MONITORING AND COMMUNICATING CHANGES IN DISTURBANCE REGIMES

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Monitoring and Communicating Changes in Disturbance Regimes (Version 1.0)

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Executive Summary

Shifts in disturbance patterns across the Northeast are of increasing concern as the climate continues to change. In particular, changes in patterns of frequency, severity and extent of disturbance event may have detrimental cascading impacts on forest ecosystems and human communities. To explore how changing disturbance regimes might impact future forest health and management it is necessary to understand the historical trends and impacts of disturbance in the region. Although individual types of disturbance have already been analyzed, there is a need for a consolidated overview of the current state of disturbance in northeastern forests.

To address this need, the Forest Ecosystem Monitoring Cooperative (FEMC) developed the *FEMC: Tracking Shifts in Disturbance Regimes* web portal for users to explore changes over time of key disturbance drivers, identify important disturbance responses, and discover where monitoring is happening for both drivers and responses. In collaboration with our advisory committee, we identified key disturbance drivers—flood, high winds, fire, drought, pests—and responses—macroinvertebrates, cold-water fisheries, invasive plants—that are of particular concern in the region. For each of the drivers we identified a suitable regional dataset and analyzed changes over time in frequency, severity, and extent. We also created a structured framework to catalogue programs across the region that are monitoring for these disturbance drivers and responses.

Version 1.0 of the *FEMC: Tracking Shifts in Disturbance Regimes* (https://uvm.edu/femc/disturbance) web portal, first released in October 2021, contains 272 data programs, 11 drivers and three responses. Through the web portal users can browse programs by state, driver type or response type, and explore where monitoring is happening across the region. Driver-specific analyses allow users to quickly see the trends in severity, frequency and extent of selected disturbances and compare the impacts in selected states to regional data. We hope that this collection of programs and the analysis of trends provide researchers and land managers with an easy way to understand the current state of disturbance in northeastern forests that enables them to analyze and plan for future impacts.

Introduction

Globally, unpredictable shifts in climate patterns are increasing, causing changes to forest disturbance regimes (IPCC 2021). Forests are resilient to regular low intensity or infrequent high intensity disturbance events. However, as the climate continues to change there is concern that the severity, frequency, and extent of disturbance may be changing, with cascading impacts on northeastern forest ecosystems and human communities. For the purposes of this project, we define disturbance as any biotic or abiotic event that cause changes to or disrupts the function of forest ecosystems and the services they provide. Disturbance regimes are the patterns of a given disturbance event(s) and its impacts. Understanding historical disturbance patterns is vital to understanding changing disturbance regimes, identifying monitoring needs and exploring future disturbance impacts.

In 2020 the FEMC Steering Committee and State Partnership Committees identified the need for a regional overview of the historical trends in key disturbances that impact New England and New York. To address this need, FEMC synthesized data region-wide and analyzed historical trends in key disturbance categories throughout northeastern forests. The web portal also provides resources to better summarize the current state of knowledge and monitor how disturbance regimes might be shifting in the Northeast.

Objectives

The objective of this project is to synthesize data region-wide to better understand how disturbance regimes are changing in northeastern forests, and what monitoring gaps exist to track these changes. This project identifies key drivers of and responses to disturbance to better explore and monitor the relationships between climate and disturbance patterns. The ultimate goal of this project is to better understand the current state of knowledge on select disturbance regimes and the potential implications for sustainable management of forests across the region.

Outcomes

The outcomes of this project are:

- **Develop data visualization and information access** tools to capture temporal trends and spatial extent, allowing users to explore the changing extent of a subset of disturbance categories.
- **Aggregate and archive historical data** on disturbance extent and timing from current and historical research, surveys and reports.
- **Develop easy to use datasets summarizing** historical trends and, where possible, spatial extents of key disturbance agents and responses to disturbance.

Key Products

The key products of this effort are listed below:

- Interactive information portal showcasing existing monitoring efforts and analysis of long-term trends in historical severity, extent, and frequency for key disturbance drivers in northeastern forests.
- Compilation of information about monitoring efforts and studies related to key ecosystem responses to disturbance.
- New archived historical data on disturbance extent and timing from surveys and reports.
- This report, which summarizes development of the web portal, the long-term trends in the frequency, severity and extent in the regional data, and identifies future areas of work.

Project Development

COOPERATIVE ENGAGEMENT

Advisory Committee

An advisory committee was selected from a group of regional forest health specialists with a range of expertise to advise the FEMC project team throughout the development of the web portal (Appendix 1). They provided direction on project objectives, supplemented the resource identification process, supported the justification of included data and gave insight on the interpretation of disturbance trend analyses.

The advisory committee convened three times over the course of the project. The first advisory committee meeting happened at the onset of the project to determine the broader scope of the project and the preliminary goals for development. In this meeting, the advisory committee formalized the selected disturbance drivers and responses and identified the target audience of the project (primarily land managers, landowners, and researchers). They also identified the constraints of the final project outcomes. The second meeting provided an opportunity for the advisory committee to review and provide feedback on the selected datasets and analyses for each of the disturbance drivers. The third advisory committee meeting was held to provide a structured review of the web portal and data criteria at milestone points in the project when the beta version of the web portal was largely completed. Advisory committee members also provided input on an individual basis at various points in the project based on their expertise.

FORMS OF FOREST DISTURBANCE

There are many factors that cause disturbance events and influence disturbance patterns in northeastern forests. We refined an initial list of 21 suggested disturbances and disturbance sensitive ecosystems through conversation with our advisory committee and based on the availability of regional long-term datasets to use for analysis. The resulting list of 13 drivers we then categorized each process as either a driver of disturbance or a system that demonstrates an important response to disturbance events.

Drivers

Disturbance drivers are the phenomena that cause changes in forest structure or condition. These changes in structure or condition can lead to wider shifts in forest health or forest ecosystems. The disturbance drivers included in this project are:

- extreme weather, including flooding and high winds
- pests
- fire
- drought

We analyzed change over time in the severity, frequency and extent of these disturbance drivers. These metrics answer the question 'is a given disturbance driver happening more often, is it causing more impact to forest structure or condition over time, and is it impacting more of the region?'.

Wind

Small scale disturbance caused by high winds are a common driver of change and successional dynamics in northeastern forests. Forest gaps created by canopy openings allow for regeneration of flora and habitat diversity for fauna. However, changes in the frequency, extent and severity of high wind events can alter sensitive habitats and species composition, and lead to invasion by non-native plants. Climate projections indicate that high wind events may become more common across the region (USGCRP 2017, Knutson 2021).

Flood

Flooding is a natural component of riparian systems, however, depending on the intensity of the discharge, flooding can cause damage to surrounding forest ecosystems. Flood risk is impacted by several factors including climate change, changes in land cover (such as reduced vegetation) and anthropogenic intervention. Persistent flooding and soil saturation can lead to tree mortality. Similarly, deterioration of river and stream banks from erosion can cause physical damage to riparian forests. As climate changes in the region, changes to the severity, extent and frequency of flood events may have negative impacts on a larger proportion of the northeastern forests (IPCC 2021).

Drought

Drought is a driver of forest disturbance that impacts various ecosystem processes across populations and increases forest susceptibility to other disturbance agents. Quantified as the cumulative lack of precipitation over time in a given area, drought can be used to quantify the direct effects of moisture stress on forests as well as related forest disturbances. As temperatures are anticipated to increase and precipitation is anticipated to become less consistent across the region, the impacts of drought may become more severe in the Northeast (IPCC 2021).

Fire

Fire is a natural component of terrestrial ecosystems in the Northeast, with many forest ecosystems adapted to fire. However, intense or sustained fires can have large impacts on forest regeneration and community composition. Although the Northeast is a relatively wet region of the country with few large fires, changing climate may bring hotter and drier weather that could result in increased fire frequency, extent and severity (IPCC 2021).

Pests

Native Pests

All ecosystems have natural pest dynamics that evolve alongside host species over time. Under ideal conditions, native pests have controlled population cycles and maintain an equilibrium in their community. However, as abiotic conditions shift due to climate change, native invasive pests may lead to more severe damage. Changes in temperature and precipitation, among other factors, can alter the phenological timing of native pests and increase the intensity of impacts to trees and forest systems. Monitoring trends in the extent and severity of native pest damage patterns can help anticipate impacts to forest systems under changing climate conditions. Native pests of concern included in this project are eastern spruce budworm (*Choristoneura fumiferana)* and forest tent caterpillar (*Malacosoma disstria)*.

Established Invasives

Established invasive pest species are exotic insects that have naturalized in the region after many years. These pests cause damage to several species of trees in northeastern forests. In comparison to novel invasive pests, established invasives often have a predictable life cycle that is easy to anticipate and overlaps with the life cycles of native predators. Therefore, established invasives cause disturbance in forests, but natural ecosystem dynamics can help to regulate uncontrolled spread. These species include the *Lymantria dispar*[1] and the browntail moth (*Euproctis chrysorrhoea)*.

Advancing invasives

Advancing invasive pests are novel species with the potential to disrupt forest ecosystems. Extreme cold typically limits the spread of many invasives into our region, but as temperatures increase across the region so does the threat of invasive species. Novel pest introductions often lead to severe defoliation and tree mortality due to lack of natural biological controls and unanticipated, irregular lifecycle dynamics. Tracking the advance of novel invasive species can help quantify impact and inform management to mitigate those impacts. High priority pest species included here are southern pine beetle (*Dendroctonus frontalis*), hemlock woolly adelgid (*Adelges tsugae*), and emerald ash borer (*Agrilus planipennis*). Others, such as beech leaf disease and oak wilt, are increasingly of concern, but do not yet have enough occurrence in the region to have sufficient data to analyze. Due to the fairly recent introduction of these agents into the region, we did not include frequency in the analysis.

Responses

Disturbance responses are key systems within forests that change following forest disturbance. These systems can be used as indicators of the occurrence, severity, and implications of disturbance. Studying response dynamics can help to understand the impacts of disturbance regimes and how disturbance regimes might be changing. The disturbance responses highlighted in this project are macroinvertebrates, cold water fisheries, and invasive plants. Analyzing the impact of drivers on these responses or analyzing the changes in these responses in relation to the disturbance drivers is beyond the scope of this project. The studies and programs identified as responses can be used to highlight additional impacts of disturbance regimes on northeastern forest ecosystems and to provide resources on key systems that are sensitive to changes in disturbance regimes.

Macroinvertebrates

The specific composition of macroinvertebrate communities is an established indicator of stream and freshwater health. Abundance and diversity of sensitive macroinvertebrate species shift quickly in response to disturbances in their ecosystem. Specifically, abiotic damage due to gouged stream beds from flood events cause acute

[1] The Entomological Society of America discontinued gypsy moth as a common name of *Lymantria dispar* in their effort to remove common names that "perpetuate negative ethnic or racial stereotypes", see https://www.entsoc.org/entomological-society-america-discontinues-use-gypsy-moth-ant-names

responses in these communities. Regular monitoring of macroinvertebrate indicators over time may provide insight into the impact of disturbance regime fluctuations on aquatic systems (Nevins et al 2018).

Invasive plants

Disturbance events can create ideal conditions for invasive plant species to establish and spread in forested ecosystems. Forest patches caused by fallen trees or eroded stream banks promote the growth of early successional herbaceous species and non-native invasive plants that outcompete native genera. Although disturbance events can be part of a healthy ecosystem, increased severity, frequency, and extent of these events can increase opportunities for invasive plants, leading to impacts on the regeneration of native plant communities and potentially decreasing forest resiliency. Regularly conducting vegetation surveys can capture possible indirect effects of shifting disturbance on plant species composition (Burnham and Lee 2010, Driscoll et al 2016).

Coldwater fisheries

Coldwater fish species in the Northeast depend on specific habitat requirements to reproduce and survive. In particular, coldwater fisheries are impacted by warming of ambient water temperatures. As climatic conditions shift regionally, coldwater fisheries are expected to reflect the indirect impacts of this change. Regular monitoring of this community may provide insight into the effects of irregular or increased disturbance events (Williams et al 2015).

Data Sources and Standardization Methods

RESOURCE IDENTIFICATION

Initial resource identification started with a structured literature review of the current body of knowledge of each disturbance category and subtype as defined by the cooperative (Table 1). The literature review was focused specifically on disturbance events that had direct record of damage to forest systems. For example, included literature attempted to detail the exact wind speeds in each event and any associated tree mortality as opposed to literature that solely detailed high wind event occurrence. These criteria were meant to direct our analyses towards connecting disturbance events with forest-based outcomes and determining thresholds of impact.

Table 1: Hierarchical categorization of disturbance drivers and responses.

Disturbance Category	Disturbance Category	Disturbance Type	Included Species
Driver	Drought	Drought	N/A
	Extreme Weather	Flood	N/A
		High Winds	N/A
	Pest	Established Invasives	*Lymantria dispar*
			Browntail Moth
		Advancing Invasives	Southern Pine Beetle
			Hemlock Wooly Adelgid
			Emerald Ash Borer
		Native Pests	Eastern Spruce Budworm
			Forest Tent Caterpillar
	Fire	Fire	N/A
Response	Stream Macroinvertebrates	Stream Macroinvertebrates	N/A
	Coldwater Fisheries	Coldwater Fisheries	N/A
	Invasive Plants	Invasive Plants	N/A

Following this review, we conducted an inventory of relevant data programs and data products that were available across the region. These documents were located through online search engine queries, recommendations from cooperators and input from the advisory committee. Large, comprehensive datasets, such as the NOAA daily summaries dataset of high wind events, were used to conduct analyses. The map and monitoring portion of the web portal makes related data programs and data products that are not comprehensive enough to conduct a historical trend analysis, but contain useful data easier to discover and access alongside the main analysis.

DATABASE DEVELOPMENT

Programs and datasets (referred to here as 'data products') that fit the criteria for inclusion were compiled and processed. Necessary metadata from each item were systematically extracted into a database (Table 2). This database captured important data program information, metadata, and dataset information. These data did not include the larger datasets used in the analysis component of the project. Additional programs tracked in the database were used to supplement analytical findings and provide detail on where relevant monitoring efforts are occurring. This information appears in the 'Monitoring & Resources' component of the resulting web portal.

Table 2: Titles and descriptions of key objects and their contents within the database.

DISTURBANCE CATEGORIES

Field Name	Field Description	Field Type
Disturbance Category	The disturbance category associated with a given program.	Text
Disturbance Type	The disturbance type associated with a given data program.	Text
Pest Type	For Pest type, the related 'Advancing Invasives', 'Native Pests', and/or 'Established Invasives' category associated with a given program.	Text

PROGRAMS

Field Name	Field Description	Field Type
Program Title	The title of the program.	Text
Program URL	The link to the program web portal.	Text
Program Description	The description of program details and methods.	Text
Years Program	The years the program started through the end date.	Numeric
Area State(s)	The states the program covers.	Text
Area Notes	Any notes that further detail the specific location of a given program.	Text
Organization Name	The name of the organization responsible for creating or publishing the program.	Text
Organization URL	The link to the organization web portal.	Text
Contact Name	The name of the primary contact person affiliated with the program.	Text
Contact E-mail	The e-mail address of the primary contact person.	Text

DATA PRODUCTS

Field Name	Field Description	Field Type
Data Product Name	The name of the data product.	Text
Data Description	The detailed description of what the data product contains.	Text
Years	The years the data product covers.	Numeric
Data Product URL	The link to the data product.	Text

DRIVER DATASETS FOR ANALYSIS

We selected a single regional long-term dataset for each disturbance driver to analyze changes in severity, frequency and extent (Table 3).

Table 3: Analyses conducted for each driver to asses changes over time in severity, frequency and extent.

Driver	Analysis Category	Analysis
Wind	Frequency	Total number of high wind events
		Average number of high wind events
	Extent	Number of stations recording at least one high wind event
		Number of stations recording at least five high wind events
	Severity	Average maximum windspeed
		Number of high wind events in the 95th percentile
Fire	Frequency	Number of fires
	Extent	Total acres burned
		Average acres burned
	Severity	Maximum acres burned in a single fire
		Number of fires over 5 acres (in the 97.5 percentile)
Flood	Frequency	Number of floods in each NOAA flood category
	Extent	Percent of stations recording flooding in each NOAA flood category
	Severity	Average gauge height
Drought	Frequency	Number of weeks in each USDM drought category present in the Northeast
	Extent	Acres affected by each USDM drought category present in the Northeast
	Severity	Number of weeks in severe or extreme drought
Pests	Frequency	Number of years since previous outbreak
		Annual acres damaged
		Acres damaged over the duration of the outbreak
	Extent	Total acres damaged
	Severity	Acres of damage categorized as mortality
		Percent of total damage categorized as mortality

High winds

We used the fastest 5-second wind speed dataset from the NOAA Global Daily Summaries dataset (NOAA 2021a) to analyze changes in wind disturbance. We retrieved all 5-second wind speed data from stations within the FEMC region (CT, MA, ME, NH, NY, RI, VT) We then assessed these data for completeness by identifying which stations had consecutive annual daily records. We started the analysis 2001 since it was the earliest date identified with consistent reporting of at least 350 daily records annually across the majority of stations. The seven stations without complete records between 2001 and 2020 were excluded. Mount Washington (NH) was excluded as an outlier because its average fastest 5 second wind speed exceeded 60 mph, which is almost three times the average fastest 5 second winds speed for all other stations and its maximum annual fastest 5 second wind speed always exceeded 120mph.

We determined a 'high wind threshold' by comparing the effect descriptions of four different scales for wind speed: the Beaufort Scale (Storm Prediction Center 2021), Thunderstorm damage in VT and NY (National Weather Service 2021a), the Enhanced Fujita Scale (National Weather Service 2021b) and the Saffir-Simpson scale (National Hurricane Center 2021) (Appendix 2). We compared the damage category thresholds of each of these scales where some tree damage is expected to wind events that appeared in the annual aerial detection surveys (Duncan et al 2018). Based on the observed events of high wind causing forest damage and the wind speeds where tree damage was expected on the four scales, we established a 'high wind threshold' of 55 mph. This corresponds to the threshold for small and shallow trees becoming uprooted in both the Beaufort scale and the scale for Thunderstorm damage in VT and NY. We then extracted all wind events that met or exceeded this threshold as the final 'high winds' dataset with 1886 events recorded at 73 stations across the region from 2001 to 2020 (Table 4, Figure 1).

Table 4: Distribution of the number of stations and the number of high wind events in each state.

State	*Number of events*	*Number of stations*
CT	172	8
MA	822	19
ME	86	9
NH	47	7
NY	640	22
RI	55	3
VT	64	5
Total	*1886*	*73*

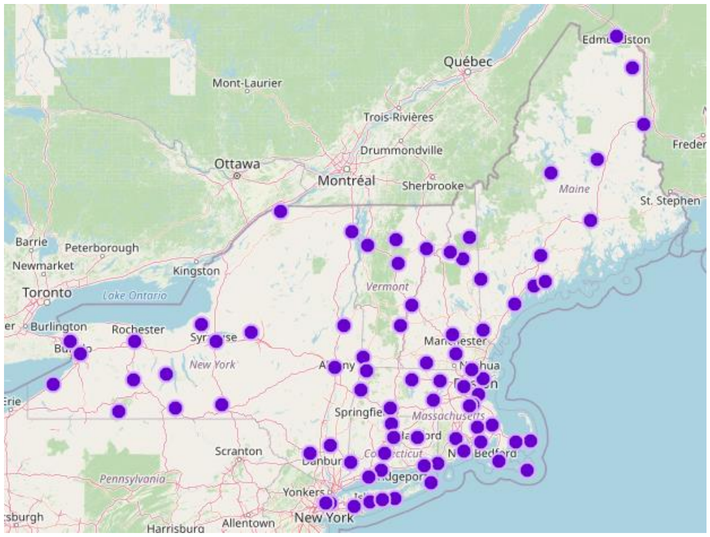

Figure 1: Distribution of weather stations recording high wind events (5-second max >55mph) that recorded data for at least 350 days each year between 2001 and 2020.

Fire

We used the Fire Program Analysis (FPA) fire-occurrence database (Short 2021), a research grade dataset that spans 1992-2018, to analyze trends in fire disturbance. FPA is a collection of fires reported by each state, so the data available varies in reporting method and consistency across states. We excluded any fires without a recorded acreage resulting in a total 125,116 fires with New York reporting significantly more fires over the 26-year period than any other state (Table 5, Figure 2).

Table 5: Number of fires reported by each state between 1992 and 2018.

State	*Number of Fires Reported*
CT	6,006
MA	6,778
ME	14,924
NH	2,935
NY	93,171
RI	631
VT	671
Total	*125,116*

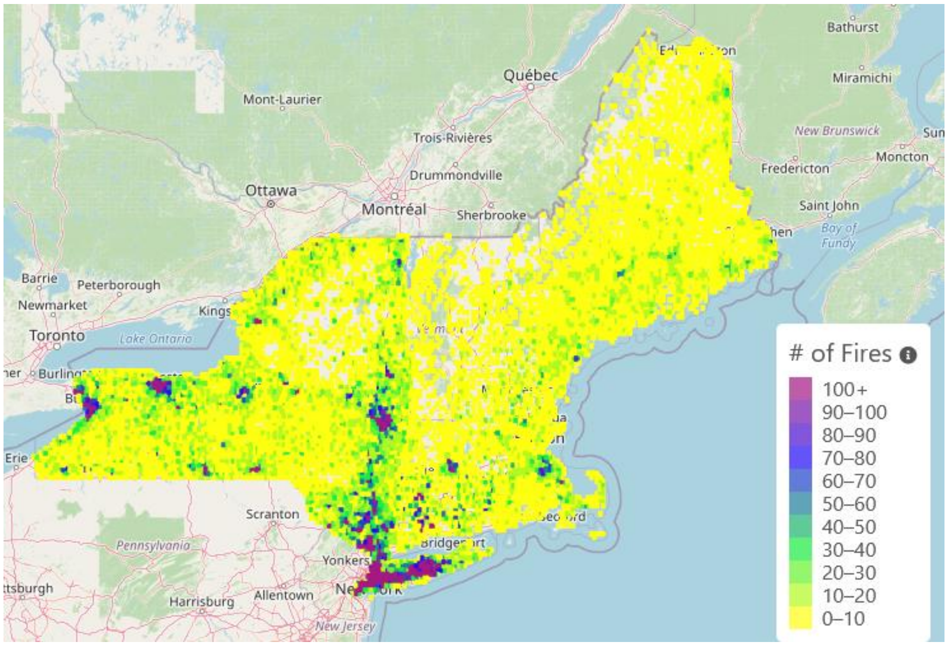

Figure 2: Distribution of fires across the region displayed as the number of fires within a five-kilometer grid.

Flood

We used two different datasets to assess changes in flooding. The USGS historical instantaneous stream gauge data (National Weather Service 2020) from 2008 to 2020 and the NOAA National Weather Service flood gauge data (National Water Information System 2021) which indicates at what level a given gauge is considered in 'flood', 'moderate flood' or 'major flood' stage. The USGS stream gauge data was retrieved from the USGS application programming interface while the NOAA site locations were downloaded as a shapefile. The gauges used in the NOAA dataset are the same as those recording data for the USGS. However, the NOAA dataset does not identify the collocated USGS gauge, preventing us from linking the two without significant manual work. Instead, we linked NOAA stations and USGS gauges by spatial proximity. Stream gauges are not placed within 350ft of each other, so we matched stations that were within 350ft of a stream gauge. We excluded gauges that didn't have records for at least 300 days each year. The resulting dataset included 179 gauges (Table 6, Figure 3).

Table 6 : Number of stations from each state used in the flood analysis.

State	Number of stations
CT	15
MA	31
ME	18
NH	19
NY	73
RI	6
VT	17
Total	179

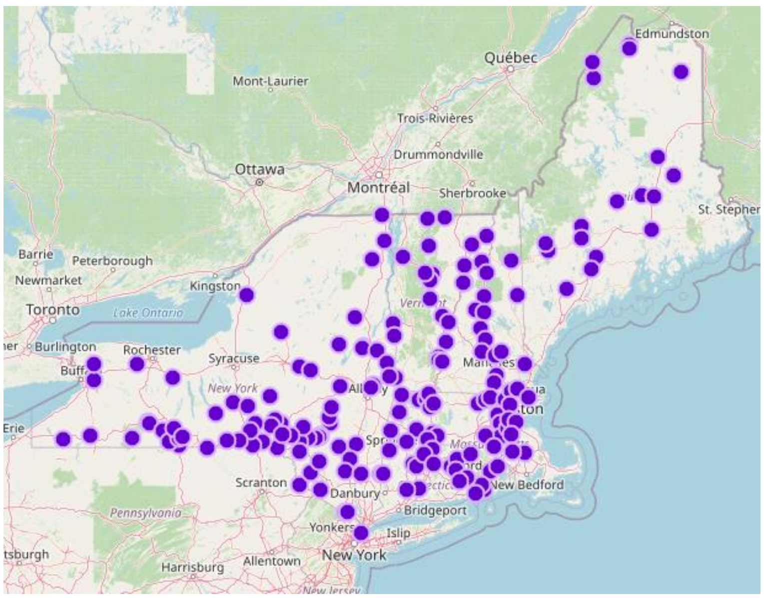

Figure 3: Distribution of stream gauges across the region with at least 300 daily records each year from 2008-2020.

Drought

To assess changes in drought in the Northeast we used data from the [US Drought Monitor] (USDM) (National Drought Mitigation Center, USDA and NOAA 2021). The USDM records weekly drought conditions in five categories across the United States back to 2000 (Figure 4). We retrieved the weekly statistics for all states in the region as well as downloading the spatial data of the weekly extent of drought in each category. We used drought categories D0 - D3, we excluded D4 because no area in the Northeast has been in D4 category drought since 2000.

Category	Description	Possible Impacts	Ranges				
			Palmer Drought Severity Index (PDSI)	CPC Soil Moisture Model (Percentiles)	USGS Weekly Streamflow (Percentiles)	Standardized Precipitation Index (SPI)	Objective Drought Indicator Blends (Percentiles)
D0	Abnormally Dry	Going into drought: • short-term dryness slowing planting, growth of crops or pastures Coming out of drought: • some lingering water deficits • pastures or crops not fully recovered	-1.0 to -1.9	21 to 30	21 to 30	-0.5 to -0.7	21 to 30
D1	Moderate Drought	• Some damage to crops, pastures • Streams, reservoirs, or wells low, some water shortages developing or imminent • Voluntary water-use restrictions requested	-2.0 to -2.9	11 to 20	11 to 20	-0.8 to -1.2	11 to 20
D2	Severe Drought	• Crop or pasture losses likely • Water shortages common • Water restrictions imposed	-3.0 to -3.9	6 to 10	6 to 10	-1.3 to -1.5	6 to 10
D3	Extreme Drought	• Major crop/pasture losses • Widespread water shortages or restrictions	-4.0 to -4.9	3 to 5	3 to 5	-1.6 to -1.9	3 to 5
D4	Exceptional Drought	• Exceptional and widespread crop/pasture losses • Shortages of water in reservoirs, streams, and wells creating water emergencies	-5.0 or less	0 to 2	0 to 2	-2.0 or less	0 to 2

Figure 4: US Drought Monitor drought categories, reproduced from https://droughtmonitor.unl.edu/About/WhatistheUSDM.aspx

Pests

Pest data were extracted from the FEMC Northeastern Forest Health Atlas (NEFHA) (Duncan et al 2018) which is a standardized dataset of aerial detection survey map data from the region. Aerial surveys are conducted annually by each state to record forest disturbance, and NEFHA standardizes these data over time into a single coherent dataset. The NEFHA data is complete back to 1997 when both reports and the original data have been collected and digitized by the USFS. Prior to 1997, data were recorded by states and summarized in reports while states retained the raw map data. Much of this historical data has been digitized by a combination of state efforts and FEMC collaborations with state partners, however, some of the original maps are missing or have not been retrieved for digitization. We utilized the entire dataset because many of the significant outbreaks of key species have been recorded as far back as 1918. In addition to the caution about the completeness prior to 1997, these data should be interpreted with caution, as aerial detections methods have changed over time, with some states mapping general zones of occurrence vs. exact delineations of affected areas, and some flights occurring at certain times of year for operational or management needs that may result in other damages going undetected that year. It is also important to note that the acreage affected by pests is calculated from the digitized polygons using ArcGIS Pro (Esri 2021) software and therefore may differ from the acreage documented in the corresponding reports. We extracted the spatial data for each pest from the larger dataset to calculate extent and severity for all selected pests. In addition, we used historical state forest health reports to determine the years and duration of outbreaks for *L. dispar*, forest tent caterpillar and spruce budworm to correlate with the aerial detection data.

TECHNICAL IMPLEMENTATION

Web portal

The *FEMC: Tracking Shifts in Disturbance Regimes* web portal is and online database-driven web portal hosted within the larger FEMC web portal, which is built in the commonly-used Linux-Apache-MySQL-PHP stack. It was designed and developed based on the project objectives and assumed user needs, targeting landowners, researchers, and land managers who might be analyzing or monitoring related disturbances in their region. The portal is implemented primarily using open-source software. The tables are created using DataTables available under the MIT license. All maps except those for the pests and drought use OpenLayers, a dynamic web mapping API that is provided as a free open-source JavaScript software under a FreeBSD license. The drought time series map is built using Esri ArcGIS Online, a web map server and application building service provided through University of Vermont's Esri license. The pest maps leverage CARTO, a location intelligence platform that supports large spatial datasets. These components were combined in a custom-built web front-end framework using Bootstrap 4 (available under MIT license) to create a portal that provides seamless interaction across devices. Custom scripts were written in Python and R to clean and analyze each of the datasets for the web portal (Table 7)

Table 7: List of scripts used to analyze datasets used to assess change over time for the selected disturbance drivers.

Driver	**Scripts**
High Winds	https://www.uvm.edu/femc/file/info/11729
Fire	https://www.uvm.edu/femc/file/info/11730
Flood	https://www.uvm.edu/femc/file/info/11731
Drought	https://www.uvm.edu/femc/file/info/11732
Pests	https://www.uvm.edu/femc/file/info/11733

Outcomes and Findings

PROJECT OVERVIEW

The outputs of this project, available at https://www.uvm.edu/femc/cooperative/projects/disturbance_regimes, are a) an interactive compilation of information about abroad set of monitoring and datasets related to forest disturbance made accessible online and b) detailed trend analyses of key datasets that can be used to look for shifts in disturbance patterns over time. Compiled resources included in the project are representative of all six New England states and the state of New York. In total, there are 272 unique data programs and 171 data products documented and searchable through the portal. Each disturbance type had similar coverage across states (Figure 5) and many programs were associated with two or more disturbance types. The programs included covered a wide range of years, with one study reviewing historical wind data as far back as 1620. Although there is variation in the data, most of the studies include historical data that dates to at least the year 2000. The resources compiled in this project are publicly accessible through external links and are searchable through use of the web portal.

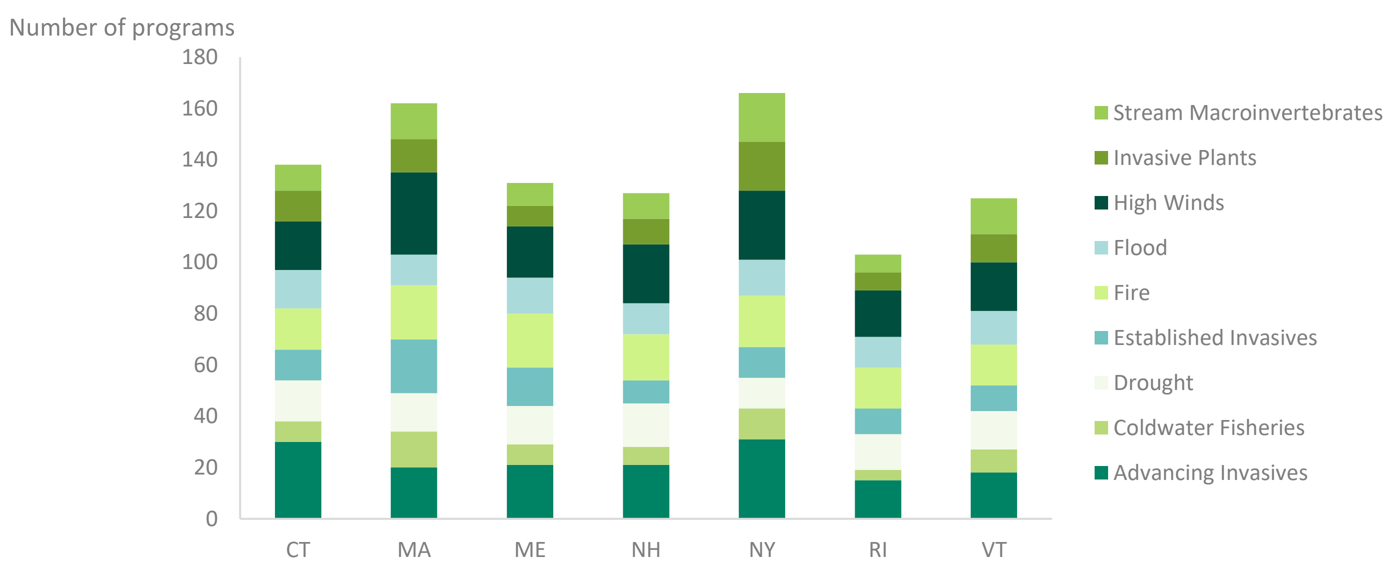

Figure 5: Distribution of programs by state according to disturbance type.

This initial version (Version 1.0) of the web portal is not intended to be a complete catalogue of relevant data programs, but will hopefully grow as data is added and users contribute more data sources. Below, the usage of the web portal and a discussion of the patterns of key disturbance drivers observed through our analyses are described in more detail. While the web portal summarizes the change over time at both the state and regional scale, we only discuss the regional patterns here.

PATTERNS OF DISTURBANCE IN THE NORTHEAST

High Winds

We used two analyses to represent the **frequency of high wind events** (over 55 mph); the average number of events per station per year, and the total number of events annually. While long-term trends across the region indicate that the average number of high wind events is stable, the total number of high wind events reported across the region appears to be increasing, though the trend is not statistically significant (Figure 6).

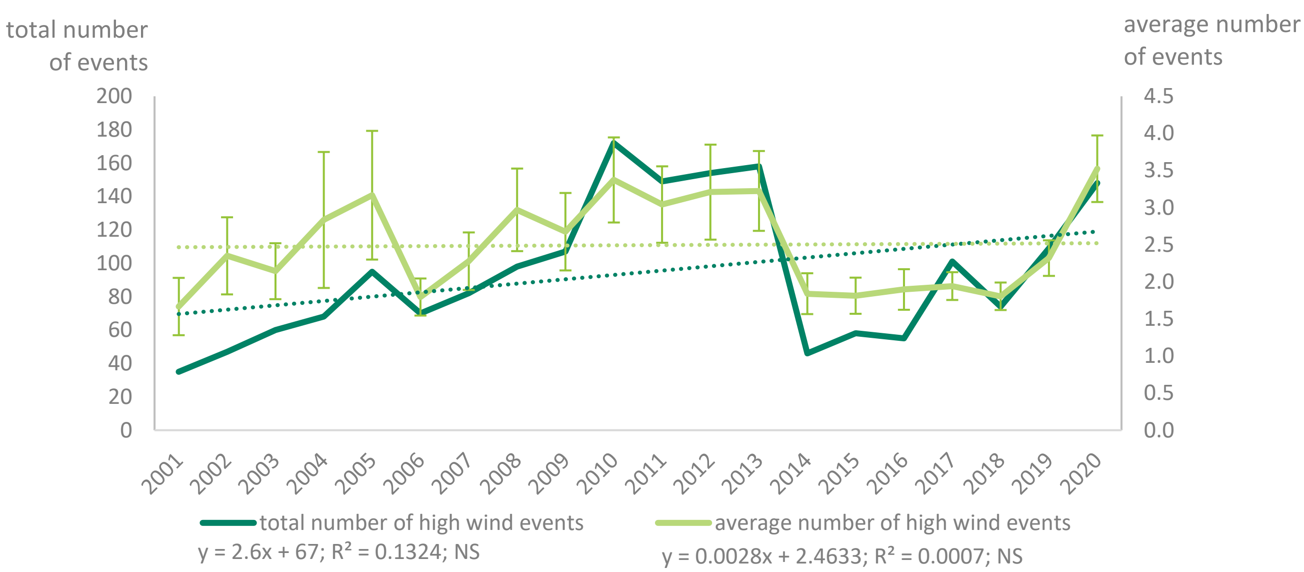

Figure 6: Regional frequency of high wind events was assessed by the change in both the total number of events per year (dark green, left axis) and the average (±SE) number of events per station per year (light green, right axis). While the total number of events appears to be increasing slightly the average is stable over time.

We also used two analyses to represent the **extent of high wind events**; the total number of stations in the network that recorded at least one high wind event, and the number of stations in the network that recorded at least five high wind events annually. The regional long-term trend indicates that the number of stations recording at least one event and the number of stations recording at least five events are both increasing, though only the increase in stations reporting one event is statistically significant (Figure 7). Though not significant (p=0.11) the apparent increase the total number of events along with the increase in the number of stations reporting at least one event suggests that events aren't just increasing but more of the region is seeing high wind events.

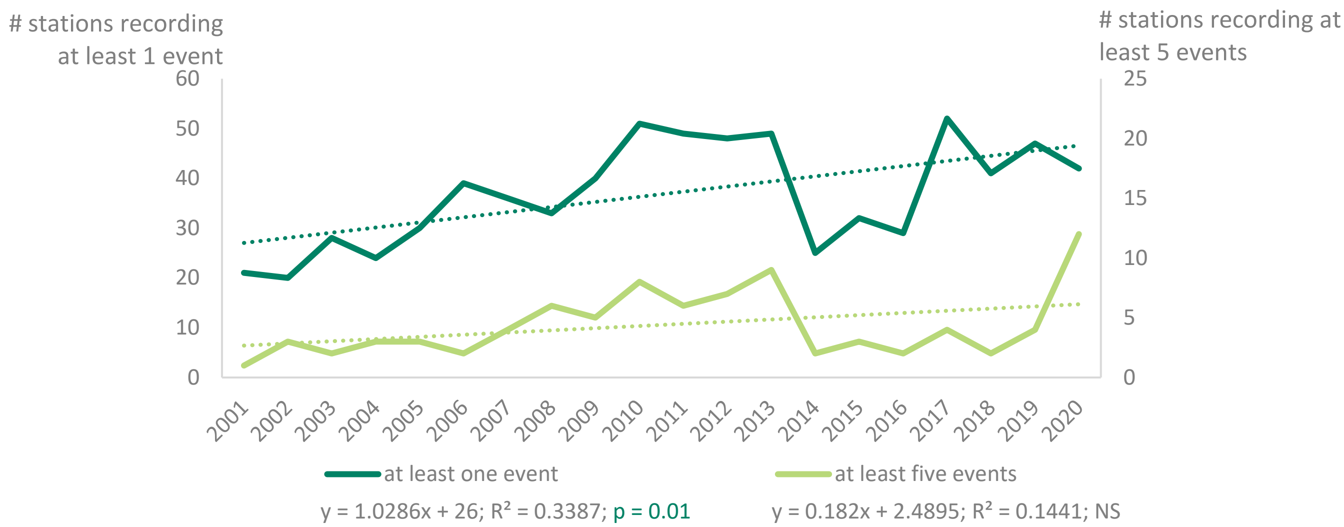

Figure 7: Regional extent of high wind events was evaluated as the number of stations recording at least one event (dark green, left axis) and the number of stations recording at least five events (light green, right axis). There is a significant positive linear trend in the number of stations recording at least one event but not in those recording at least five events.

To represent **wind severity**, we calculated the average maximum miles per hour across all stations in the network as well as the number of events in the 95th percentile (184 mph or more). The long-term trends in both the average maximum wind speed and the number of extreme high wind events (95 percentile) have a statistically significant decrease indicating that while high wind events are becoming more widespread and frequent, extreme wind events are not (Figure 8).

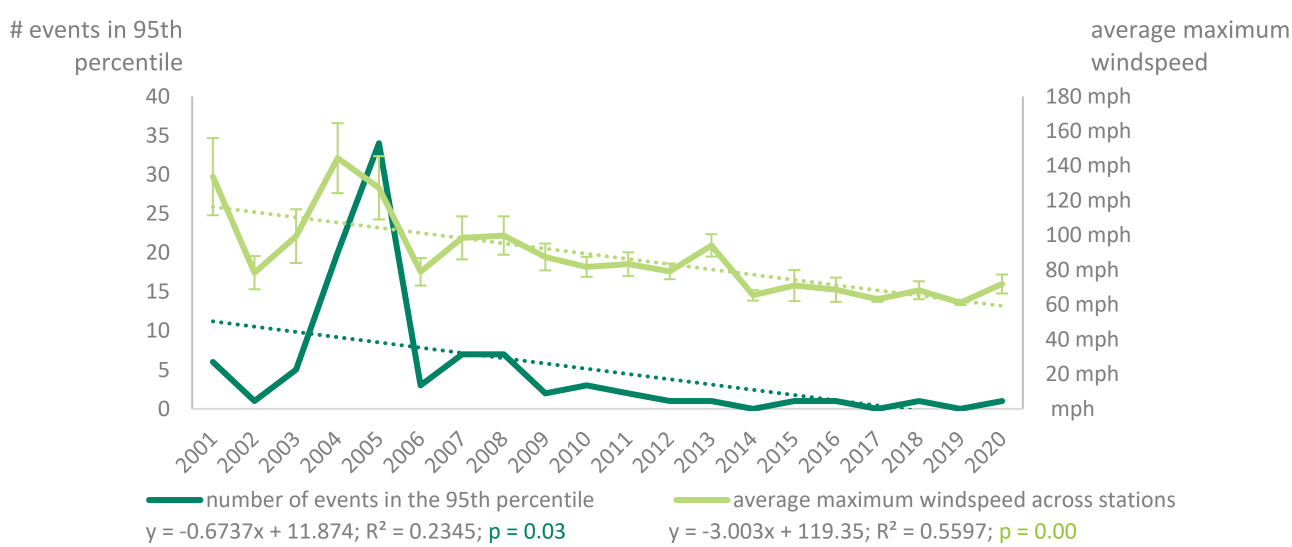

Figure 8: Regional severity of high wind events is represented as the number of events in the 95th percentile (dark green, left axis) and the average maximum wind speed (light green, right axis) each year. Both show a significant positive decrease over time.

While the above analysis focuses on the regional perspectives, the state trends can provide a more nuanced picture of how these high wind events impact different parts of the region (Table 8). Individual states may have significant trends for these analyses even when the regional trend is not significant.

*Table 8: The slope of the trend for each state for each analysis. Slopes followed by ** indicate a significant trend. The orange cells indicate significantly increasing trends while the blue cells indicate significantly decreasing trends.*

	Extent		Frequency		Severity	
	At least 5 high wind events	At least 1 high wind event	Average # high wind events	Total # high wind events	Average max windspeed	# events in 95th percentile
Region	0.18	1.03	--	2.6	-3	-0.67**
CT	0.01**	0.16**	-0.01	0.38	-3.28**	-0.04**
MA	0.12**	0.43	0.02	1.41	-2	-0.1
ME	--	0.02	0.03	0.11	-2.4**	-0.02
NH	--	-0.06	--	-0.1	-7.8**	-0.12
NY	0.05	0.23**	-0.01	0.48	-3.1**	-0.45**
RI	0.02**	0.03	0.07	0.13**	-2.83**	--
VT	-0.03	-0.03	-0.08	-0.23	-6.24	-0.05

Key highlights of this analysis include:

- 2005 recorded the highest number of extreme high wind events, likely due to Hurricane Katrina. This serves as a reminder, that even in inland parts of the region, hurricanes can be a widespread driver of disturbance. Note that Hurricane Sandy (2012) and Tropical Storm Irene (2011) did not contribute high wind events like Hurricane Katrina, as they were primarily rain events (see Flood).
- 2013 had several storms that brought damaging wind to the region including winter storm Nemo, Tropical Storm Andreas and an early season blizzard. Similarly, Nor'easters in 2010 brought high winds and heavy rain across the region. This highlights that hurricanes are not the only driver of high wind events, with more localized, lower level storms also impacting northeastern forests.
- Temporal patterns in frequency and extent indicate that high wind events are becoming more widespread across the region. However, a decrease in average wind speed indicates that smaller, localized events are driving this pattern.

Fire

We calculated **fire frequency** as the number of fires that occurred annually. These data show a significant increase in the number of fires annually (Figure 9). We used two different analyses to calculate **fire extent**: the total area (acres) burned annually and the average size (in acres) of the fires. The slight increase in the total number of acres burned is not statistically significant due to the high variability in the data year to year, however there is a significant decrease in the average acres burned indicating that the change in fire frequency is driven by smaller, localized fires (Figure 10).

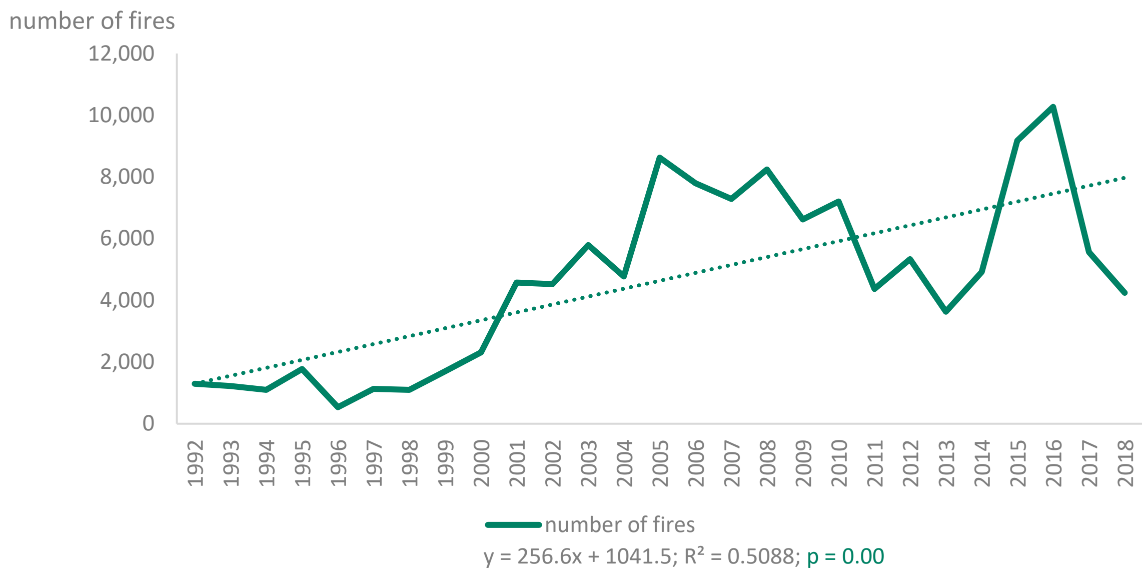

Figure 9: Frequency of fires in the region calculated as the number of fires annually. There is a significant positive linear trend in the number of fires occurring each year.

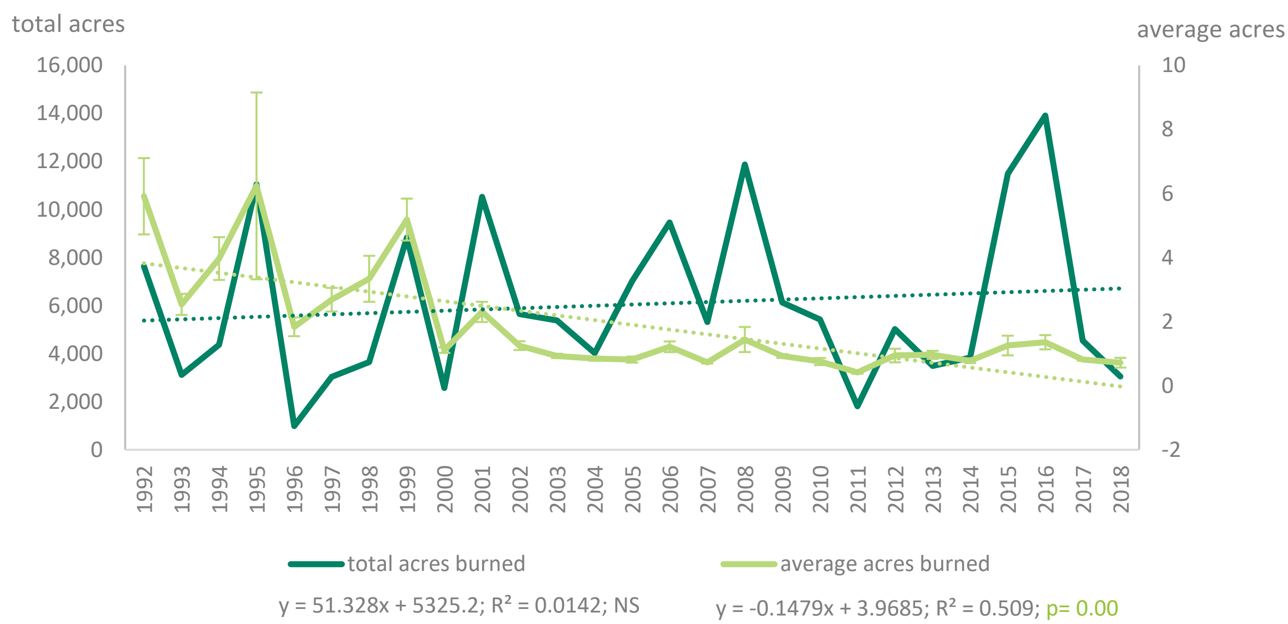

Figure 10: Extent of fire in the region displayed by the total acres burned annually (dark green, left axis) and the average acres burned annually (light green, right axis). There is a significant negative linear trend in the average acres burned annually. The slight increasing trend in the total acres burned is not significant.

Fire severity is assessed in two ways, the first looking at the maximum area burned in a single fire and the second at the number of fires with a burned area over 5 acres (the 97.5th percentile for the dataset). The number of fires over 5 acres is increasing slightly while the maximum acres burned in a single fire is decreasing slightly, but due to the high year to year variability neither are statistically significant (Figure 11).

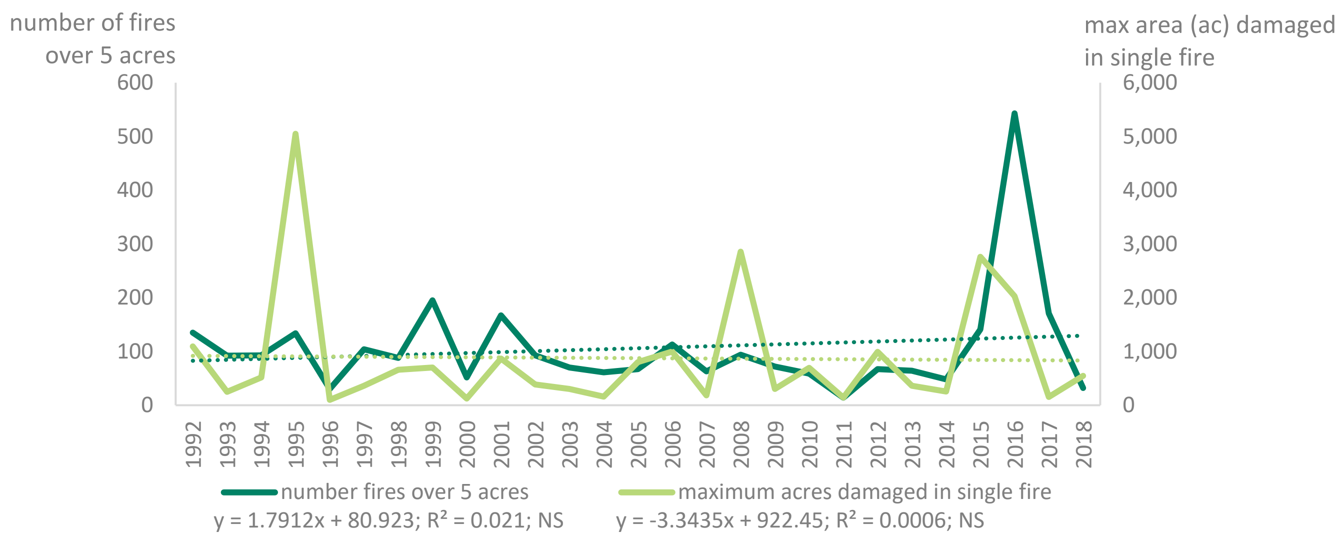

Figure 11: Severity of fires calculated as the number of fires over 5 acres (dark green, left axis) and the maximum area burned in a single fire (light green, right axis). Neither trend is significant.

While the above analysis focuses on the regional perspectives, the state trends can provide a more nuanced picture of how fires impact different parts of the region (Table 9). Individual states may have significant trends for these analyses even when the regional trend is not significant.

*Table 9: The slope of the trend for each state for each analysis. Slopes followed by ** indicate a significant trend. The orange cells indicate significantly increasing trends while the blue cells indicate significantly decreasing trends.*

	Frequency	**Extent**		**Severity**	
	Number of fires	Average acres burned	Total acres burned	Max acres burned in a single fire	Number of fires over 5 acres
Region	256.6**	-0.15**	51.33	-3.34	1.79
CT	11.57**	-0.14**	-3.07	2.97	-0.35
MA	44.38**	0.82	36.91**	6.55	0.64**
ME	-6.85	-0.09**	-62.36**	-14.52**	-1.17**
NH	0.49	0.01	5.44	3.9**	0.1
NY	206.62**	-0.31**	73.21	7.33	2.4
RI	1.94	-0.82**	-0.01	-0.69**	-0.01
VT	3.43**	-2.49	6.06	0.06	0.22**

Key highlights in these analyses include:

- The maximum fire size in any given year is generally low, but large fires can occur in the region (e.g. 5,000 acres in NY in 1995).
- We are seeing an increase in both the total acres burned and the total number of fires reported across the region but a decrease in the average size of those fires indicates that smaller fires are becoming more common.
- New York has the largest number of reported fires and largely drives the regional increase in frequency. This suggests that reporting methods may be introducing bias into the dataset since the FPA FOD dataset used for this analysis relied on state reported data.

Flood

We calculated **flood frequency** as the average number of days within each flood stage category (flood, moderate flood, major flood). The data show a slight decrease in the average number of days a station floods each year (Figure 12), which holds true across the higher-severity flood categories. To evaluate **flood extent**, we used the percent of stations reporting flooding, and this also shows a slight but non-significant decrease over time (Figure 13). **Flood severity**, calculated here as the average annual height across all stream gauges in the network, is stable over time (Figure 14). However, these long-term trends are highly influenced by several large storms early in the data record.

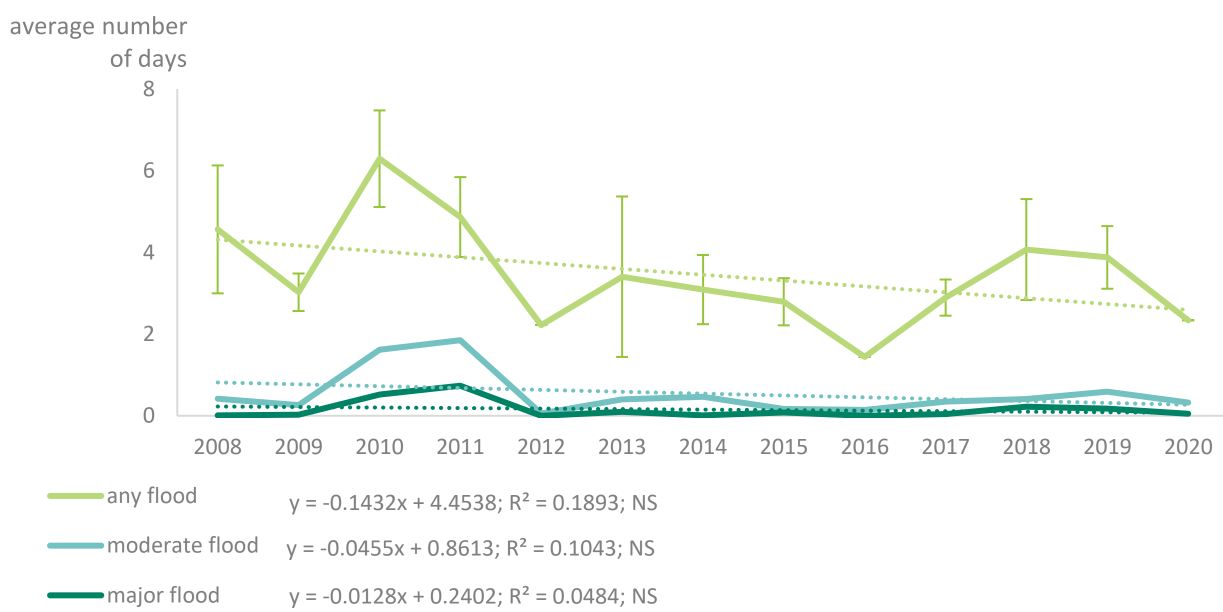

Figure 12: Frequency of flood events calculated as the average number of days flooded (±SE for any flood category) in any flood (light green), moderate flood (light blue), and major flood (dark green). None of the decreasing trends are statistically significant.

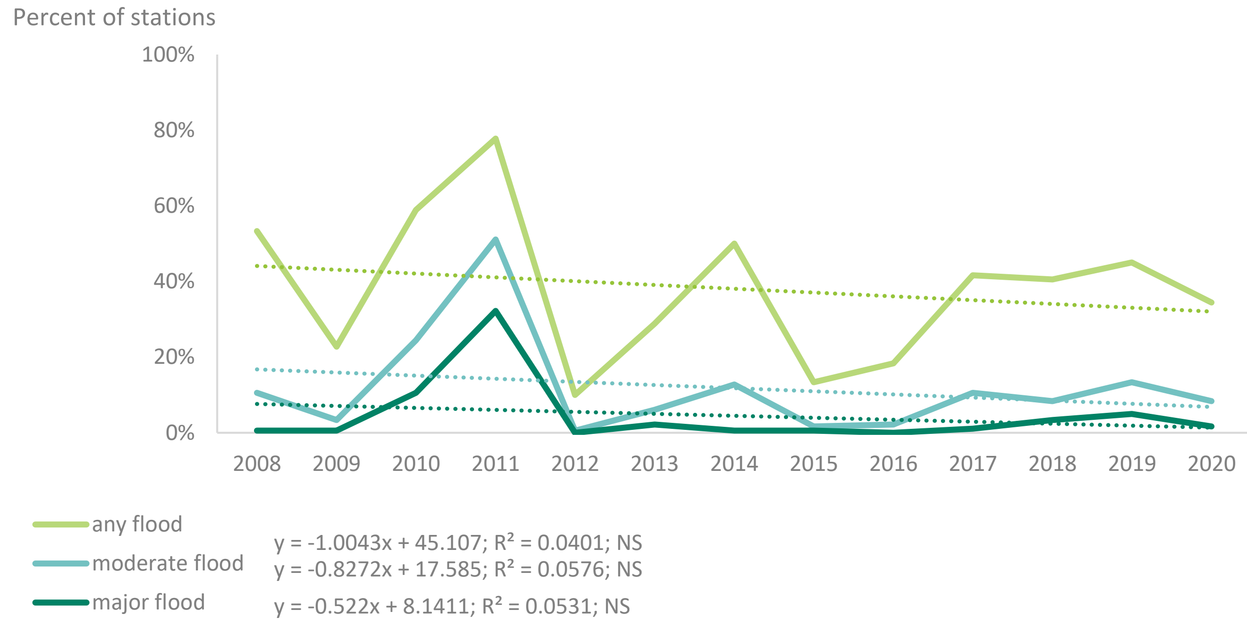

Figure 13: Extent of flooding displayed as the percent of stations recording flood events in any flood (light green), moderate flood (light blue), and major flood (dark green). None of the trends are statistically significant

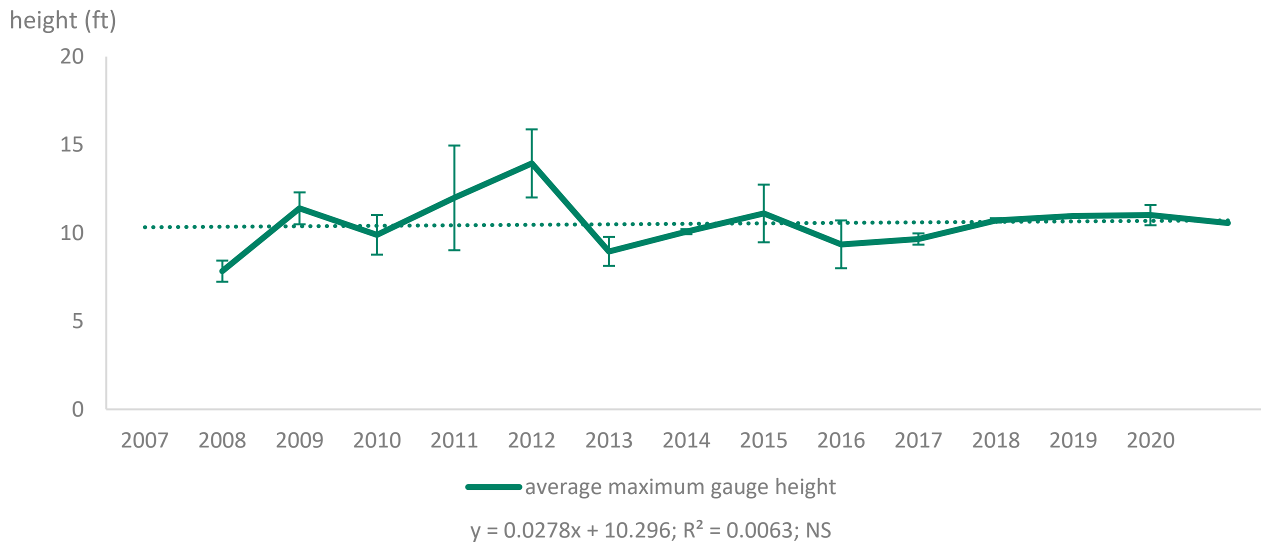

Figure 14: Severity of flooding calculated as the average maximum height of gauges (±SE) annually. The slight positive trend is not significant.

While the above analysis focuses on the regional perspectives, the state trends can provide a more nuanced picture of how these flood events impact different parts of the region (Table 10). Individual states may have significant trends for these analyses even when the regional trend is not significant.

*Table 10: The slope of the trend for each state for each analysis. Slopes followed by ** indicate a significant trend. The orange cells indicate significantly increasing trends while the blue cells indicate significantly decreasing trends.*

	Extent:			frequency:			severity
	Avg. # of days in Any Flood	Avg. # of days in Major Flood	Avg. # of days in Moderate flood	% stations recording Any Flood	% stations recording Major Flood	% stations recording moderate flood	Avg. max gauge height
Region	-0.87	-0.55	-0.83	-0.15	-0.01	-0.05	-0.07
CT	-1.05	-0.59	-2.2	-0.34**	-0.01	-0.12	-0.1
MA	-2.29	-0.66	-1.3	-0.33	-0.01	-0.07	-0.07
ME	-0.7	0.03	0.06	0.04	--	0.01	-0.04
NH	0.32	-0.39	-0.39	-0.19	--	-0.01	0.01
NY	-0.97	-0.61	-0.57	-0.1	-0.01	-0.01	-0.08
RI	-1.42	-1.8	-3.22	-0.24	-0.09	-0.18	-0.22
VT	0.1	-0.55	-0.74	0.01	-0.01	-0.02	-0.03

Key highlights from this analysis include:

- Hurricane Irene (2011) was a heavy rain event that caused major flooding across the entire region. Years like 2011 indicate that even in inland areas, hurricanes can cause widespread and severe flooding across the region.
- Hurricane Sandy (2012) however, was not a significant flood event despite being a hurricane.
- In 2010 two different severe storms impacted the Northeast. In 2014 a slow-moving storm dumped record amounts of rainfall across New York, causing widespread and severe flooding. These events highlight that while hurricanes can cause widespread damage, slow-moving storm systems can also cause major flooding.

Drought

We analyzed drought frequency as the number of weeks of drought recorded in the four USDM drought categories found in the region (categories: D0 - Abnormally Dry, D1 - Moderate Drought, D2 - Severe Drought and D3 - Extreme Drought). The data indicate that, in terms of the **frequency of drought**, while the number of weeks in moderate to extreme drought is relatively stable over the study period, the number of weeks with abnormally dry conditions shows a weak, non-significant increase (Figure 15).

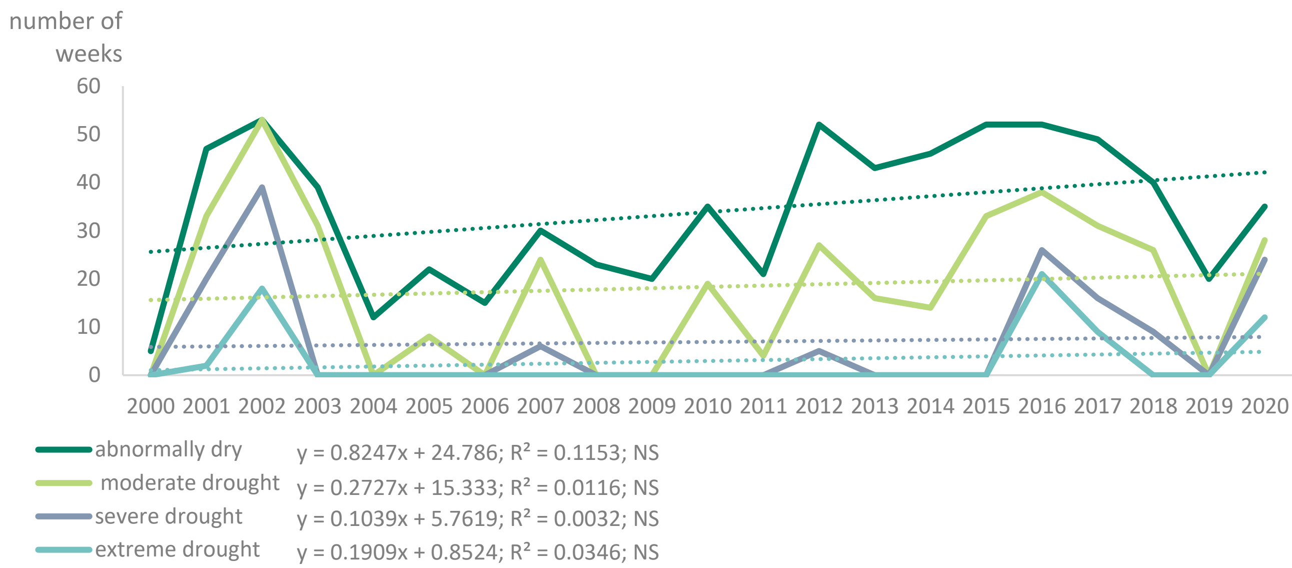

Figure 15: Frequency of drought displayed as the number of weeks in abnormally dry (dark green), moderate drought (light green), severe drought (grey green) and extreme drought (light blue). None of the trends are statistically significant.

A similar pattern exists for the **extent of drought**, represented as the percent of the region experiencing drought in any given year, with no discernible long-term trend for moderate to severe drought but slight increases in the percent of the region experiencing abnormally dry conditions (Figure 16). In assessing the **severity of drought** as the number of weeks in either severe or extreme category, the Northeast sees relatively few weeks in either category, and a slight decrease over time that is not statistically significant (Figure 17).

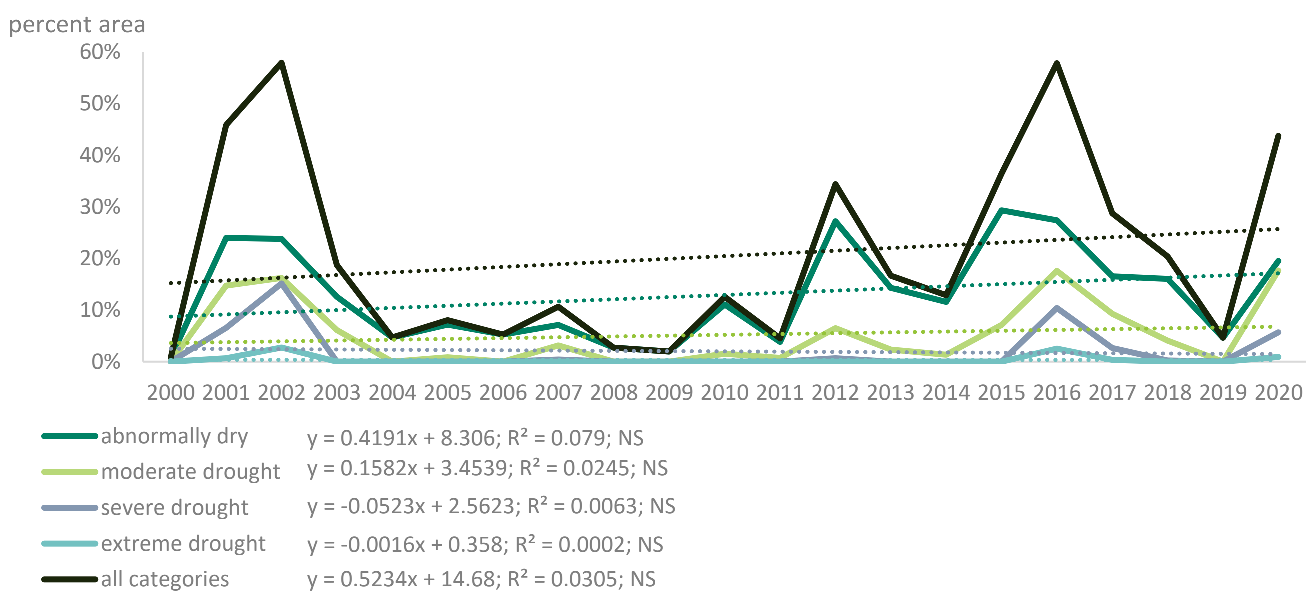

Figure 16: Extent of drought displayed as the percent of the region (ac) in abnormally dry (dark green), moderate drought (light green), severe drought (grey green), extreme drought (light blue) and all drought categories (black). None of the trends are statistically significant.

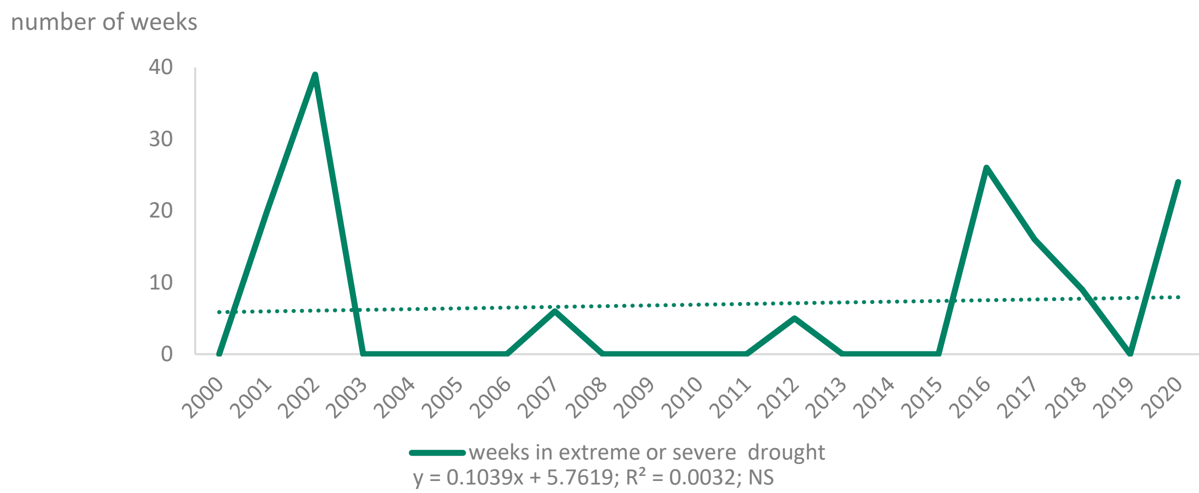

Figure 17: Severity of drought in the region displayed as the combined number of weeks in severe or extreme drought annually. The slight positive trend is not statistically significant.

While the above analysis focuses on the regional perspectives, the state trends can provide a more nuanced picture of how drought impacts different parts of the region (Table 11). Individual states may have significant trends for these analyses even when the regional trend is not significant.

*Table 11 : The slope of the trend for each state for each analysis. Slopes followed by ** indicate a significant trend. The orange cells indicate significantly increasing trends while the blue cells indicate significantly decreasing trends.*

	Frequency				**Extent**				**Severity**
	# weeks in D0	# weeks in D1	# weeks in D2	# weeks in D3	% acres in D0	% acres in D1	% acres in D2	% acres in D3	# weeks in D3 or D4 drought
Region	0.82	0.27	0.1	0.19	0.42	0.16	-0.05	--	0.1
CT	1.06**	0.70	0.26	0.2**	0.39	0.54	-0.04	0.12	0.26
MA	1.45**	0.68	0.24	0.34	0.44	0.28	0.16	0.16	0.24
ME	1.08	0.17	0.06	0.05	0.08	-0.13	-0.27	-0.1	0.06
NH	1.24**	0.38	0.15	0.3	0.48	0.34	-0.09	0.07	0.15
NY	0.9	0.61	0.16	0.1	0.53	0.25	0.04	0.01	0.16
RI	0.63	0.50	0.08	0.14**	0.46	0.39	-0.04	0.14	0.09
VT	1.07**	0.52	0.12	--	0.97**	0.19	0.02	--	0.12

Key highlights from this analysis include:

- 2002 was abnormally dry, with drought conditions reported somewhere in the region for every week of the year, and extreme drought reported for 39 weeks.

- 2016 was also particularly dry, with drought conditions reported across almost 60% of the region. It is notable as being one of the primary causes of the extensive *Lymantria dispar* outbreaks in southern New England (more on the severity and extent of outbreaks in the section on *Lymantria dispar*).
- Trend data indicates that drought conditions are becoming more common and widespread but the high year-to-year variability prevents any of these trends from being statistically significant.

Pests

The seven pests included in this project are all pests of concern across the region. However, they do not all impact the same parts of the region in the same way (Figure 18). Some historically have impacted large portions of the entire region regularly, while others have historically impacted more localized parts of the region at both large and small scales. In this section, each pest is analyzed for its regional impact, with state trends noted but not explored.

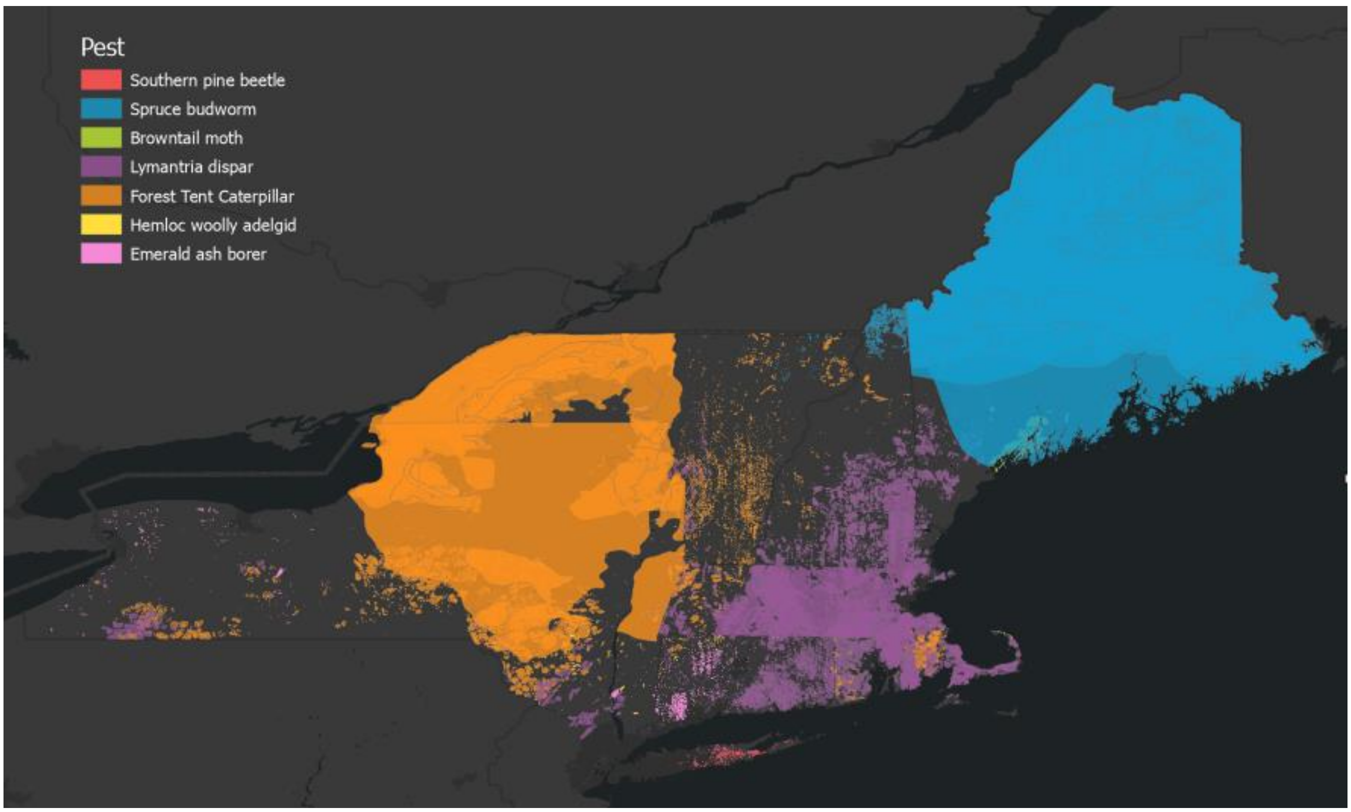

Figure 18: All mapped damage for southern pine beetle (red), spruce budworm (blue), browntail moth (green), L. dispar (purple), forest tent caterpillar (orange), hemlock woolly adelgid (yellow), and emerald ashborer (pink). Spruce budworm, forest tent caterpillar and L. dispar are the extensive pests in the region.

Native pests

Forest tent caterpillar

Forest tent caterpillar (*Malacosoma disstria*, FTC) is a pest native to the Northeast that has outbreaks that occur roughly every 10-15 years and last 2-4 years. FTC is a defoliator that rarely causes tree mortality, however, FTC damage does stress trees, making them more susceptible to additional stressors. We represented the **frequency of FTC disturbance** using three metrics: the number of years since the last outbreak started, as determined from state and federal forest health publications, the total acres damaged during the duration of the outbreak, and the annual acres damaged. There are too few outbreak events in the historical record to analyze trends, however, the number of years between outbreaks has been decreasing over time (Figure 19). The **extent of FTC damage**, calculated as the total acres damaged annually, is decreasing significantly over time (Figure 20).

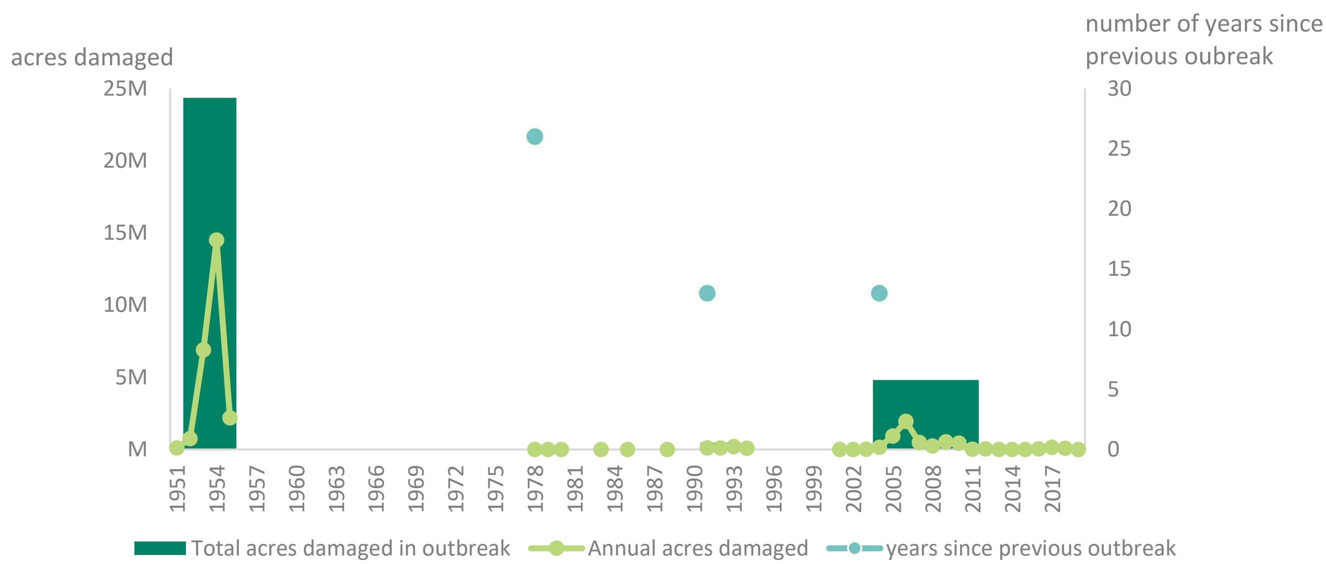

Figure 19: Frequency of forest tent caterpillar outbreaks displayed as the acres damaged (light green, left axis) both annually and the total damage over the duration of the outbreak (dark green, left axis) and as the number of years since the previous outbreak (light blue, right axis).

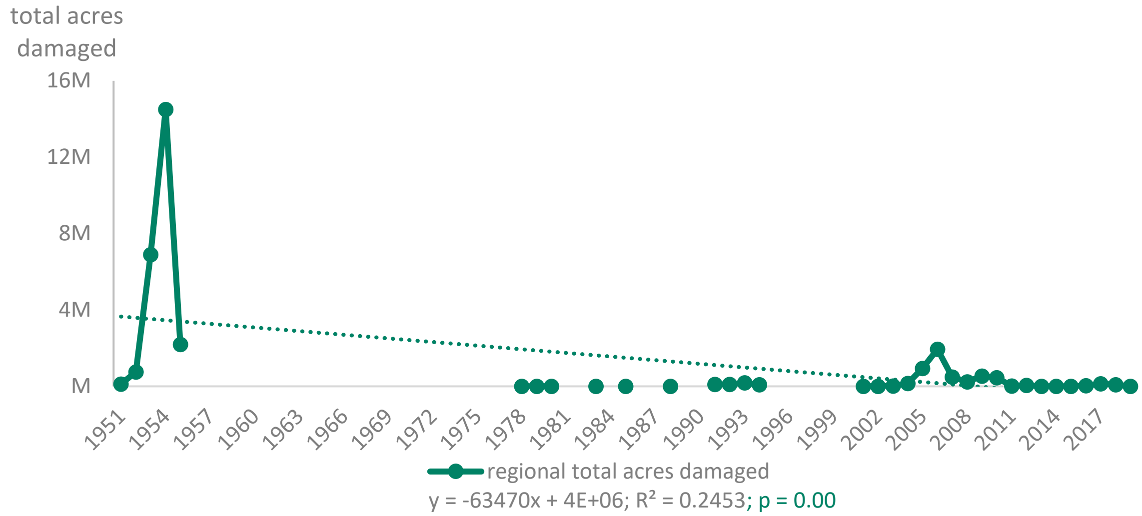

Figure 20: Extent of forest tent caterpillar damage displayed as the total area (ac) damaged. There is a significant negative trend in acres damaged by forest tent caterpillar annually. Note: The way that damage was tallied has changed over time so there is less certainty about exact acreage, particularly in historical data. Also, the acreage used in this analysis was calculated using ArcGIS Pro software from digitized historical map data and therefore may differ from reported acreage in corresponding forest health reports.

This decrease over time is driven largely by the outbreak in New York in 1950, which damaged over 15 million acres. We represented **severity of FTC damage** by both the area (acres) of damage categorized as mortality and the percent of the total damage categorized as mortality (Figure 21). The overall trend in both of these metrics is increasing significantly.

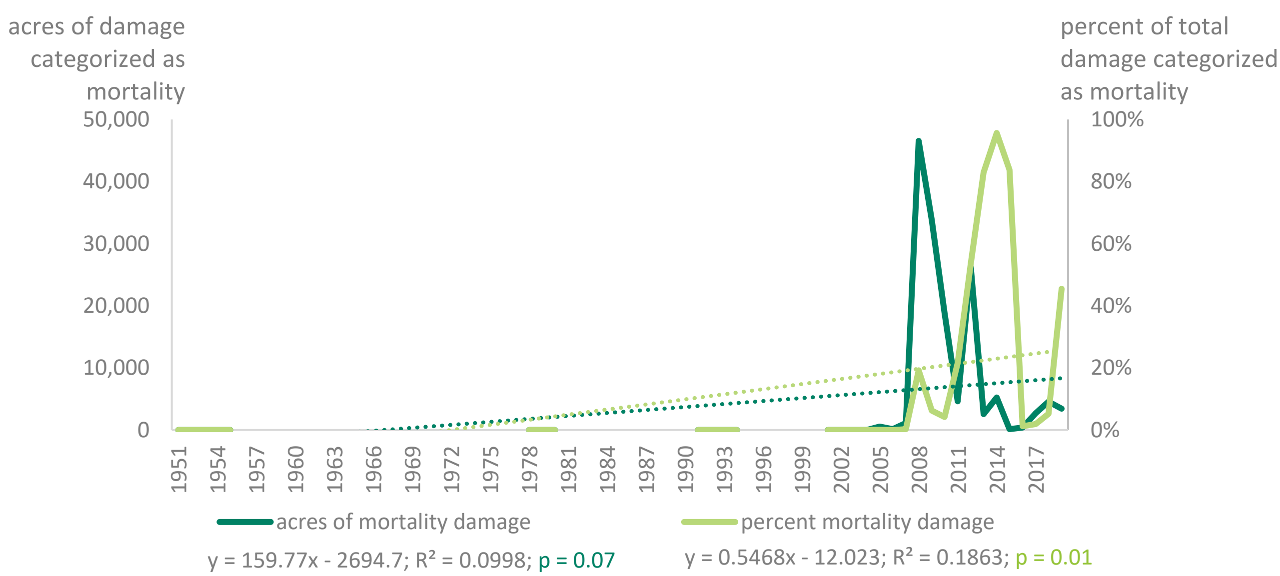

Figure 21: Severity of forest tent caterpillar disturbance calculated as the acres of damage categorized as mortality (dark green, left axis) and the percent of the total damage that was categorized as mortality (light green, right axis). Both the number of acres and the percent of total damage categorized as mortality have significant positive trends over time.

While the above analysis focuses on the regional perspectives, the state trends can provide a more nuanced picture of how FTC impacts different parts of the region (Table 12). Individual states may have significant trends for these analyses even when the regional trend is not significant.

*Table 12: The slope of the trend for each state for each analysis. Slopes followed by ** indicate a significant trend. The orange cells indicate significantly increasing trends while the blue cells indicate significantly decreasing trends.*

	Extent	**Severity**	
	Total acres damaged	Percent of total damage categorized as mortality	Acres categorized as mortality
Region	-63470.28**	0.55**	159.77
CT	-110.57	0.33	6.2
MA	1328.49	0.26	4.03
ME	-1.22	--	--
NH	-383.14	--	--
NY	-77385.74**	0.61**	138.55
RI	1410	--	92.77
VT	806.17	1.1	73.07

Key highlights from this analysis include:

- The most recent outbreak started in 2004 in Vermont, expanding to New Hampshire in 2005 and 2006. In 2007 populations crashed in VT and NH but soared in New York while also appearing in CT and RI. The outbreak continued in New York through 2010. This demonstrates that the extent and location of outbreaks can shift over time.
- Forest tent caterpillar outbreaks typically last three years in an area (but may last 2-9) and tend to happen roughly every 10 years. The extensive duration of the most recent outbreak is due to the migration of the pest across the region, with 2- to 3-year outbreak cycles moving from east to west.
- The decrease in total acres damaged and the increase in the percent of damage categorized as mortality indicates that forest tent caterpillar damage is less extensive and more severe, possibly caused by compounding with other stress agents.

Spruce budworm

Eastern spruce budworm (*Choristoneura fumiferana)* is a native pest that infests spruce-fir forests. About every 30-40 years, it has a periodic outbreak which typically lasts several years. We represented the **frequency of spruce budworm disturbance** using three metrics: the number of years since the last outbreak started, as determined from state and federal forest health publications, the total acres damaged during the duration of the outbreak, and the annual acres damaged (Figure 22). There are too few outbreak events in the historical record to analyze the trend in outbreaks, however, the number of years between outbreaks has increased over time suggesting that outbreaks may be happening less often.

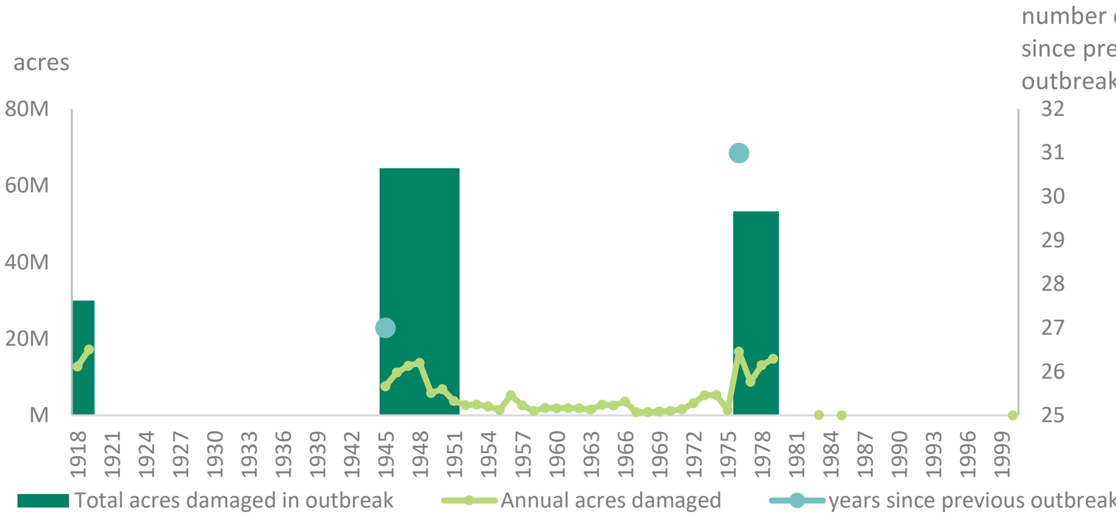

Figure 22: Frequency of spruce budworm outbreaks displayed as the acres damaged (left axis) both annually (light green) and the total damage over the duration of the outbreak (dark green) and as the number of years since the previous outbreak (light blue, right axis)

We calculated the **extent of spruce budworm damage** as the total acres damaged by spruce budworm annually (Figure 23). The overall trend in the total annual acres damaged by spruce budworm is decreasing over time and this decrease is statistically significant. We represented the **severity of spruce budworm damage** by both the number of acres of damage categorized as mortality and the percent of the total damage categorized as mortality. None of the spruce budworm damage was recorded as mortality so it is not possible to assess the trend in severity.

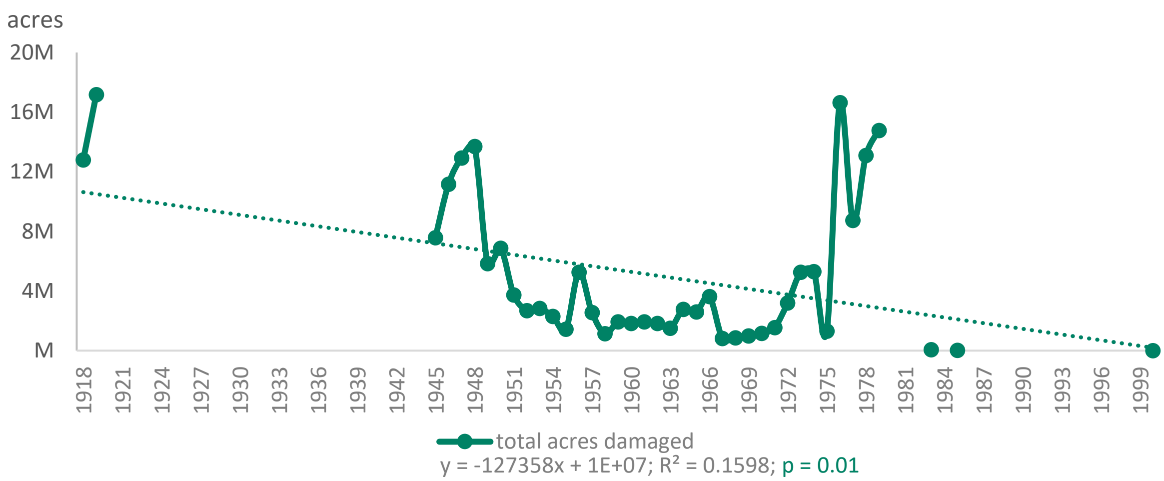

Figure 23: Extent of spruce budworm damage displayed as the total area (ac) damaged. There is a significant negative trend in acres damaged by spruce budworm annually. Note: The way that damage was tallied has changed over time so there is less certainty about exact acreage particularly in historical data. Also, the acreage used in this analysis was calculated using ArcGIS Pro software from digitized historical map data and therefore may differ from reported acreage in corresponding forest health reports.

While the above analysis focuses on the regional perspectives, the state trends can provide a more nuanced picture of how spruce budworm impacts different parts of the region (Table 13). Individual states may have significant trends for these analyses even when the regional trend is not significant.

*Table 13 : The slope of the trend for each state for each analysis. Slopes followed by ** indicate a significant trend. The orange cells indicate significantly increasing trends while the blue cells indicate significantly decreasing trends.*

	Extent
	Total acres damaged
Region	-127358.83**
CT	--
MA	--
ME	-111825
NH	-2464.03
NY	--
RI	--
VT	--

Key highlights from this analysis include:

- Spruce budworm has primarily impacted Maine where a large proportion of forests are spruce/fir. The only other state that has recorded presence of spruce budworm is New Hampshire in the 70s and 80s but the acres damaged were minimal.
- There has not been a large scale spruce budworm outbreak since the 1980s and it has not been recorded in the annual aerial detection surveys since 2000. However it continues to be a pest of concern in northern Maine.
- All spruce budworm damage has been recorded as defoliation. This is likely due to a combination of the variability of the mapping methods prior to 1997 when the forest service established more rigorous criteria for mapping and reporting pest and disease disturbance, and spruce budworm being primarily a defoliator, with mortality only showing up in later years of an outbreak.

Established Invasives

Lymantria dispar

Lymantria dispar (formerly known as gypsy moth[2]) is a non-native pest originally introduced to North America in the 1860s that has been established in the Northeast since the early 1900s. We represented the **frequency of *L. dispar*** disturbance using three metrics: the number of years since the last outbreak started as determined from

[2] The Entomological Society of America discontinued gypsy moth as a common name of *Lymantria dispar* in their effort to remove common names that "perpetuate negative ethnic or racial stereotypes", see https://www.entsoc.org/entomological-society-america-discontinues-use-gypsy-moth-ant-names

state and federal forest health publications), the total acres damaged during the duration of the outbreak, and the annual acres damaged. There are too few outbreak events in the historical record to analyze the trend in outbreaks, however, the number of years between outbreaks has increased over time suggesting that outbreaks may be happening less often (Figure 24). We calculated the **extent of *L. dispar* damage** as the total acres damaged annually. The data indicate a slight increase in the total acres damaged by *L. dispar,* but this increase is not significant (Figure 25).

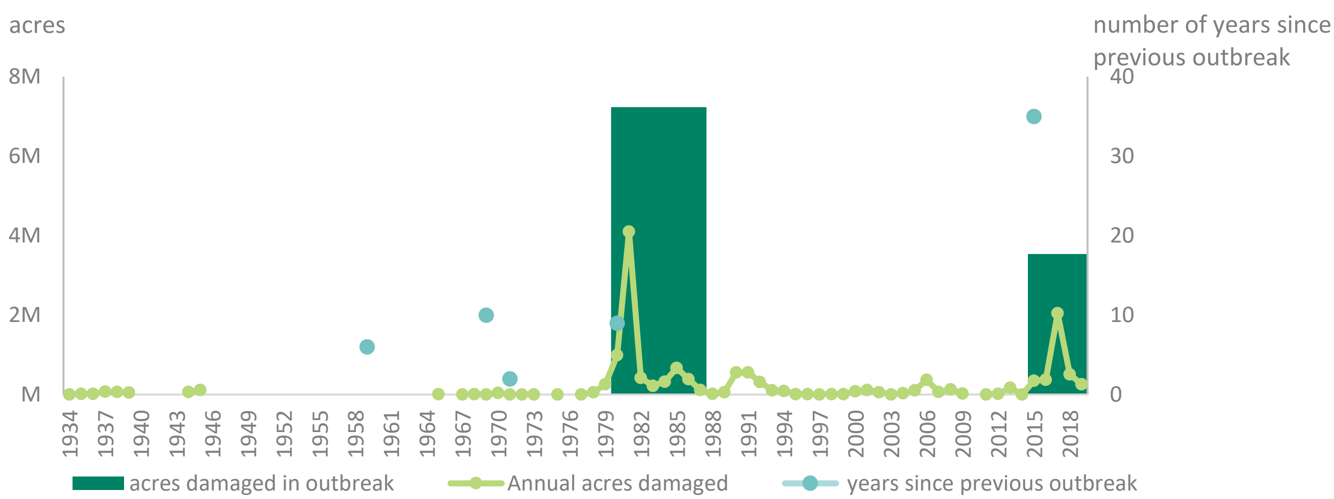

Figure 24: Frequency of L. dispar outbreaks displayed as the acres damaged (left axis) both annually (light green) and the total damage over the duration of the outbreak (dark green) and as the number of years since the previous outbreak (light blue, right axis)

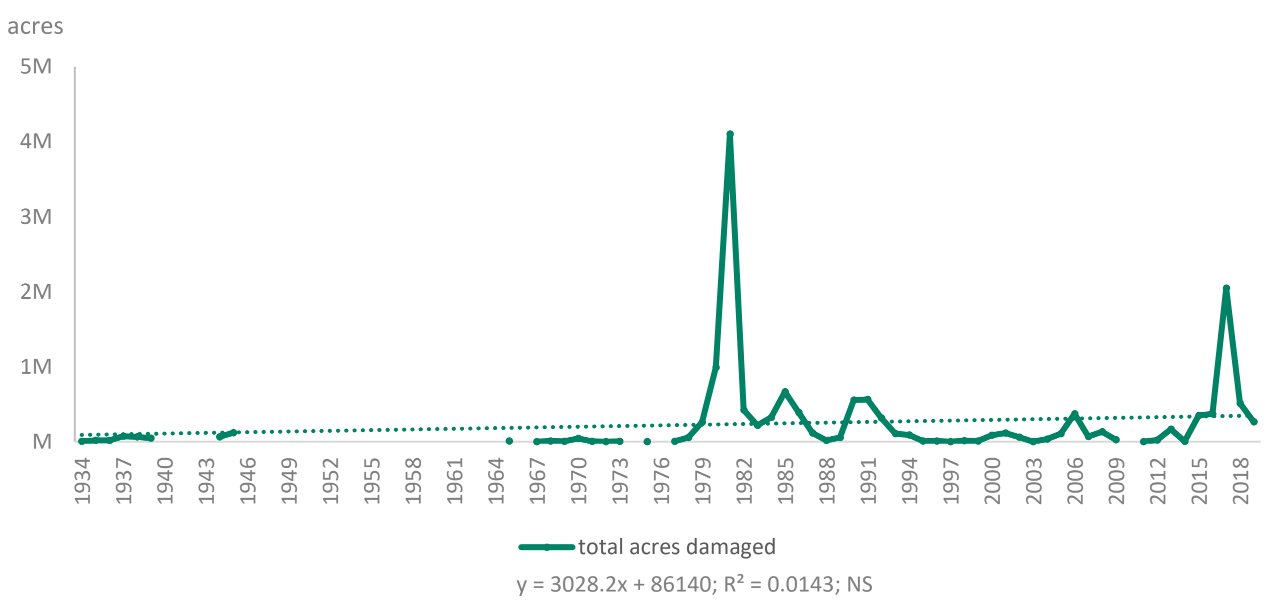

Figure 25: Extent of L. dispar damage displayed as the total area (ac) damaged. The trend in annual L. dispar damage is not significant.

We represented **severity of *L. dispar* damage** by both the number of acres of damage categorized as mortality and the percent of the total damage categorized as mortality (Figure 26). Both the trend in acres of damage categorized as mortality and the trend the percent of all damage that is categorized as mortality are increasing significantly.

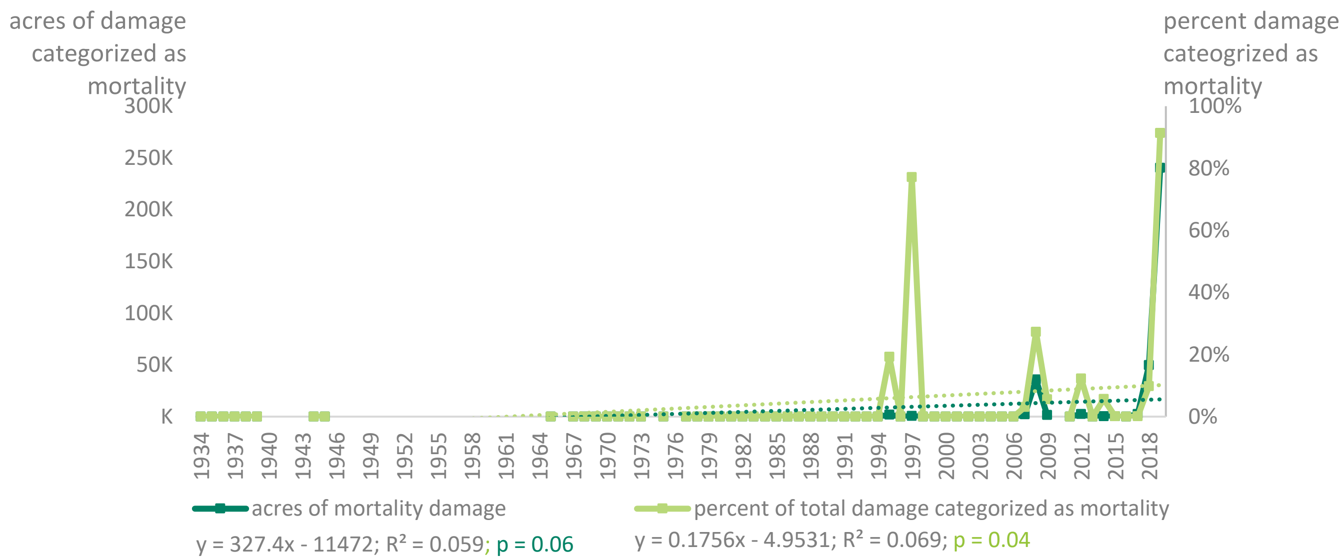

Figure 26: Severity of L. dispar disturbance calculated as the acres of damage categorized as mortality (dark green, left axis) and the percent of the total damage that was categorized as mortality (light green, right axis). Both the number of acres and the percent of total damage categorized as mortality have significant positive trends over time.

While the above analysis focuses on the regional perspectives, the state trends can provide a more nuanced picture of how *L. dispar* impacts different parts of the region (Table 14). Individual states may have significant trends for these analyses even when the regional trend is not significant.

*Table 14 : The slope of the trend for each state for each analysis. Slopes followed by ** indicate a significant trend. The orange cells indicate significantly increasing trends while the blue cells indicate significantly decreasing trends.*

	Extent	**Severity**	
	Total acres damaged	Percent of total damage categorized as mortality	Acres categorized by mortality
Region	3028.21	0.18**	327.4
CT	15239.01	2.01	3304.08
MA	890.24	0.31**	109.33**
ME	-9387.8	--	--
NH	-1534.58	0.54**	1.18**
NY	1312.88	0.96	-10.41
RI	7276.97	1.72	537.35
VT	-1874.65	--	--

Key highlights from this analysis include:

- The 1981 outbreak is the worst in the history of *L. dispar* in North America damaging more than 6 million acres across the region.
- In 1989 a fungus - *Entomophaga maimaiga* - that is a native biological control to *L. dispar* in Japan was first found established in the region and impacting *L. dispar* populations in North America. It significantly contributed to the decline of the 1980s outbreak and to *L. dispar* population management since. In 2015 and 2016 conditions in the Northeast were too dry for *E. maimaiga* resulting in a dramatic increase in *L. dispar* populations.[3] [4]

Browntail moth

Browntail moth (*Euproctis chrysorrhoea*) is a non-native invasive species originally introduced to North America in the late 1890s. Since initial infestations when first introduced, browntail moth has caused little damage in northeastern forests. However, in the last few years, these patterns have shifted. We represented the **frequency of browntail moth disturbance** using three metrics: the number of years since the last outbreak started as determined from state and federal forest health publications, the total acres damaged during the duration of the outbreak, and the annual acres damaged (Figure 27).

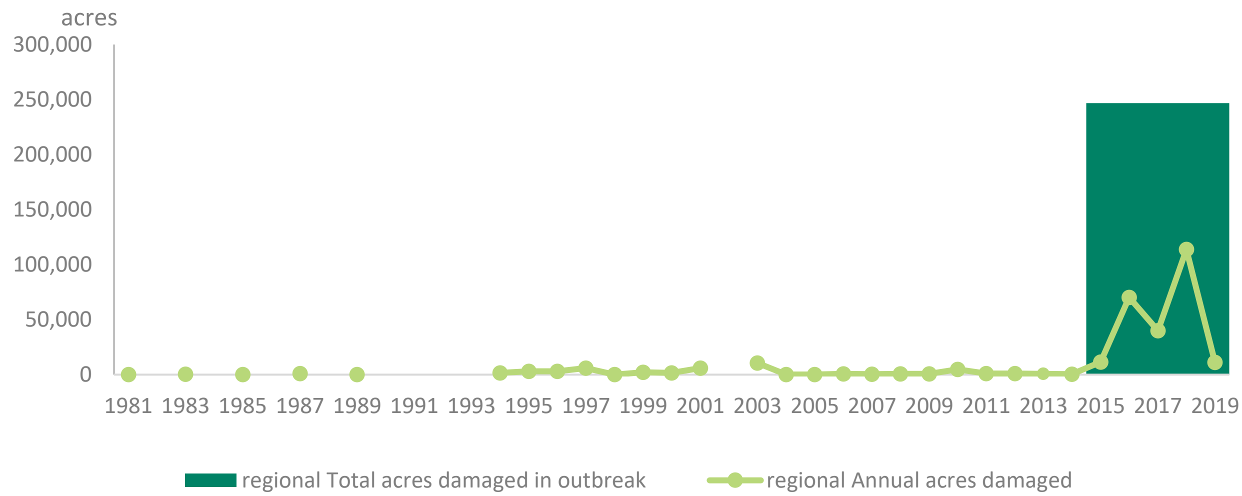

Figure 27: Frequency of browntail moth outbreaks displayed as the acres damaged both annually (light green) and the total damage over the duration of the outbreak (dark green).

The outbreak that started in 2015 is the only severe outbreak of browntail moth in the aerial survey data record, however, there are reports of extensive outbreaks shortly after its introduction in the late 1890s and early 1900s. The **extent of browntail moth disturbance**, calculated here as the total acres damage, is increasing

[3] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC53709/pdf/pnas01032-0087.pdf
[4] https://portal.ct.gov/DEEP/Forestry/Forest-Protection/The-Gypsy-Moth-in-Connecticut---An-Overview

significantly (Figure 28). We represented severity by both the number of acres of damage categorized as mortality and the percent of the total damage categorized as mortality (Figure 29). The only year with damage categorized as mortality in the aerial detection survey record was 1997.

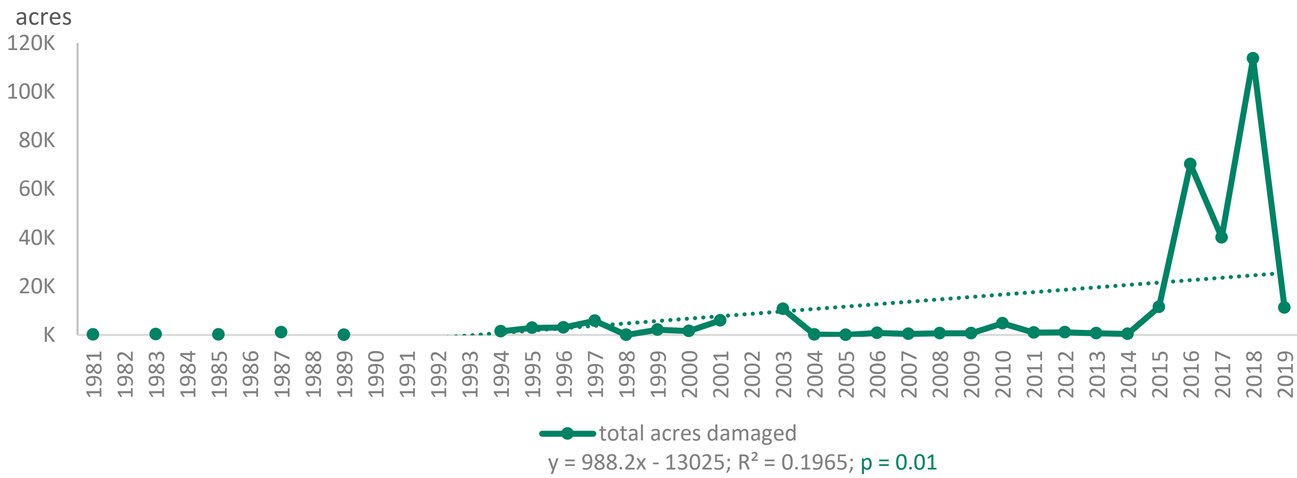

Figure 28: Extent of browntail moth damage displayed as the total area (ac) damaged. There is a significant positive trend in acres damaged by browntail moth annually.

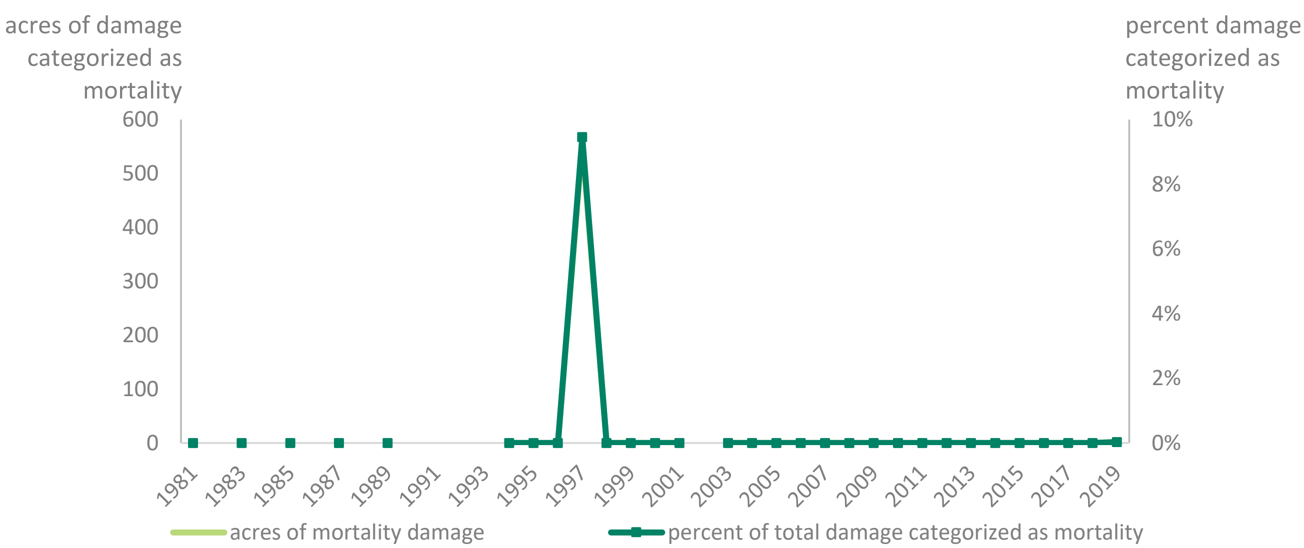

Figure 29: Severity of browntail moth disturbance calculated as the acres of damage categorized as mortality (dark green, left axis) and the percent of the total damage that was categorized as mortality (light green, right axis). Neither the number of acres or the percent of total damage categorized as mortality have significant trends over time.

While the above analysis focuses on the regional perspectives, the state trends can provide a more nuanced picture of how browntail moth impacts different parts of the region (Table 15Table 8). Individual states may have significant trends for these analyses even when the regional trend is not significant.

*Table 15 : The slope of the trend for each state for each analysis. Slopes followed by ** indicate a significant trend. The orange cells indicate significantly increasing trends while the blue cells indicate significantly decreasing trends.*

	Extent
	Total acres damaged
Region	988.20**
CT	--
MA	-10.73
ME	165.23**
NH	-2464.03
NY	--
RI	--
VT	--

Key highlights from this analysis include:

- The most recent outbreak (2015-2019) is the first outbreak in the record of the aerial survey data and the first major outbreak since the widespread outbreak that occurred directly after its introduction to the region in 1897, impacting not only the forest ecosystem but also causing rashes on people who come into contact with the moth's toxic hairs (Groden et al 2020).
- Maine and Massachusetts are the only states in the region to record damage from browntail moth, with Maine experiencing the brunt of the damage, particularly from the recent outbreak which continues to expand into several areas of the state.

Advancing Invasives

Hemlock woolly adelgid

Hemlock wooly adelgid (*Adelges tsugae*) is an invasive insect that attacks hemlock trees which are a key species in northeastern forest ecosystems due to its abundance, shade-tolerance and longevity. First detected in Connecticut in 1985, hemlock woolly adelgid (HWA) has led to widespread mortality in southern portions of the region. Here we are tracking its advancement across the region. We calculated the extent of HWA disturbance as the total acres damaged by HWA annually. Hemlock woolly adelgid has a longer history in the region, allowing us to see the trend in the **extent of HWA damage,** represented as the total acres damaged, increasing (though not significantly) over the reporting period, with high levels of year-to-year variability primarily driven by winter HWA mortality in extremely cold years (Figure 30). We represented **severity of HWA damage** by both the number of acres of damage categorized as mortality and the percent of the total damage categorized as mortality. Both the acres of damage categorized as mortality and the percent of damage categorized as mortality have been relatively stable, indicating that some hemlock may be tolerating low levels of HWA infestation (Figure 31).

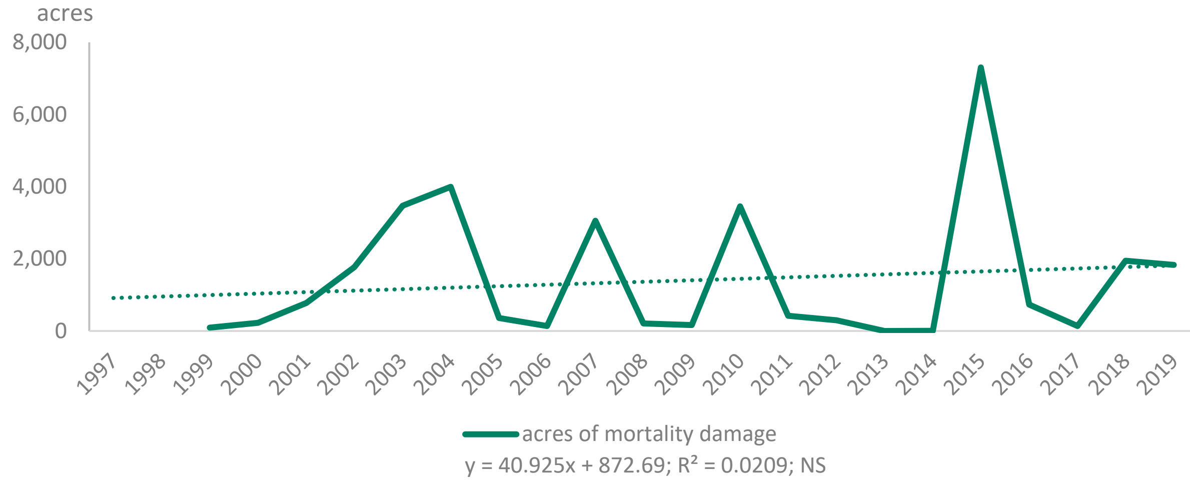

Figure 30: Extent of hemlock woolly adelgid damage displayed as the total area (ac) damaged. The positive trend over time is not significant

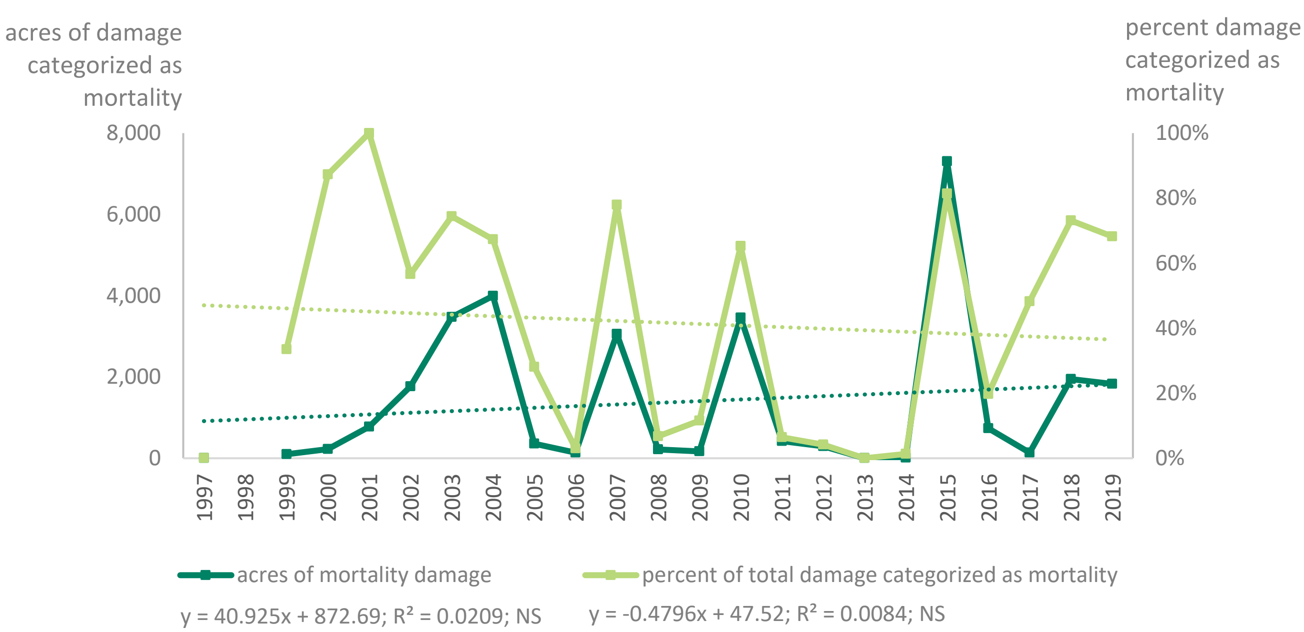

Figure 31: Severity of hemlock woolly adelgid disturbance calculated as the acres of damage categorized as mortality (dark green, left axis) and the percent of the total damage that was categorized as mortality (light green, right axis). Neither the number of acres nor the percent of total damage categorized as mortality have significant trends over time.

While the above analysis focuses on the regional perspectives, the state trends can provide a more nuanced picture of how HWA impacts different parts of the region (Table 16Table 8). Individual states may have significant trends for these analyses even when the regional trend is not significant.

*Table 16 : The slope of the trend for each state for each analysis. Slopes followed by ** indicate a significant trend. The orange cells indicate significantly increasing trends while the blue cells indicate significantly decreasing trends.*

	Extent	**Severity**	
	Total acres damaged	Percent of total damage categorized as mortality	Acres of damage categorized as mortality
Region	140.54	-0.48	40.92
CT	85.81	2.02	47.35**
MA	0.03	1.44	6.55
ME	-41.42**	2.64	0.27
NH	-6.5	-4.42	-9.66
NY	-59.02	-3.14	-53.32
VT	-38.57	--	--

Key highlights from this analysis include:

- While the total acreage of reported HWA damage has increased slightly over the study period, acres in mortality has not. This indicates that some hemlock have been able to persist in spite of infestation.
- Year-to-year variability is high, primarily driven by extreme cold winters resulting in high HWA mortality.
- Connecticut and New York have been hardest hit by HWA, accounting for most of the damage in the region.

Emerald ash borer

Emerald ash borer (*Agrilus planipennis*) is an invasive beetle originally from Asia that has caused widespread ash mortality. Emerald ash borer (EAB) was introduced to the US Midwest in 2002 and was first spotted in the Northeast in 2012. It has moved steadily north from initial infestations in Connecticut and Massachusetts into New York, New Hampshire and Vermont. Maine and Rhode Island have recorded EAB presence but not at a large enough scale to appear in the aerial surveys. It is likely that with changing climates and warmer temperatures EAB will continue to move north. As a newly relevant species to the Northeast, the historical record of emerald ash borer damage only goes back to 2013, which is insufficient to analyze long-term trends. In addition, due to the relatively low densities of ash in northern temperate forests, it is difficult to map from aerial surveys. The **extent of EAB disturbance**, calculated here as the total acres damaged by EAB annually is relatively stable until 2019 when it increased dramatically (Figure 32).

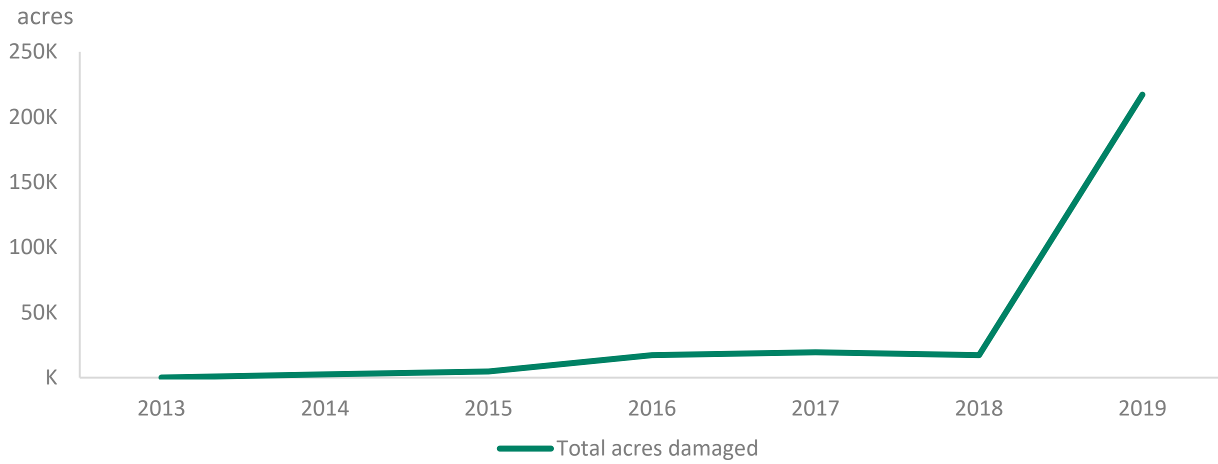

Figure 32: Extent of emerald ash borer damage displayed as the total area (ac) damaged.

We represented the **severity of EAB disturbance** by both the number of acres of damage categorized as mortality and the percent of the total damage categorized as mortality. The number of acres of damage categorized as mortality is increasing slightly while the percent of damage categorized as mortality is increasing more sharply, with almost 100% of all EAB damage classified as mortality in 2019 (Figure 33).

Figure 33: Severity of emerald ash borer disturbance calculated as the acres of damage categorized as mortality (dark green left axis) and the percent of the total damage categorized as mortality (light green, right axis).

Key highlights from this analysis include

- While the total acres damaged by EAB is has increased fairly slowly over the last few years, the percent of the damage that has caused tree mortality is increasing, with more than 50% categorized as mortality for the last three years.
- 2019 reported a significant spike in total acres damaged, with 100% mortality. All states in the region except Maine and Rhode Island recorded damage detectable from aerial surveys, with this being the first year of widespread damage recorded in Vermont.

Southern pine beetle

Southern pine beetle (*Dendroctonus frontalis*) (SPB) is a small bark beetle that is native to the southeastern US. SPB primarily infects pine trees, but may also damage hemlock and spruce. Its range has expanded northward from New Jersey recently as temperatures warm in the region (Dodds et al 2018). In the Southwest, fires play a key role in mitigating the impacts of SPB by thinning pine stands and disrupting pheromone communication among southern pine beetle populations. It is anticipated that as the climate of the Northeast continues to change and warm, SPB will become an increasing concern. As a newly relevant species to the Northeast, the historical record of southern pine beetle damage only goes back to 2015, which doesn't provide enough data to explore long-term trends. The **extent of SPB disturbance**, calculated here as the total acres damaged annually is decreasing (Figure 34). We represented **severity of SPB damage** as both the number of acres of damage categorized as mortality and the percent of the total damage categorized as mortality (Figure 35).

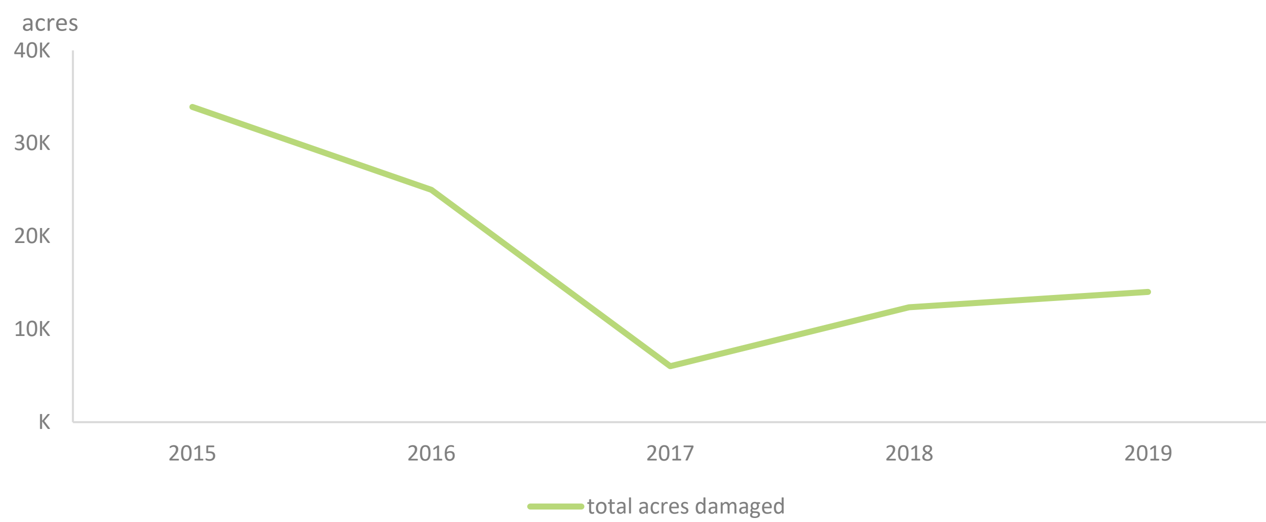

Figure 34: Extent of southern pine beetle damage displayed as the total area (ac) damaged.

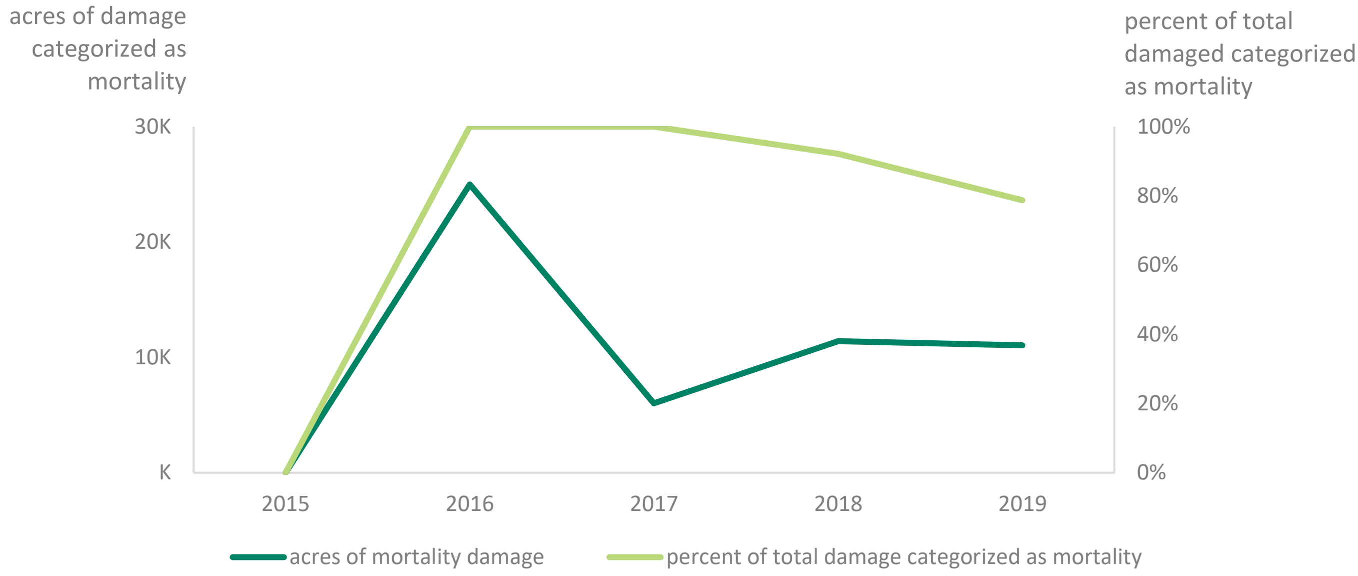

Figure 35: Severity southern pine beetle disturbance calculated as the acres of damage categorized as mortality (dark green, left axis) and the percent of the total damage that was categorized as mortality (light green, right axis).

Key highlights from this analysis include:

- New York is the only state in the region to have recorded instances of southern pine beetle damage detected in aerial surveys, primarily on Long Island. However, there have been isolated occurrences in Orange, Rockland and Ulster counties in New York as well as several detections in Connecticut since 2015, causing concerns about spread (Dodds et al 2018).
- The first year that SPB was recorded was the most widespread impact. However, it didn't cause any mortality until subsequent years.

MONITORING CHANGES IN DISTURBANCE REGIMES

The first version (Version 1.0) of the *FEMC: Tracking Shifts in Disturbance Regimes* web portal is both a compiled inventory of 272 programs conducting monitoring for key disturbance drivers as well as a viewer for a regional analysis of the long-term trends in the severity, frequency and extent of these drivers. The home page introduces the web portal and project as well as summarizes information about key disturbance drivers and responses (Figure 36).

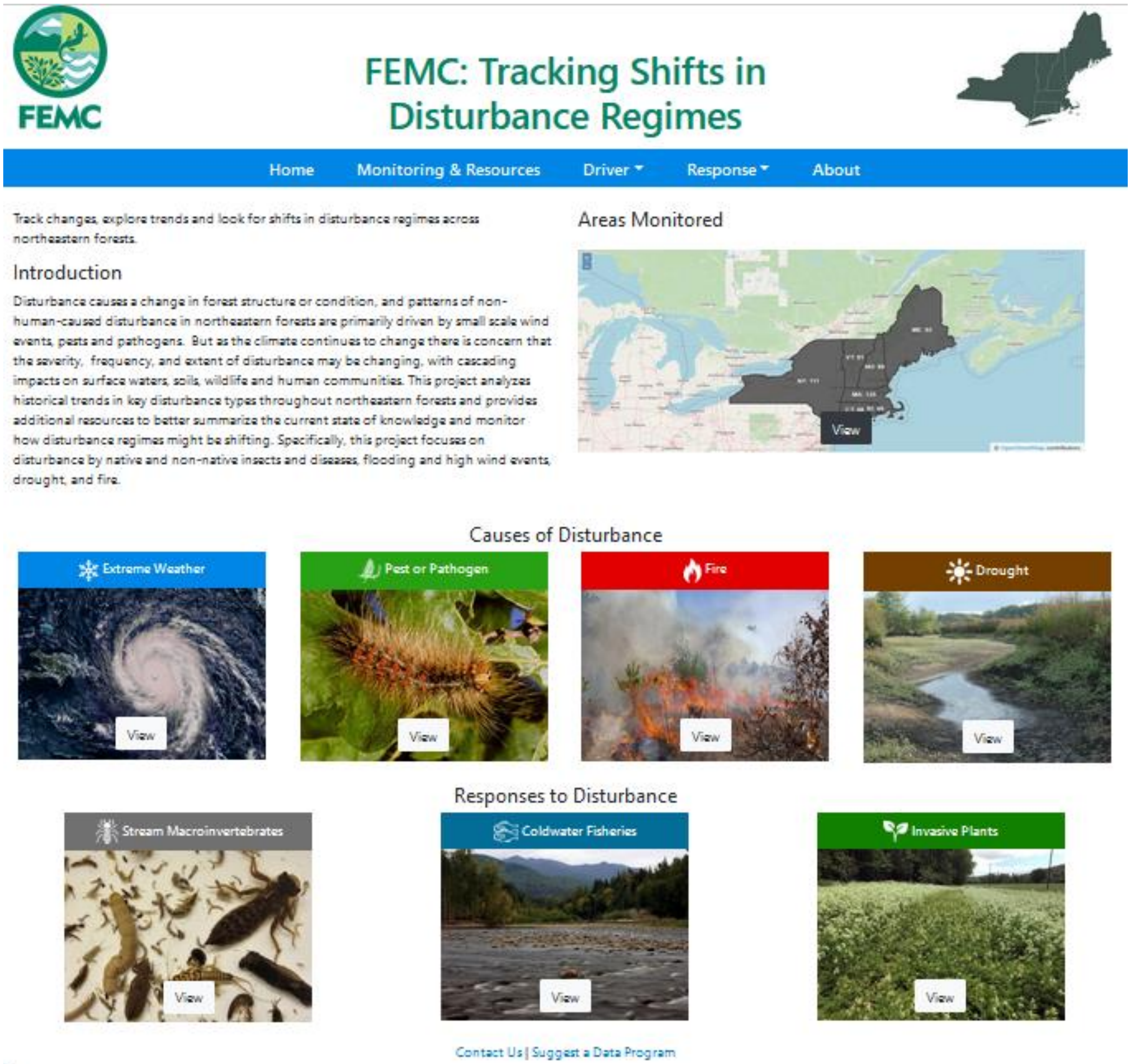

Figure 36: The home page of the FEMC: Tracking Shifts in Disturbance Regimes *web portal, Version 1.0*

Each of the disturbance driver pages summarize information on the driver and its impact in northeastern forests. Charts on this page include historical data and long-term trends of the frequency, severity and extent of the selected disturbance in the region and in each state (Figure 37). The spatial extent of the disturbance or the location of data collected are provided to illustrate the distribution of the data across the region.

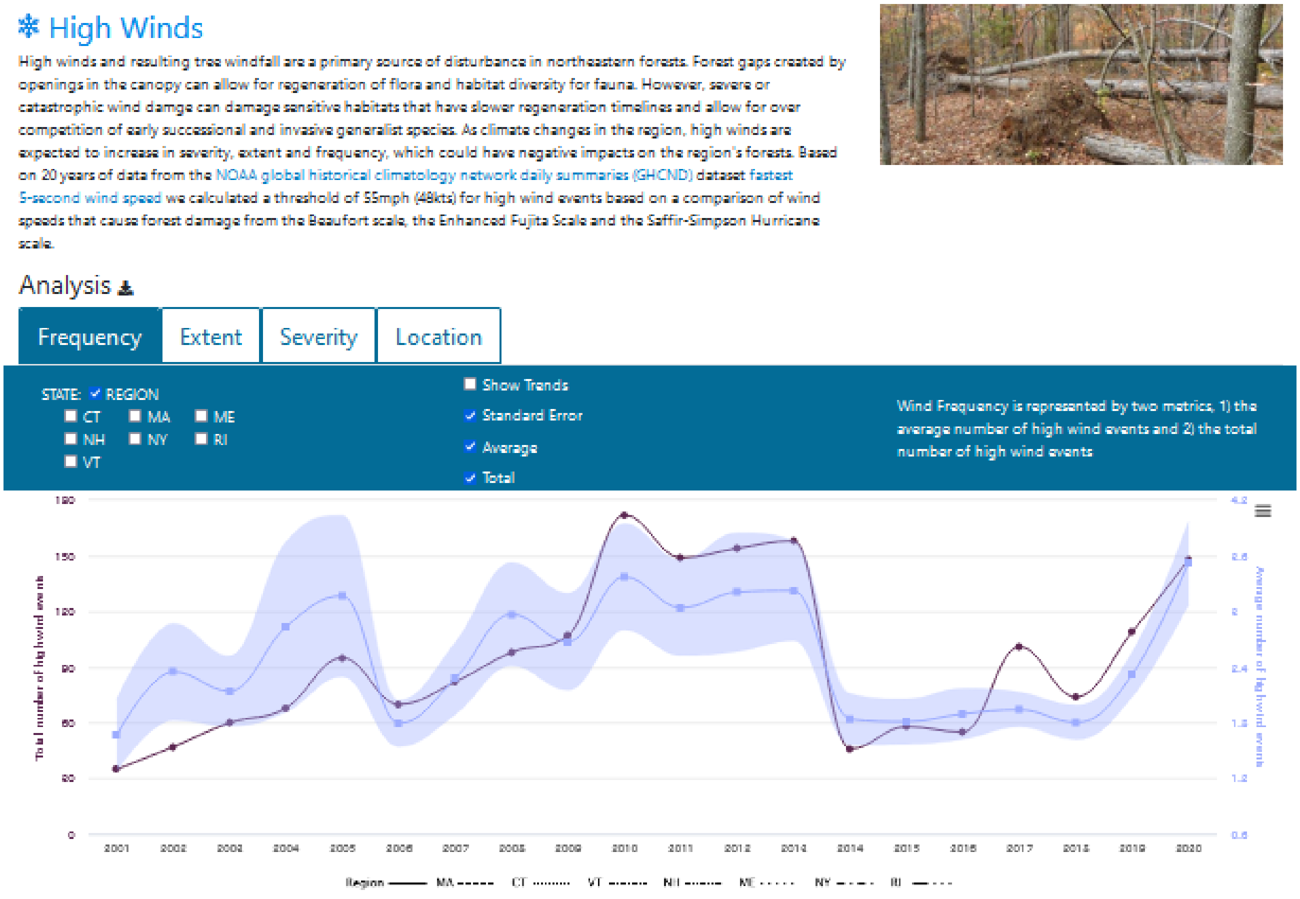

Figure 37: Example of the driver overview, and interactive charts that analyze severity, frequency and extent on a driver page of the FEMC: Tracking Shifts in Disturbance Regimes *web portal, Version 1.0.*

The trend analyses for each metric are summarized and key events and preliminary interpretation of the trends are also highlighted. A table of other programs that monitor the selected disturbance driver across the region are also provided (Figure 38). More detailed information about these programs is provided in popup when a program is selected, including the geographic extent of the program study area and any available datasets provided by the program.

Disturbance Trend Summary

The overall annual trend in the **average number of high wind events** is stable while the **total number of high wind events** is increasing by about 26 events per decade (2-3 events per year), however year to year variability is so high that the change is not statistically significant.

The annual trend in the **number of stations recording at least one** high wind event is increasing by about 10 events per decade and this increase is statistically significant. The **number of stations recording at least five** events is increasing slightly but the year to year variability is high enough that the increase is not statistically significant.

The trends in both the **average maximum wind speed** and the number of extreme high wind events (95 percentile) has a statistically significant decrease by 30 events per decade for the former and 6 events per decade for the latter.

Highlights

- 2005 had the highest number of severe high wind events (in the 97.5 percentile), likely due to Hurricane Katrina. Years like 2005 indicate that hurricanes are a major disturbance, causing widespread and severe wind events. Projections from NOAA and the Fourth National Climate Assessment indicate that the intensity of hurricanes (category 4 and 5) is likely to increase in the future.
- The average number of high wind events remains stable but the maximum number of events is increasing. This increase is occurring in areas that were not typically getting high wind events.
- The number of stations recording at least one high wind event indicates that more of the region is seeing at least one event annually (an increase of 10 stations per decade) but that the stations that regularly see high wind events (those recording five or more annually) are seeing a much smaller increase in events.
- The decrease in the number of truly extreme high wind events (in the 97.5 percentile) indicates that while we are seeing an increase in one-off events, they aren't hurricane strength. Instead we are seeing more widespread and frequent smaller events.

Additional Resources

Data Program	Years	Org	Data Products
A Catalog of New and Existing GIS Data Layers for the Oswegatchie/Black River Watershed	1916-1997	U.S. Environmental Protection Agency (EPA)	not available
Annual Summaries of North Atlantic Storms	1872-2011	National Oceanhic and Atmospheric Administration (NOAA)	not available
Barn Tower Meteorological Station at Harvard Forest	2009-ongoing	Harvard Forest	view
Blue Hill Observatory	1885-ongoing	Blue Hill Observatory and Science Center	not available
Climate Change Impacts on Forest Biodiversity at Harvard Forest	2011-ongoing	Harvard Forest	view

Figure 38: Example of the trend summaries, highlights and additional resources on a driver page of the FEMC: Tracking Shifts in Disturbance Regimes *web portal, Version 1.0.*

The complete list of resources can be found under 'Monitoring and Resources' in both tabular and map format (Figure 39). Both the table and the map can be filtered by year, disturbance driver or response, and state. The map shows the number of programs conducting monitoring in each state. Clicking on a the map provides a list of programs by driver or response type. Selecting a program in either the map or the table provides a popup containing detialed information (Figure 40).

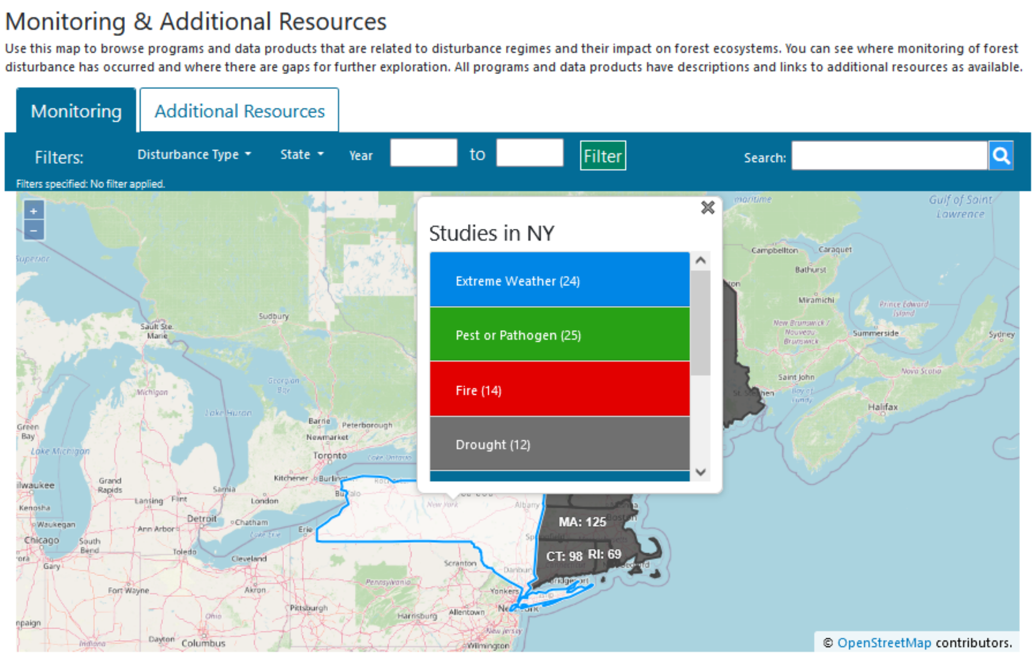

Figure 39: The Monitoring and Resources page providing a list of all available programs by driver or response category and state. FEMC: Tracking Shifts in Disturbance Regimes *web portal, Version 1.0*

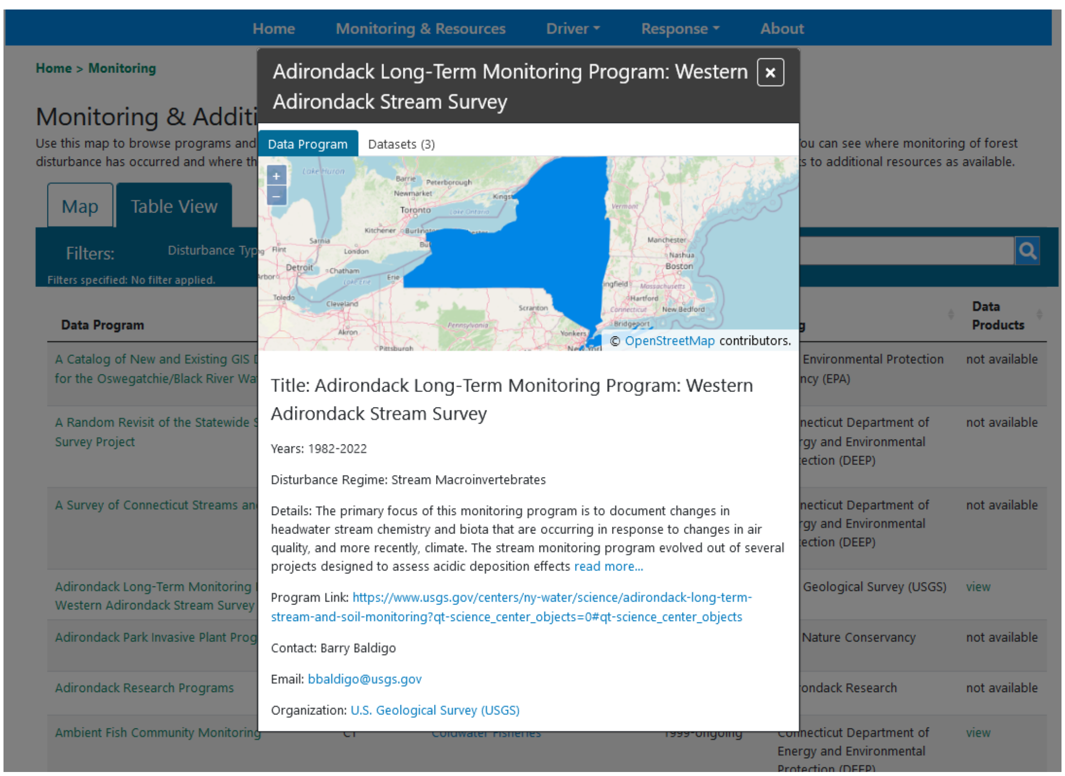

Figure 40: Popup providing additional program details, FEMC: Tracking Shifts in Disturbance Regimes *web portal, Version 1.0*

The ‘Responses’ pages provide an overview of the response as well as where monitoring is happening for that response, and a list of the programs conducting such monitorng (Figure 41). An individual program is highlighted on a rotating bases and additional resources that are related to the response are also featured.

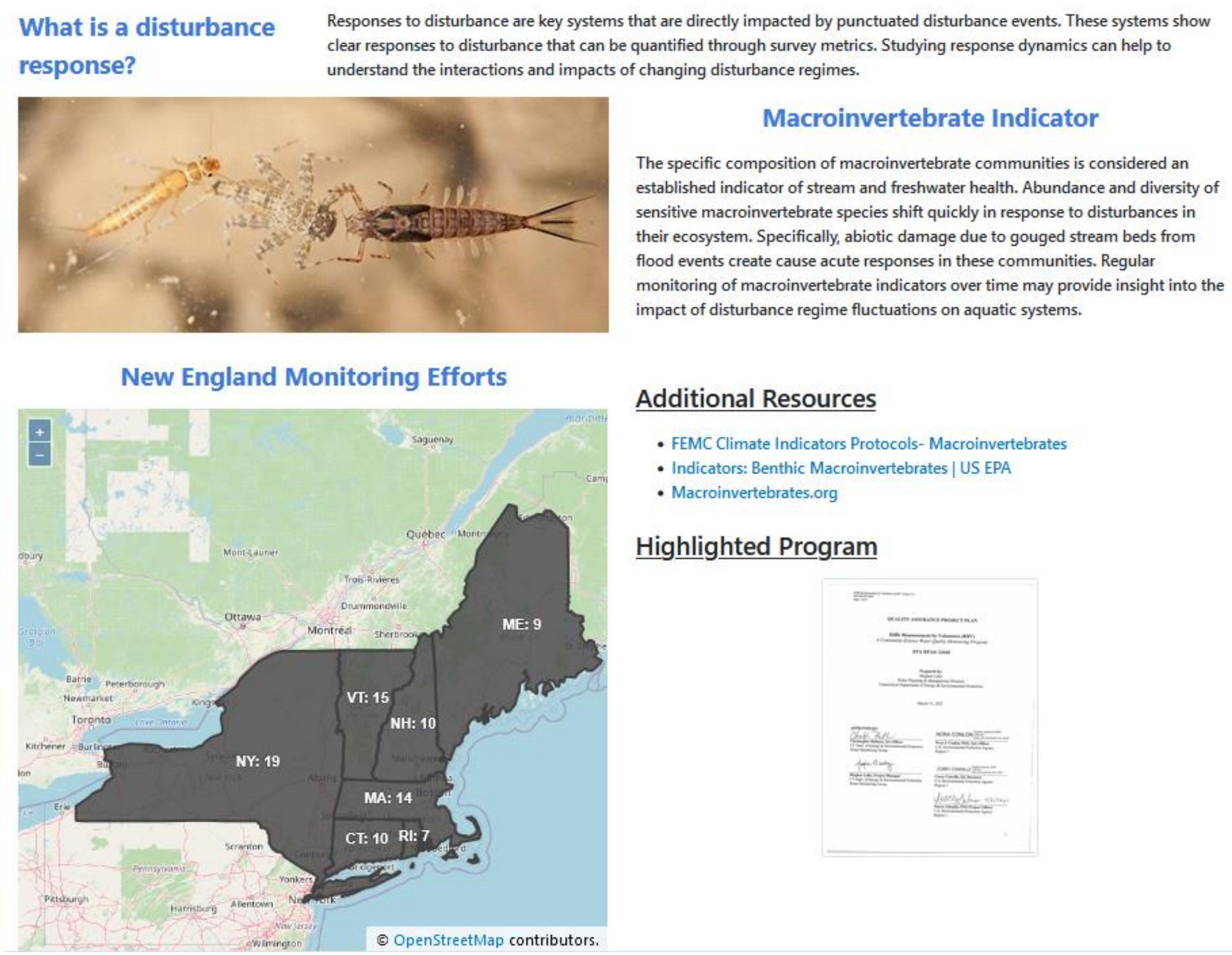

Figure 41: Example of the Responses page on the FEMC: Tracking Shifts in Disturbance Regimes *web portal, Version 1.0*

HISTORICAL FOREST HEALTH REPORT INDEX

To supplement the long-term datasets we used to assess disturbance driver trends and better understand how these drivers impact forest ecosystems we also extracted key data from 251 state forest health reports (Appendix 3). We retrieved state forest health reports from 1994-2019 from the US Forest Service. To enhance the historical record of forest health reports we reached out to our partners in the region for any digitized reports prior to 1994. Vermont, Maine, and Massachusetts had additional historical reports resulting in a collection of forest health reports spanning 1932 to 2019. FEMC staff then read through these reports, noting any mention of pests, pathogens, animal damage, extreme weather events, and other damage agents as well as locations and extents of damage. These reports contain relevant historical information on a wide variety of disturbance events across the region and have not previously been compiled into a single collection. To increase the accessibility, relevance and utility of these reports, FEMC created the [Index of State Forest Health Reports] which allows users to search key report metadata to find reports related to topics of interest as well as download the reports themselves (Figure 42).

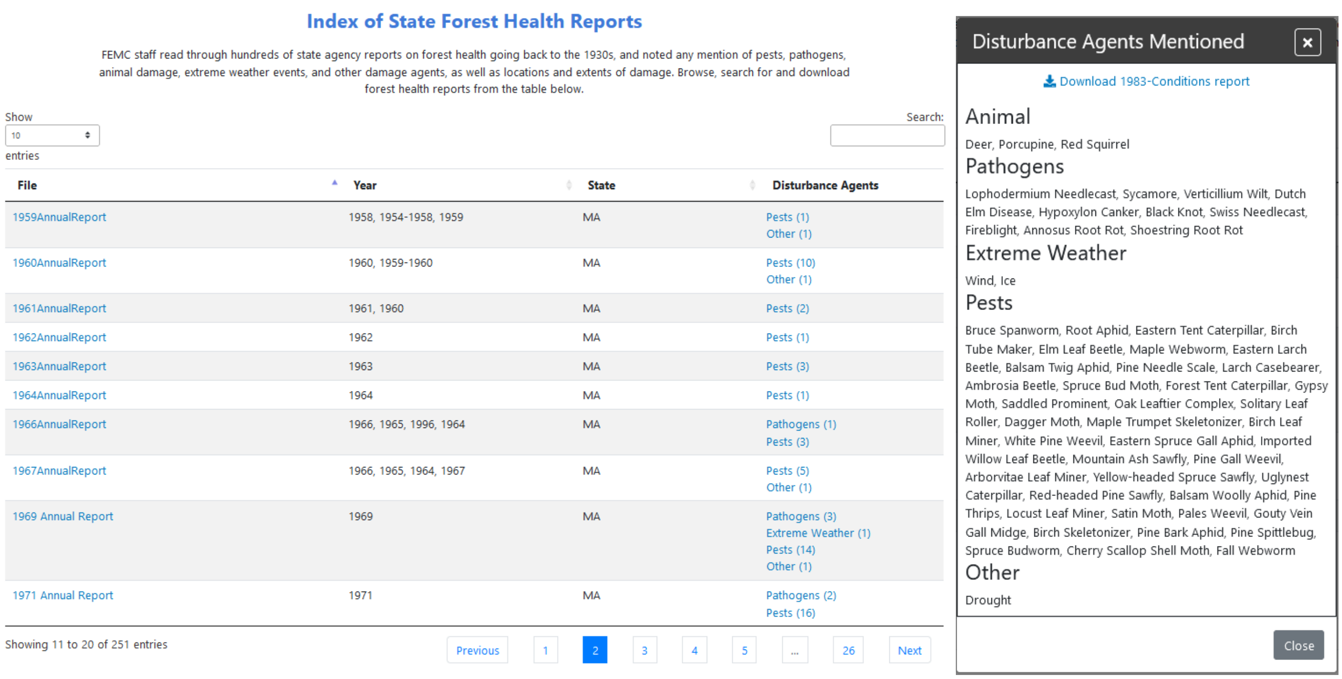

Figure 42: The index of forest health reports with extracted and searchable key metadata (right). A download of the report additional information on specific damage agents is available in the popup (left). FEMC: Tracking Shifts in Disturbance Regimes, Version 1.0.

Next Steps

Currently, the web portal only allows users to see the data and trend visualization for a single disturbance driver at a time. Future work could focus on providing a customizable charting component that would allow users to visualize data about multiple disturbance drivers at once. This would provide a more complex illustration disturbance in the region and allow users to investigate the relationship between disturbance trends.

The web portal provides trend analysis for each of the drivers, and some preliminary interpretation of the implication of these trends. However, these analyses would be greatly enriched by including expert interpretation of the trends and how they are expected to shift in the future as well as what the implications might be both for future forest management and forest health going forward. In particular, the Pests section relies solely on aerial detection data, enriching this with additional lines of information could provide a more complete picture of trends in these key pests in the Northeast.

The overall picture of how disturbance regimes are changing across the region would be enhanced by additional spatial representation of the driver datasets and analysis. Currently the spatial visualization is fairly simple, primarily showing the location of collection sites or geographic coverage of disturbance events. Using different analyses to display these locations (such color coding station locations by average number of high wind events) would provide a more nuanced illustration of how disturbance patterns are distributed over space.

This project has provided insight into how the extent, severity and frequency of disturbance is changing over time. Future work could involve engaging our partners to support research projects that utilize the web portal such as assessing the connection between the trends illustrated in the disturbance driver analysis and the key responses highlighted in this web portal or analyzing the impact that the trends in these disturbance drivers will have on future forest composition in the Northeast.

This project was designed to provide an overall understanding of the state of disturbance in the Northeast and how it has been changing over time so that we can better understand how it might change in the future, particularly in response to climate change. To provide this overview of disturbance in the northeast we created the FEMC: Tracking Shifts in Disturbance Regimes web portal which includes information on relevant programs, an index of historical state forest health reports, resources on key disturbance responses and analyses of the change in the frequency severity and extent of key disturbance drivers. We hope that this collection of programs and the analysis of trends provide researchers and land managers with an easy way to understand the current state of disturbance in northeastern forests that enables them to analyze and plan for future impacts.

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Providing the information needed to understand, manage, and protect the region's forested ecosystems in a changing global environment

Appendices

Appendix 1 - Advisory Committee Member Information

Advisory committee member affiliation and contact information.

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Appendix 2 - Wind Speed Scale Comparison

Comparison of four wind speed scales, the Beaufort Scale (https://www.spc.noaa.gov/faq/tornado/beaufort.html), Thunderstorms damage in VT and NY (https://www.weather.gov/btv/skywarn_hailwind), the Enhanced Fujita Scale (https://www.weather.gov/oun/efscale) and the Saffir-Simpson scale (https://www.nhc.noaa.gov/aboutsshws.php)

MPH		Beaufort Scale	Thunderstorms (VT and NY)		Tornado: Enhanced Fujita Scale (EF-Scale)				Hurricane: Saffir-Simpson
39	8	Gale: twigs and small branches breaking off trees	twigs break off trees						
47	9	Severe Gale: large branches breaking							
55	10	Storm: small trees uprooted	shallow rooted trees uprooted						
60						Hardwood: Small libs (<1" diameter) broken	Softwood: Small libs (<1" diameter) broken		
64	11	Violent Storm: large trees uprooted							
65				0	large tree branches broken, trees may be uprooted				
73	12	Hurricane: trees uprooted	peels surfaces off roofs, windows broken, moving cars pushed off road						
74						Hardwood: Large branches (3"-6") diameter		1	large branches of trees will snap and shallowly rooted trees can be uprooted
75							Softwood: Large branches (3"-6") diameter		
83									
86				1	trees uprooted				
87							Softwood: trees uprooted		
91						Hardwood: trees uprooted			
96								2	shallow rooted trees snapped or uprooted
104									
110				2	tree trunks snap		Softwood: trunks snapped		
111						Hardwood: trunks snapped		3	many trees snapped or uprooted
112									
130								4	most trees snapped or uprooted
131							Softwood: trees debarked with only stubs of larges trees remaining		
136									
143				3	trees debarked	Hardwood: trees debarked with only stubs of largest branches remaining			
157									
166								5	nearly all trees snapped or uprooted
200				4					

APPENDIX 3 – FOREST HEALTH REPORT FRAMEWORK

Metadata fields extracted from the historical state forest health reports.

Category	***Field***
Date	Year
	Season
Disturbance Factor	Pest
	Disease
	Animal
	Extreme Climate Event
	Population_Size
	Population_Description
	Other
Damage	Type
	Host(s)
	Severity
	Projected_Severity
	Other
Location	State
	Area
	District
	County
	Town
	Grid_Location
	Other
	Projected_Damage_Location
Acres_Damage	Trace
	Trace_light
	Light
	Light_Moderate
	Moderate
	Moderate_Heavy
	Heavy
	Total
	Dead
	Percent
Count	Number_Trees_Dead
	Volume_Lost_Cords
	Percent_Dying
	Percent_Dead

Percent_damage
Number_trees
Number_occurrences
Ave_Crown_with_Symptoms
ccf/year
cubic_feet/Acre/year