
Wildlife	Mammal Biodiversity	Moose Population
		Northern Flying Squirrel Population
		Little Brown Bat Population
		Snowshoe Hare Population
	Bird Biodiversity	Wintering Range
		Bicknell's Thrush
		Black-Throated Blue Warbler
		Change in Arrival Date
Trees	Tree Mortality	Stand Health
	Range Shifts*	Elevation*
	Regeneration	Seedling Regeneration
	Storm Damage	Physical Damage to Trees
Forest Systems	Understory Plants	Community Composition
		Invasive Species Abundance
	Pest and Pathogens	Hemlock Woolly Adelgid
		Southern Pine Beetle
	Asynchronicity: Pollinators	Phenology/Physiology of Pollinators
	Growing Season	Temporal Shifts: Trees
	Extent of Sensitive Communities	Distribution of Vulnerable Flora
		Distribution of Vulnerable Fauna
Aquatic Systems	Vernal Pool Biodiversity: Amphibians	Amphibians: Wood Frog Population
	Stream Biodiversity	Macroinvertebrates
		Community Composition
		Brook Trout Population
		*Removed from final list due after literature review evaluation

Compiling Information on Relevant Monitoring

Resource Identification

Initial resource identification started with a structured literature review of the current body of knowledge of each climate indicator defined by the Advisory Committee (Table 1). The literature review was focused specifically on linkages between the ecosystem processes (indicators) and the impacts of climate change. If a climate indicator category did not have sufficient documentation in the literature to support being included, it was dropped as an indicator of consideration. “Subcategory: Range Shifts” and “Indicator: Elevation” were excluded from the final product because the literature had conflicting interpretations of the directionality of the impacts of climate change.

Following this review, we conducted an inventory of studies, protocols, and related datasets that are available across the region. These documents were located through online search engine queries, recommendations from cooperators, and input from the Advisory Committee and working group participants. From the inventory, protocols were selected for inclusion based on a set of criteria; protocols had to be standardized, replicable, and have a spatial component that would allow us to determine, at a minimum, in which state(s) the effort was being conducted. Monitoring efforts and studies directly related to the indicators were also included whether or not they included replicable protocols. These monitoring efforts and studies were used to populate the web tool map to show where monitoring is occurring in the Northeast. The current inventory of protocols, datasets, and studies is considered a first round of data gathering to test the implementation of the Version 1.0 of this tool—additional data will be added in future versions to increase the accuracy and completeness of the tool.

Data Framework Development

Monitoring protocols, related studies and datasets that fit the inclusion criteria, were compiled and processed by FEMC data technicians. Necessary metadata from each item were systematically extracted into a multi-tabbed data framework and imported into the webtool platform. This framework captured important project data information, metadata, and methods information. Categories within the framework are described in Table 2 below and a more detailed definition of each ‘Metric’ and ‘Category’ can be found in Table 3.

Table 2. Titles and descriptions of metadata components and their contents within the data extraction framework.

Metadata component	**Description**
Basic Info	Describes the metadata for each study, dataset, or protocol including its title, contents and external source information.
Study Protocol	Describes linkages between a specific study and the protocols that are used in the study. Studies can have multiple protocols and/or monitor multiple indicators.
Datasets	Describes linkages between a study and any related dataset. It includes the separate name and external location of the data product or dataset. A study can have multiple associated datasets that are related to multiple climate indicators categories.
Protocols	Describes protocol specific information including the original creator of the protocol and where it can be found externally.
Contacts	Describes any contact information associated with a given study.
Organizations	Describes affiliated organizations that are connected to studies, datasets, or protocols.
Categories	Describes the indicators of the impacts of climate change at the ecological category, subcategory, and indicator level. Each study is assigned at least one indicator category. Many studies encompass more than one indicator category.
Metrics	Describes the key ecological metrics that studies address within their methodologies. Studies can be associated with more than one metric (Appendix 2).
States	Describes location information of studies at the state level. Many studies have more than one associated state.
Protocol Indicators	Describes the linkages between protocols and indicators. Each protocol is assigned at least one indicator and many protocols relate more than one indicator category.
Years	Describes the temporal duration of a study in years.

Table 3. Titles and descriptions of metrics used to categorize study methods.

Metric	Description	Short desc
Survivorship	Survivorship is used to quantify changes in population dynamics, this metric demonstrates the demographics of a population and the likelihood that different aged organisms survive over a period. This metric can be used for most living organisms in a population.	Plant and animal: lifespan measured
Abundance	Abundance is an ecological metric used to quantify the relative representation of a species in a community. This metric includes coverage of abundance of vulnerable or invasive species and is often considered alongside richness when evaluating **community composition**.	# individuals of a species (how many individuals)
Fecundity	Fecundity can be described as a the 'maximum potential reproductive output' of an organism over its lifetime and is often considered when predicting growth or decline of populations.	Animal: birth rate measured throughout lifespan

Population Density	Population density measures the numbers of individuals in each area and describes the density of individuals in a given population.	# adults of a species, has spatial extent where you can say - this species is more dense here than there (how many individuals in a specific space compared to another space)
Mortality	Mortality is the measure of deaths by individual in a population. It is a counter metric to fecundity and is often considered in tandem predicting population survival trends.	Plant and animal: lifespan measured
Center of Abundance	Center of abundance is a species abundance pattern that is used to identify the relative center of a species range. Changes in center of abundance can be used to identify shifts in bird populations among other species.	Plant and animal: # individuals of a species measured across entire range
Distribution	Distribution is used to quantify where individuals are in given area. This is used alongside abundance to determine where individuals in a population or community. This metric can be used to quantify things such as tree line shifts in a given region.	distribution of adults of species, data has spatial component - where you can say presence/absence (where individuals are)
Migration Dynamics	This metric is a broader metric that includes 'Migratory intensity' and 'Migratory trajectory' which quantify the spatial and temporal aspects of a species' migration pattern. This can include changes in arrival times for birds and insects as well changes in physical path of migration.	Animal: spatial and temporal movement of a species
Richness	Richness is an ecological quantification of the number of different species in a community. Richness is often considered in tandem with abundance and distribution when evaluation overall **community composition.**	# adult individuals of multiple species (how many types of individuals)
Biomass	Biomass is the total mass of organisms in a given are or population. It is common metric in aquatic and forested systems and is often used to quantify growth in trees. Includes measurements of basal area (a good proxy for biomass)	Plant and animal: weight of organism measured
Canopy Cover	Canopy cover is a metric of the amount of light that reaches the forest floor, most often determined by tree canopy. This metric can be used to evaluate tree stand health.	Tree: canopy cover measured
Seed Establishment	Seed establishment is a regeneration metric used to predict population growth by species. This includes regeneration of seedlings of vulnerable species, and regeneration by forest type (i.e., Softwood/hardwood composition).	Plant: seedlings counted
Tree Crown Condition	Crown Condition is a common forest health metric used to measure the condition of tree crown by individual and can be used to suggest tree damage by storms.	Tree: canopy condition measured
Tree Dieback	Dieback is a common forest health metric used to measure the progressive death of tree branches often due to physical damage or disease. This metric is a measure of stand health as well as storm damage and pest/pathogen damage.	Tree: canopy dieback measured
Functional Trait Composition	A metric of abundance that focuses on the types of functional traits represented by species in each ecosystem.	Plants: measurement of a plant's role in a community

Phenological Timing	Phenology is a metric to measure the seasonal changes in climate and biological shifts in dependent organisms. This includes shifts in timing of first bloom, first leaf, and fall senescence of trees.	Plants: bloom, buds, leafing out timing Animals: life cycle stages
Physiological Timing: Pollinators	Physiological Timing: Pollinators evaluates the timing of physiological changes in insects in relation to climatic shifts. This includes changes in peak activity, changes in diapause, and early emergence from larval stages	Pollinators: time when insects emerge
Occurrence	Used for Inventories, a metric that focuses on occurrences of species in a given location. Like distribution but only presence/absence	

TECHNICAL IMPLEMENTATION

The Forest Impacts of Climate Change: Monitoring Indicators portal is hosted within the FEMC website. It was designed and developed based on the project objectives and assumed user needs, targeting landowners, researchers, and land managers who might be monitoring related indicators in their region. The protocol, study and dataset metadata discussed above is stored in its own MySQL database within the FEMC data storage architecture and the portal utilizes the data archive and discovery infrastructure developed by FEMC. The portal is implemented using the Linux-Apache-MySQL-PHP open-source software and technology stack. The tables are created using DataTables (https://datatables.net/) available under the MIT license. The metadata PDFs are built using FPDF (http://www.fpdf.org/) and FPDI (https://www.setasign.com/products/fpdi/about/), free open-source PHP software also available under the MIT license. The map uses OpenLayers (https://openlayers.org/) a dynamic web mapping API that is provided as a free open-source JavaScript software under a FreeBSD license. These components were combined in a custom web front-end framework using Bootstrap 4 (https://getbootstrap.com/docs/4.0/ available under MIT license) to create a portal that provides seamless user experience and interaction across devices.

Outcomes and Findings

PROJECT OVERVIEW

This project had three main outputs: a.) a compiled set of resources, b.) an interactive web tool to explore data, and c.) an initial assessment of the gaps identified by the project.

Resources were compiled in the project from all six New England states and the state of New York. For Version 1.0 of this tool, we collected at least 20 studies per indicator unless there were less available after a thorough search. In total there were 346 studies/monitoring efforts added and 168 replicable protocols identified across all indicators. The state of New York had the most studies across indicators (n=117), followed by Massachusetts (n=113). However, the state of RI had the most studies proportional to its size (n=55). It is more important to note that if the same study or monitoring effort takes place across multiple states, it is counted separately within each state, which impacts the total study counts. Across states, there is a similar proportional representation of each indicator with more studies represented in the 'Forest Systems' category and less in the 'Aquatic Systems' category. The resources compiled in this project are publicly available for use through external links and are searchable through use of the tool.

The function of the tool and the initial assessment of patterns is covered in more detail below.

TOOL FUNCTION

An introductory homepage provides general context and summary information of selected indicator types for users to explore. From this page, the user can navigate directly to the "Monitoring" tab to filter through a map tool to see specific studies (Figure 1). Filters can constrain results by the 'ecological', 'indicator', or 'subindicator' category of a study as well as the state(s) of interest and the time range. Users looking for a specific study can also search by title on this page.

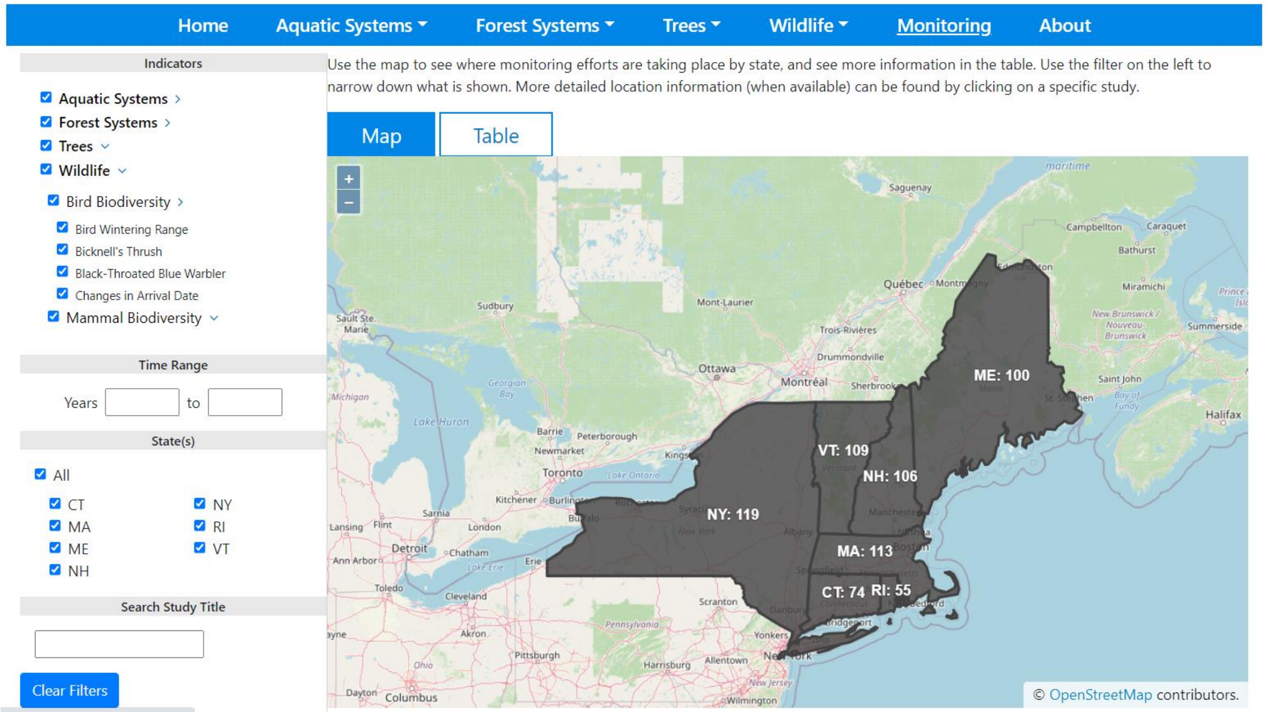

Figure 1 Screenshot of the filterable map located on 'Monitoring' page of the Forest Impacts of Climate Change: Monitoring Indicators tool, Version 1.0. The map shows filtering capacity with filters selected.

The information displayed on the map can also be viewed in a tabular format by toggling the 'Table' tab (Figure 2). In this view, users can quickly see the study titles, associated indicator subcategories, and if the study has associated protocols and datasets. Any filters set in the map view are retained in the table view.

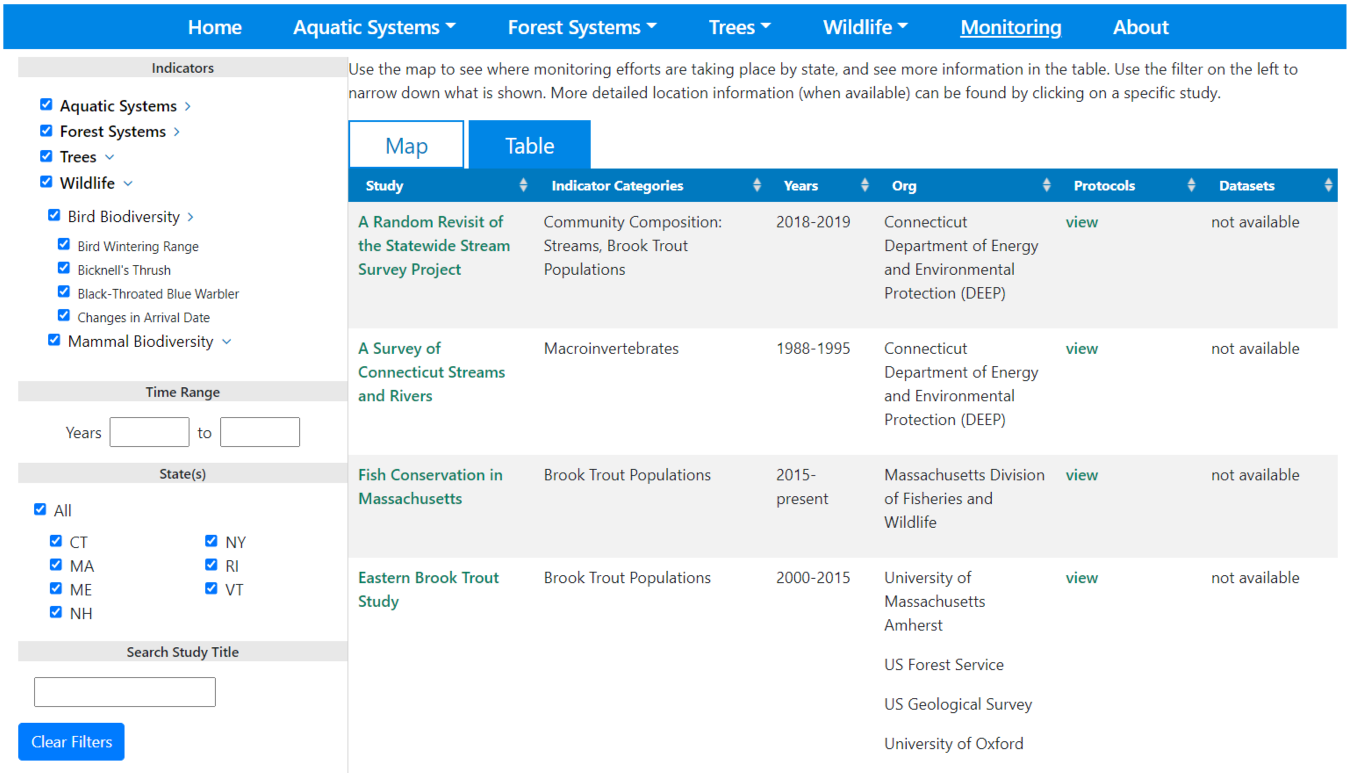

Figure 2 Screenshot of the filterable tabular view located on 'Monitoring' page of the Forest Impacts of Climate Change: Monitoring Indicators tool, Version 1.0. The table shows filtering capacity with filters selected.

If a specific study is selected, a pop-up window with more detailed study information is displayed including key contacts, affiliated organizations, and more detailed location information if available (Figure 3). Users can also easily navigate within the pop-up to see any datasets or protocols associated with a specific study by using the tabs at the top of the box.

Figure 3 Screenshot of the 'Study Info' pop-up modal that engages when a specific study is selected (Version 1.0).

As mentioned above, the homepage also provides more detailed information about each indicator and why it is a priority for monitoring efforts. The user can click through ecological categories to see more information about each category and the related subcategories and indicators (Figure 4).

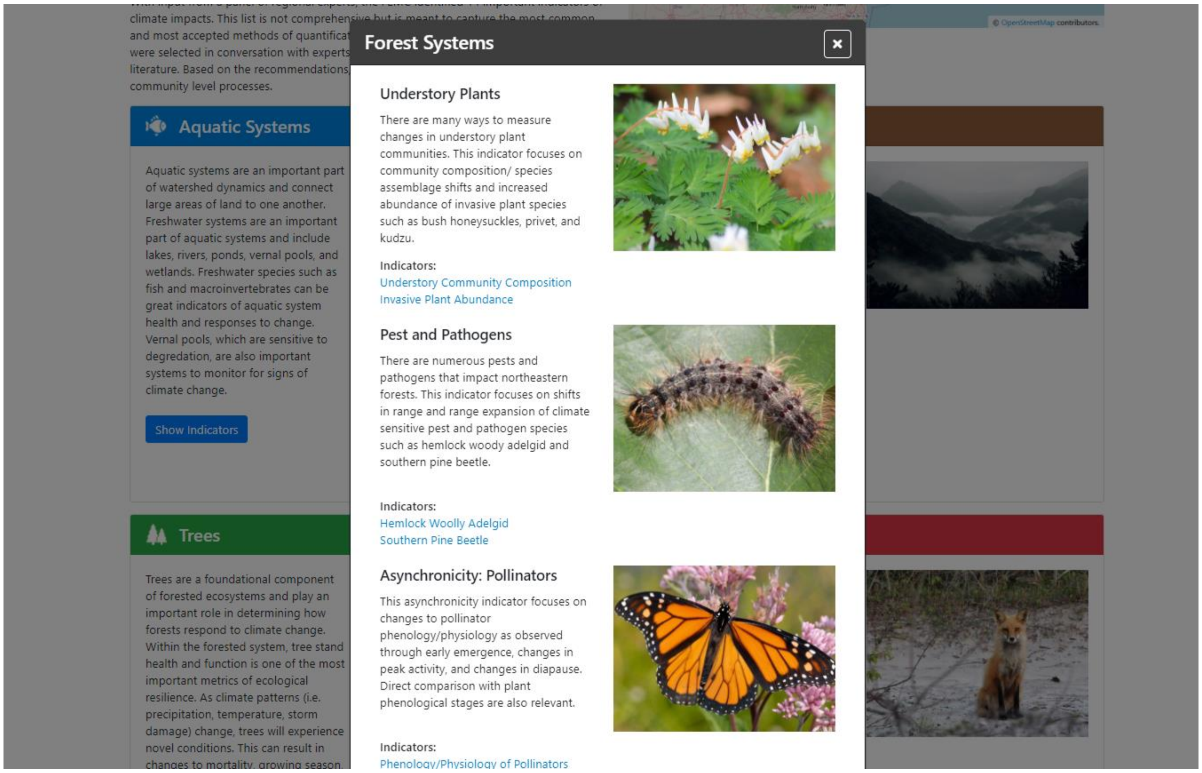

Figure 4 Screenshot of the 'Indicator categories' pop-up that is shown when users click "view more" from the 'Ecological categories' boxes on the homepage.

Every indicator has an individual page that provides more information on the protocols available to monitor the indicator, the metrics used in related studies and a map that shows quick location information and gaps in monitoring for that indicator (Figure 5). These pages provide contextual information on indicators and provide a more direct link to protocol documents via a table view.

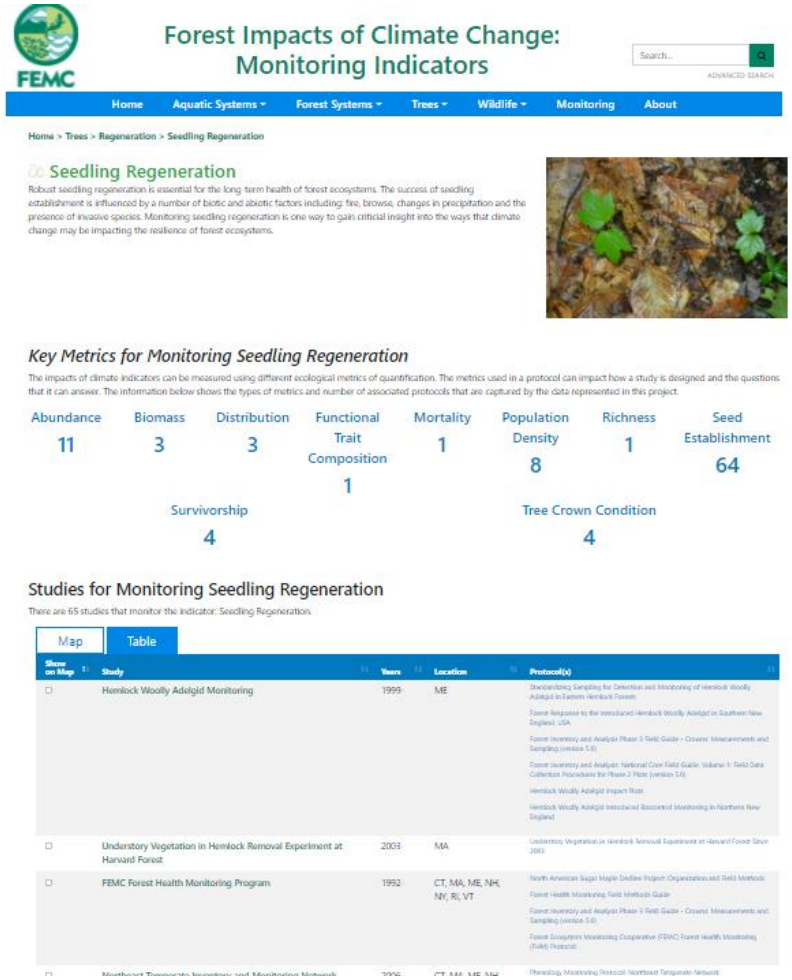

Figure 5. Screenshot of the individual 'Indicator' page. This example shows tabular information about protocols and a list of metrics associated with the 'Seedling Regeneration' indicator.

INITIAL ASSESSMENT OF PATTERNS

An initial assessment of the gaps focused on three main types of disparity that were apparent in examining the collected information: uneven representation of specific indicators, uneven geographic and/or temporal distribution, and uneven multi-state coverage (as opposed to state- or site-specific programs). A more detailed gap analysis of the information in the tool is forthcoming.

Uneven Representation of Indicators

Although the search effort was equivalent across indicators, searches produced significantly less results for some indicators compared to others. As detailed in the methods, the search effort was designed to find at least 20 studies for all 24 indicators. However, after extensive searching, the 'Brook Trout', 'Southern Pine Beetle', 'Distribution of Vulnerable Flora', 'Distribution of Vulnerable Fauna', 'Physical Damage to Trees', 'Wintering Range' and 'Snowshoe Hare Population' indicators produced only 20 studies conducted in the Northeast (Table 4). Searches for 'Northern Flying Squirrel Population' (n=4) and 'Community Composition: Streams' (n=9) indicators produced less than 10 related studies. The reason for the lack of monitoring programs and associated data for these indicators needs to be explored more deeply, however, after discussion with our Advisory Committee, we decided to include these indicators to highlight this gap and the need for more data to be added in the future. It is possible that these indicators lack robust studies because they are newly identified as important in relation to climate change impacts or are not widely shared online or with current networks of professionals.

The number of protocols related to each indicator reflects a similar pattern to the number of studies collected. Although it was not anticipated that there would be the same number of protocols as studies, we attempted to include at least three replicable protocols for each indicator. Searches for the 'Distribution of Vulnerable Flora' and 'Distribution of Vulnerable Fauna', 'Southern Pine Beetle', 'Little Brown Bat Population', and 'Northern Flying Squirrel Population' indicators produced less than three replicable protocols for inclusion (Table 4). The results of our inventory also show that there are several indicators that have a high number of related studies, but a low number of related protocols. For example, the 'Invasive Species Abundance' protocol has 34 related studies but only four replicable protocols. There are many possible reasons for the discrepancies between study number and protocol number by indicator which need to be explored more thoroughly. However, one possible reason may be that different or multiple studies may use the same protocol, reducing the number of unique protocols available. Overall, having fewer, more robust protocols may make it easier to select and implement regionally cohesive monitoring efforts.

Table 4. Number of studies and replicable protocols included by indicator.

CATEGORY	SUBCATEGORY	INDICATOR	STUDIES IDENTIFIED	PROTOCOLS SPECIFIED FOR INDICATOR
AQUATIC SYSTEMS	Stream Biodiversity	Brook Trout Population	19	9
		Community Composition	9	3
		Macroinvertebrates	26	20
	Vernal Pool Biodiversity Indicator	Amphibians: Wood Frog	30	7
FOREST SYSTEMS	Asynchronicity: Pollinators	Phenology/Physiology of Pollinators	29	7
	Extent of Sensitive Communities	Distribution of Vulnerable Fauna	18	1
		Distribution of Vulnerable Flora	18	1
	Growing Season	Temporal Shifts: Trees	28	8
	Pest and Pathogens	Hemlock Woolly Adelgid	25	19
		Southern Pine Beetle	10	2
	Understory Plants	Community Composition	30	3
		Invasive Species Abundance	34	4
TREES	Regeneration	Seedling Regeneration	73	13
	Storm Damage	Physical Damage to Trees	18	6
	Tree Biodiversity	Community Composition	45	5
	Tree Mortality	Stand Health	28	11
WILDLIFE	Bird Biodiversity	Bicknell's Thrush	20	11
		Black-Throated Blue Warbler	34	19
		Changes in Arrival Time	32	5
		Wintering Range	11	3
	Mammal Biodiversity	Little Brown Bat Population	26	1
		Moose Population	26	4
		Northern Flying Squirrel Population	4	2
		Snowshoe Hare Population	12	4
		Total	**346**	**168**

During the literature review process, we identified that several of the selected indicators were under-represented in the literature. The reasons for this lack of information need to be explored further, but possibilities include that monitoring of specific indicators might lack appropriate funding sources, and that some indicators may only now becoming a concern due to novel and/or intersecting stressors. Based on Advisory Committee input, we decided to include indicators that are currently understudied, but will likely see increasing impacts from climate change in upcoming years and are high priority for monitoring, such as the 'Distribution of Vulnerable Flora' and 'Northern Flying Squirrel Population' indicators.

Uneven geographic and/or temporal distribution of monitoring

Determining where there are gaps in monitoring efforts is an important part of this tool. By identifying those gaps, land managers and researchers can intentionally select areas to monitor to increase cohesive knowledge. Data visualizations were created to identify potential gaps in monitoring in both space and time.

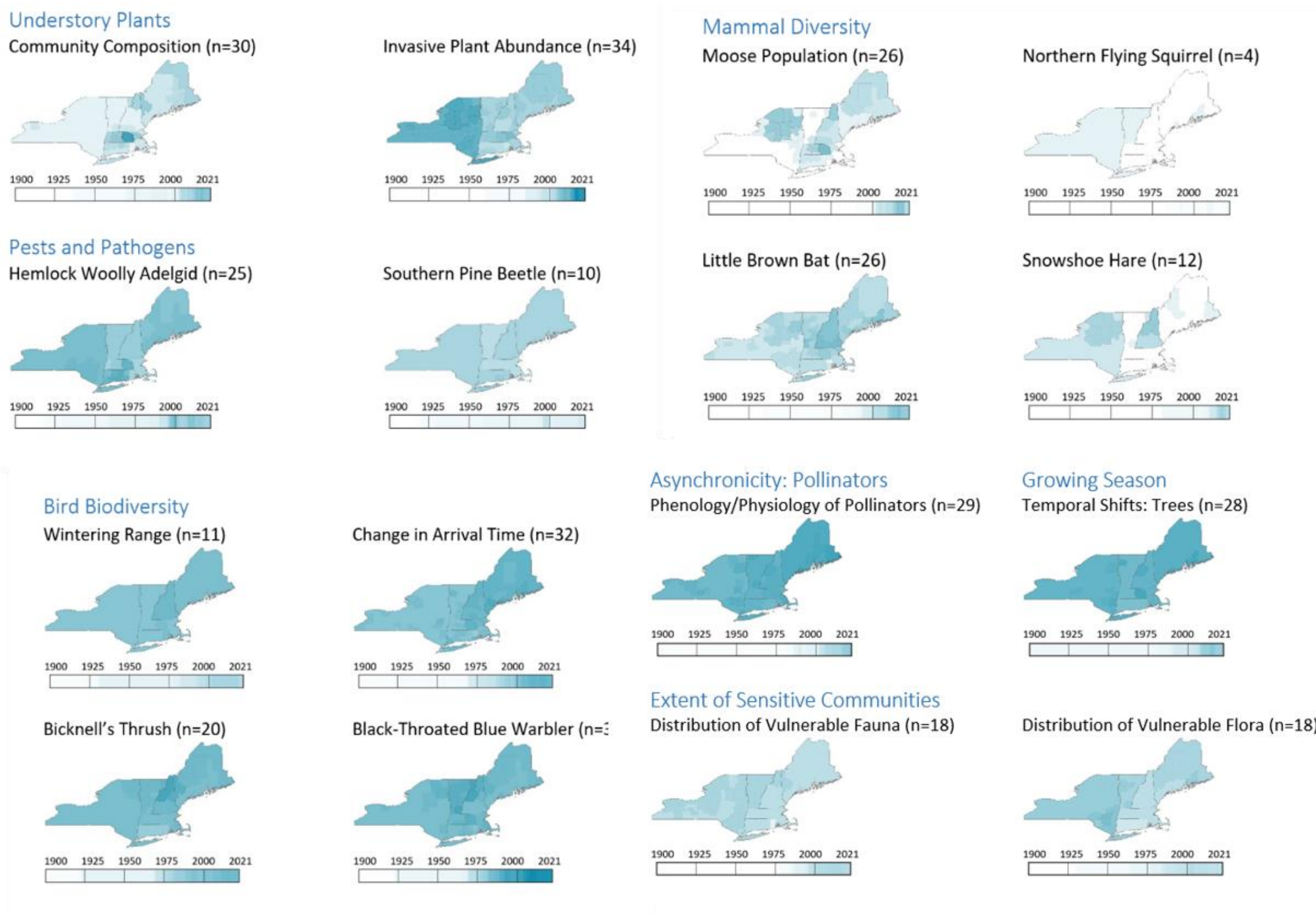

Figure 6. Geographic and temporal distribution of indicators by state over time. Colors on the map show the number of studies per state. The colored bar underneath each map shows the number of studies overlapping each year between 1900 and 2021.

As demonstrated in Figure 6, there are geographic and temporal imbalances in indicator representation across the region. These data need to be analyzed more rigorously to determine the significance of the patterns, but from this initial pass we identify several areas for further exploration. There is a clear, uneven spatial distribution in the 'Snowshoe Hare Population' and 'Northern Flying Squirrel Population' Indicators. We also see gaps in distribution for the 'Moose Population' indicator, however, some of this could be due to natural boundaries to moose habitat range. Conversely, we see even spatial coverage of all indicators in the 'Bird Biodiversity' subcategory. This is likely due to well-established, regional survey programs such as inventories collected through the Audubon Society. Within the 'Trees' subcategory, we find more even spatial distribution of the 'Seedling Regeneration' indicator. This may be due to widespread interest in seedling regeneration studies, or it could be related to a higher search effort by FEMC because of a previous project that focused on seedling regeneration methods (*REGEN: The Northeastern Forest Regeneration Data Network*) that had already identified a number of regeneration studies. Patterns in the geographic and/or temporal distribution of indicators in the 'Forest Systems' and 'Aquatic Systems' are less clear on first look and will require more extensive review.

Regional vs. state monitoring coverage

Of the 346 studies identified, 75% (n=265) only included monitoring efforts in a single state (Table 5). Monitoring efforts that implemented regional efforts only accounted for 15.5% (n=38) of the total programs identified across all indicators. This disparity is important points to a lack of cohesion in monitoring efforts across administrative boundaries. In other words, there is potential to regionalize efforts for more effective collaboration and more accurate ecological information.

Table 5. The number of studies that implement monitoring on a single state, multi-state, or regional level across each indicator.

CATEGORY	SUBCATEGORY	INDICATOR	STUDIES IDENTIFIED	SINGLE STATE	MULTI-STATE	REGIONAL
AQUATIC SYSTEMS	Stream Biodiversity	Brook Trout Population	19	18	1	1
		Community Composition	9	9	0	0
		Macroinvertebrates	24	19	5	2
	Vernal Pool Biodiversity Indicator	Amphibians: Wood Frog	30	23	7	2
FOREST SYSTEMS	Asynchronicity: Pollinators	Phenology/Physiology of Pollinators	29	17	12	7
	Extent of Sensitive Communities	Distribution of Vulnerable Fauna	18	16	2	0
		Distribution of Vulnerable Flora	18	16	2	1
	Growing Season	Temporal Shifts: Trees	28	19	9	6
	Pest and Pathogens	Hemlock Woolly Adelgid	25	20	5	3
		Southern Pine Beetle	10	7	3	3
	Understory Plants	Community Composition	30	24	6	1
		Invasive Species Abundance	34	29	5	2
TREES	Regeneration	Seedling Regeneration	73	58	15	1
	Storm Damage	Physical Damage to Trees	18	10	8	1
	Tree Biodiversity	Community Composition	45	32	13	1
	Tree Mortality	Stand Health	28	16	12	2
WILDLIFE	Bird Biodiversity	Bicknell's Thrush	20	10	10	4
		Black-Throated Blue Warbler	34	25	9	5
		Changes in Arrival Time	32	23	9	5
		Wintering Range	11	5	6	6
	Mammal Biodiversity	Little Brown Bat Population	26	18	8	1
		Moose Population	26	23	3	0
		Northern Flying Squirrel Population	4	4	0	0
		Snowshoe Hare Population	12	9	3	0
		Total	**346**	**265**	**82**	**38**

Evaluated individually, most of the indicators have at least one or two regional monitoring efforts. However, the 'Distribution of Vulnerable Flora', 'Northern Flying Squirrel Population', 'Moose Population', 'Snowshoe Hare Population' and 'Community Composition' indicators have no recorded regional studies (Figure

7). The ‘Southern Pine Beetle’ and ‘Wintering Range’ indicators are the indicators with the highest percentage (>80%) of studies/monitoring efforts that are regional in coverage by individual indicator. Some of these discrepancies may be due to natural limitation in species’ physical ranges, insufficient search effort, or lack of available data.

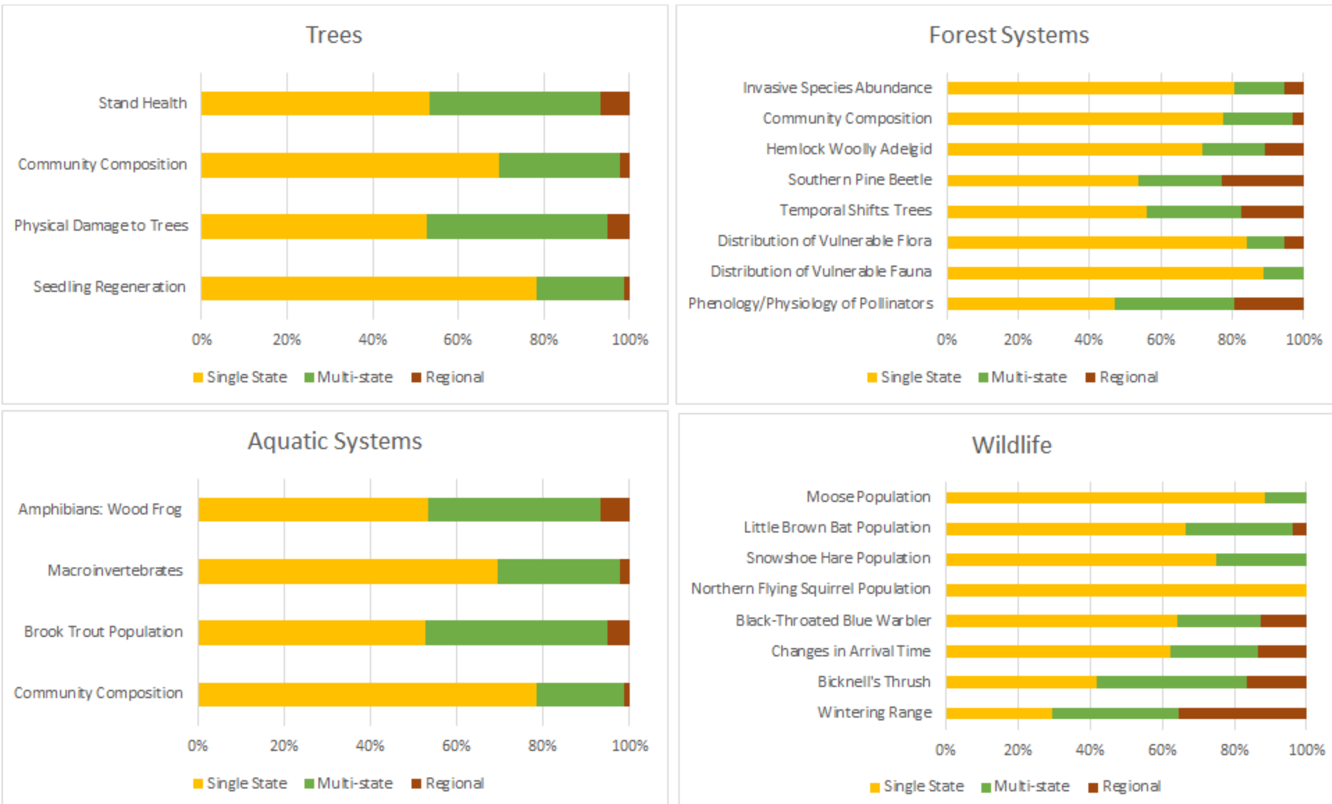

Figure 7.Stacked bar charts of the percentage of studies by indicator that cover single states, multiple states, or are regional in coverage.

SUMMARY OF INITIAL ASSESSMENT

Through our initial assessment we have identified three primary areas of interest to explore further: indicators that have low topical, geographical, and regional coverage, indicators that have high topical, geographical, and regional coverage, and indicators that have contradicting aspects of coverage. The ‘Northern Flying Squirrel Population’, ‘Snowshoe Hare Population’ and ‘Aquatic Community Composition’ indicators all have low topical, geographical, and regional coverage (Table 6). This suggests that these indicators, though deemed critical to assessing the impacts of climate change, are under studied and/or underrepresented in the literature. The reasons for such low cohesion need to be explored further and could potentially indicate a gap worthy of greater attention in future monitoring efforts.

All the indicators in the 'Bird Biodiversity' subcategory have high topical, geographical, and regional coverage in the database (Table 6). This high coverage may be due to successful programmatic efforts by monitoring organizations, but it could also be a result of the high mobility of bird species. Because many bird species have large ranges across the Northeast, there may be more studies that cover a larger area and have cohesive methodologies across the region. If these patterns are supported in our detailed analyses, these types of studies may serve as good models for regional monitoring strategies.

Finally, there are several indicators that have high representation in some aspects of coverage and low representation in others. Search efforts for data related to the 'Moose Population', 'Invasive Species Abundance', Seedling Regeneration' and Understory Composition' indicators returned high topical information (i.e., many studies about moose), but low regional coverage per study and uneven geographic distribution of studies across the northeast. This suggests that there is a high level of interest in and implementation of studies on these topics, however, there may not be cohesive regional protocols, or these indicators may not be feasible or of interest to study in every location. This preliminary assessment will need to be explored further to determine whether patterns seen here are meaningful or not.

Table 6. Indicators represented in preliminary gap analysis assessment by relationship to data coverage.

Low Topical, Geographical, Regional Coverage	**High Topical, Geographical, Regional Coverage**	**Contradicting Topical, Geographical, Regional Coverage**
• Northern Flying Squirrel Population • Snowshoe Hare Population • Aquatic Community Composition	• All indicators in 'Bird Biodiversity' Subcategory	• Moose population • Invasive Species Abundance • Seedling regeneration • Understory Composition

Next Steps

The *Forest Impacts of Climate Change: Monitoring Indicators tool, Version 1.0* was built to help users identify important indicators of the impacts of climate change, see where monitoring of these indicators is and is not already occurring, and easily access replicable protocols related to each indicator. We recognize that forested ecosystems do not adhere to administrative boundaries and therefore, to interpret any trends in forest health, there needs to be cohesive data collection across organizations and boundaries. We hope that users will use this to tool to inform their work and contribute their own datasets, studies, and protocols to the project. As information is collected in one place, it becomes more possible to share data, aggregate datasets and standardize data collection practices across the region. To promote this tool, we plan to host interactive webinars and publicize the tool widely to encourage use and feedback.

As mentioned above, we plan to conduct a more thorough review of the potential gaps identified through this work. This review will be made available in a separate report and will provide more insight and recommendations on areas in which land managers and researchers can focus their efforts to close information and monitoring gaps in the region. With detailed information about which indicators are lacking information and where, we can more efficiently target uncovered areas of concern and grow the monitoring network to understand trends. Through this gap analysis we hope to provide insight into areas of future study so that others may use the data compiled in the tool to carry out monitoring efforts or analyze trend information to being to understand the impact of climate change on indicators and ecosystem thresholds.

We hope that this webtool will become a living portal of ongoing monitoring that grows as users implement protocols in their area. With input from our cooperators and users, we hope to provide useful information at a regional scale. Although beyond our scope at this time, future efforts of this project could include providing recommendations on which protocols to use for each indicators and aggregating monitoring data to make a cohesive, regional dataset for each indicator. Monitoring is a necessary process for establishing baselines in ecosystem processes and understanding how and where dynamics are shifting. In order to be resilient in the face of climate change, we need to be able to predict changes to forest health and implement effective and adaptive management strategies at a regional scale.

Appendix 1 – Description of indicator hierarchical categories

Table A1-1. Descriptions of the 'Ecological Categories' as defined for this project.

Ecological Category	Description
Aquatic Systems	Aquatic systems are an important part of watershed dynamics and connect large areas of land to one another. Freshwater systems are an important part of aquatic systems and include lakes, rivers, ponds, vernal pools, and wetlands. Freshwater species such as fish and macroinvertebrates can be great indicators of aquatic system health and responses to change. Vernal pools, which are sensitive to degradation, are also important systems to monitor for signs of climate change.
Forest Systems	Forest systems are complex, terrestrial systems that include the ecosystem processes and functions of flora and fauna. Forested system dynamics depend on the interrelated function of all organisms and abiotic factors in a landscape. These dynamics include relationships between pest and pathogens, pollinators and host species, understory plants and invasive species. By quantifying some of the most robust metrics of forest system dynamics, the impacts of climate change can be measured.
Trees	Trees are a foundational component of forested ecosystems and play an important role in determining how forests respond to climate change. Within the forested system, tree stand health and function is one of the most important metrics of ecological resilience. As climate patterns (i.e., precipitation, temperature, storm damage) change, trees will experience novel conditions. This can result in changes to mortality, growing season, ranges, and overall biodiversity. These parameters can be monitored to identify the impacts of climate change-driven shifts.
Wildlife	Wildlife are often highly adapted to their native habitats and are thus good indicators of ecosystem health and the impacts of climate change. Due to their varying natural history and different scales of home ranges, mammal, birds, and amphibians are important indicators of overall forest health. The population dynamics of vulnerable species can provide clues to the long-term health of various forested systems.

Table A1-2. Descriptions of the 'Ecological Subcategories' as defined for this project.

Ecological Subcategory	Description
Bird Biodiversity	Bird biodiversity is impacted by changes in climate because of the complex lifecycle of many avian species. The Bird Biodiversity indicator encompasses changes to avian wintering range via 'center of abundance' studies on the ecosystem scale, as well as changes in abundance and distribution of vulnerable species such as Bicknell's Thrush and Black-throated Blue Warbler. Changes to arrival time of migratory species could also be considered.
Mammal Biodiversity	The Mammal Biodiversity indicator focuses on changes in abundance of vulnerable mammalian species that are susceptible to subtle environmental changes. These species include moose, northern flying squirrel, little brown bat and snowshoe hare.
Tree Mortality	The Tree Mortality indicator encompasses changes in overall stand biomass, ratio of dead to live trees, canopy cover and decrease of abundance of vulnerable species. Changes in climate are predicted to impact tree mortality adversely in several ways, including death from water stress, increased severity of disturbance regimes and pest defoliation.

Range Shifts	This range shift indicator focuses on changes to the upper limits of tree line in mountainous regions and changes in spatial distribution of vulnerable tree species by elevation—particularly shifts in broadleaf/conifer forest boundaries.
Regeneration	Regeneration of tree species through the establishment of seedlings is a key determinant of the future forest. The regeneration indicator focuses on the regeneration of seedlings by forest type and tree species with emphasis on softwood regeneration and hardwood regeneration.
Tree Biodiversity	This tree biodiversity indicator addresses changes to landscape-level biomass for northern species such as red spruce, paper birch, black spruce, and tamarack, as well as spruce-fir forest system and changes in community composition and abundance.
Storm Damage	Storm damage focuses on indicators of physical damage to individual trees such as tree crown damage, snags, dieback across stands from extreme weather events.
Extent of Sensitive Communities	The extent of sensitive communities can shift with climate change, and this indicator focuses on shifts in spatial distribution of vulnerable flora/fauna based on community composition monitoring.
Understory Plants	There are many ways to measure changes in understory plant communities. This indicator focuses on community composition/ species assemblage shifts and increased abundance of invasive plant species such as bush honeysuckles, privet, and kudzu.
Pest and Pathogens	There are numerous pests and pathogens that impact northeastern forests. This indicator focuses on shifts in range and range expansion of climate sensitive pest and pathogen species such as hemlock woody adelgid and southern pine beetle.
Asynchronicity: Pollinators	This asynchronicity indicator focuses on changes to pollinator phenology/physiology as observed through early emergence, changes in peak activity, and changes in diapause. Direct comparisons with plant phenological stages are also relevant.
Growing Season	Growing seasons determine how much time is available to plants to capture resources and grow. This indicator largely refers to plant physiological and phenological processes, and is based on changes in first bloom, first leaf and fall senescence.
Vernal Pool Biodiversity: Amphibians	Vernal pools are complex and sensitive systems. This indicator focuses on population-level changes and changes to abundance, mortality, and reproduction of vernal pool-dependent amphibians such as the wood frog.
Stream Biodiversity	Stream biodiversity can be examined in many ways. This indicator focuses on changes in abundance of macroinvertebrate indicators and sensitive fish species such as brook trout. On the community level, shifts in composition of cold/cool water species to warm water species.

Table A1-3. Descriptions of the 'Indicators' as defined for this project.

Indicator	**Description**
Moose Population	Moose (*Alces alces americanus*) populations in the Northeast are considered important indicators of long-term forest and ecosystem health. Population metrics can be used to predict future trends in moose populations.
Northern Flying Squirrel Population	The northern flying squirrel (*Glaucomys sabrinus*) populations in the Northeast are considered important indicators of long-term forest and ecosystem health. Population metrics can be used to predict future trends in northern flying squirrel populations, which are one of only three species of flying squirrel in North America.
Little Brown Bat Population	Little brown bat (*Myotis lucifugus*) populations in the Northeast are considered important indicators of long-term forest and ecosystem health because of their sensitivity to climate impacts. Currently, the majority of brown bat research addresses the white nose syndrome

	epidemic, but future studies on little brown bat as climate indicators are likely. Population metrics can be used to predict future trends in little brown bat populations.
Snowshoe Hare Population	Snowshoe hare (*Lepus americanus*) populations in the Northeast are considered important indicators of long-term forest and ecosystem health. Population metrics can be used to predict future trends in snowshoe hare populations.
Bird Wintering Range	Bird species inhabit wintering ranges that fulfill their specific habitat requirements; these include the availability of important habitat types and food sources as well as an ideal range of winter temperatures. As the climate changes, some bird species may adapt to warmer winter temperatures by shifting the spatial extent of their wintering ranges. Continuing to monitor the distribution of bird wintering ranges will provide valuable insight into the impacts of climate change on bird species, and the many ecosystems of which they are a part.
Bicknell's Thrush	Bicknell's thrush (*Catharus bicknelli*) is a medium-sized, migratory thrush that depends on high elevation, spruce-fir forests to breed. Long-term surveys of Bicknell's thrush suggest that populations of this species are sharply declining throughout its range. Among factors that may be contributing to this decline are airborne pollutants that damage high-elevation forest ecosystems and warming temperatures as a result of climate change. Monitoring populations of Bicknell's thrush can provide valuable insight into the ways in which climate change and other forms of ecological degradation are impacting not only this species but also the high-elevation forests upon which they depend.
Black-Throated Blue Warbler	Black-throated blue warbler is considered a species of concern because of its dependence on large, intact patches of forest during breeding season. Therefore, changes in the population dynamics of this species can be a good indicator of long-term ecosystem health and the impacts of climate changes.
Changes in Arrival Date	The timing of the arrival and departure of migratory birds is largely impacted by temperatures, therefore, changes in climate can lead to shifts in migratory bird patterns and lead to novel impacts of asynchronicity.
Stand Health	The health of trees in forest stands are impacted by numerous abiotic and biotic factors. A measure of mortality and stand health by forest type (i.e., specifically in sensitive habitat) can be a good indicator of the impacts of climate change.
Elevation	High elevation forest types are often constrained by the effects of warmer temperatures on community composition. As regional temperatures increase due to climate change, the sensitive tree species and forest types are anticipated to shift in elevation.
Seedling Regeneration	Robust seedling regeneration is essential for the long-term health of forest ecosystems. The success of seedling establishment is influenced by a number of biotic and abiotic factors including fire, browse, changes in precipitation and the presence of invasive species. Monitoring seedling regeneration is one way to gain critical insight into the ways that climate change may be impacting the resilience of forest ecosystems.
Physical Damage to Trees	As storms increase in frequency and severity across the region, physical damage to trees will likely be impacted and is therefore a good indicator of the impacts of climate change
Understory Community Composition	The composition of understory plant communities is directly impacted by the abiotic and biotic conditions of an ecosystem, including precipitation, temperature, the prevalence of invasive species and browse pressure. Climate change, forest fragmentation and other ecological stressors threaten to alter these abiotic and biotic conditions, which has the potential to undermine the resilience of these understory plant communities and the ecosystems that they are a part of. As such, monitoring the abundance, richness and distribution of particularly vulnerable understory plant species can provide valuable insight into the health of forest ecosystems.

Invasive Plant Abundance	The presence and severity of invasive plant species in a forest's understory are often impacted by factors related to climate change. Monitoring the abundance of invasive plants in understory communities can be a good way to assess the health of forest ecosystems.
Hemlock Woolly Adelgid	Hemlock woolly adelgid (*Adelges tsugae*) is an aphid-like insect that infests spruce and hemlock trees. Native to East Asia, this pest has no natural predators in the United States, allowing populations to quickly grow to levels that can cause widespread tree mortality. As climate change causes average winter temperatures to increase, the range of this pest is expected to spread northward. The presence and severity of hemlock woolly adelgid infestations are valuable indicators of the impacts of climate change on the health of forest ecosystems.
Southern Pine Beetle	The Southern Pine Beetle (*Dendroctonus frontalis*) is a species of bark beetle that infests pine trees and is native to the southeastern United States. The range of this pest has been gradually expanding northwards up the east coast, most likely due to increasing winter temperatures as a result of climate change. Monitoring pine stands for the presence of southern pine beetle and tracking the severity of existing infestations can provide valuable insight into the impacts of climate change on the health of forest ecosystems.
Phenology/Physiology of Pollinators	Insect pollinators have complex life cycle stages that are synchronized with seasonal changes in native habitats. Asynchronicity between insect life stages and plant phenology can lead to novel ecosystem dynamics, therefore, changes in phenology and physiology of pollinators can be a good indicator of the impacts of climate change
Temporal Shifts: Trees	The timing of phenological events in the life cycle of a tree, such as leaf emergence, flowering time and leaf senescence, is often influenced by temperature and other abiotic factors. As such, these phenological events are expected to be highly sensitive to climate change. Monitoring the phenology of trees can provide insight into the ways that climate change is impacting trees and the ecosystems of which they are a part.
Distribution of Vulnerable Flora	Vulnerable plants and other flora can be impacted more quickly and with more severity than other organisms in a community. Monitoring the spatial distribution of vulnerable flora can help to identify where changes due to climate impacts are occurring.
Distribution of Vulnerable Fauna	Vulnerable plant populations often respond to climate change, ecological degradation and other ecological stressors more rapidly and more severely than other organisms in a community. As such, monitoring the distribution and health of vulnerable plant populations can provide valuable insight into the regions, natural communities and species that are being the most directly impacted by climate change.
Amphibians: Wood Frog	Wood frog (*Lithobates sylvaticus*) populations in the Northeast are considered important indicators of long-term forest and ecosystem health. These frogs are vulnerable because they rely on vernal pools for several stages of their life cycle. Although this species has limited species-specific studies, it has been identified by experts as an increasingly important indicator. Population metrics can be used to predict future trends in wood frog populations.
Macroinvertebrates	Macroinvertebrate species richness and abundance can provide valuable insight into the health of stream ecosystems. With several groups of macroinvertebrates that are highly sensitive to ecological stressors, such as pollution and high-water temperature, monitoring macroinvertebrate populations is a common way to assess stream health.
Community Composition: Streams	Community composition of aquatic biota is a commonly used metric of stream health biodiversity. There are several sensitive freshwater species that are considered important indicators due to their susceptibility to mortality in response to disturbances in waterways. These species include insects, mollusks and worms. The abundance, richness, and biomass of these sensitive species can be a good indicators of the impacts of climate change in streams.
Brook Trout Populations	Brook trout *(Salvelinus fontinali*) are considered important indicators of long-term forest and aquatic ecosystem health in the Northeast. This species is migratory and relies on cold-water

	conditions to breed, making populations particularly vulnerable to changes in climate. Brook trout populations are also highly sensitive to environmental pollutants, changes in pH and low oxygen content, as such this species typically only occurs in areas with high water quality.

Appendix 2- Definitions of Metadata Fields by Category

For each category of metadata, we assessed several fields. The definition and data type are given below for each category.

Table A2-1. Descriptions of data and data type related to the 'Basic Information' of included studies.

STUDIES: BASIC INFO		
Field Title	**Field Description**	**Data Type**
Project Title	Title of the project.	Text
Study Link	Link to the study document.	URL
Description	Description of the study.	Text
Has Protocol(s)	Does the study have associated protocols.	Yes, No
Has Dataset(s)	Does the study have associated datasets.	Yes, No
Data Host Site	The link to the website where the study is hosted.	URL
Study Site Locations	Any specific location information provided about the study site(s).	Text
Categories	List of any subcategories covered by the study.	Text
Category Count	Number of subcategories associated with a given study.	Numeric
Organization Name	The name of the primary organizations associated with the study.	Text
Org URL	Link to the organizational website.	URL
Contact Name	Name of the person or organization to contact about a given study.	Text
Contact Title	The title of the contact person (if available).	Text
Contact Email	The email address of the contact person/organization (if available).	E-mail address
Contact Phone	The phone number of the contact person/organization (if available).	
State	The state(s) a given study covers.	Text
Counties	The counties covered by a given study.	Text
Extent	Whether or not the study gives more detailed extent information.	0,1
Years	The duration of a study in years. The year it began to the year that it ended.	Numeric

Ongoing	A record of if the study is ongoing	Yes, No

Table A2-2. Descriptions of data and data type related to the indicator categories of included studies.

STUDIES: INDICATOR CATEGORIES		
Field Title	**Field Description**	**Data Type**
Ecological Category	Broadest tier of indicator category; Wildlife, Forest Systems, Trees, or Aquatic Systems.	Text
Ecological Subcategory	Subcategory name within broadest ecological category.	Text
Indicator Category	Most specific category that identifies which indicator(s) is covered in a given study.	Text
CI_Metric	The interpretive metrics used in a given study.	Text

Table A2-3. Descriptions of data and data type related to the associated protocols of included studies.

PROTOCOLS FROM STUDIES		
Field Title	**Field Description**	**Data Type**
Protocol name	Name of the protocol document.	Text
Protocol File Link	Link to the protocol document.	URL
Years Used	Recorded years protocol was used in a given study.	Numeric
Technique*	Types of techniques used in each protocol.	Text
Primary Protocol Org	The organizations that published the protocol.	Text
Protocol Creator	The name of the organization or people who created the protocol.	Text
Publication Date	The date the protocol was published.	Date
Indicator Category	The indicator(s) that the protocol is related to.	Text

*Excluded from the final tool

Table A2-4. Descriptions of data and data type related to the associated datasets of included studies.

STUDY DATASETS		
Field Title	**Field Description**	**Data Type**
Program	Name of the program that hosts the dataset.	Text

URL	Link to the dataset document.	URL
Dataset Name	The name of the dataset.	Text
Dataset Years	The years the dataset covers.	Numeric

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