October 2022

Identifying New Invasives In The Face Of Climate Change: A Focus On Sleeper Populations

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Recommended Citation

O'Uhuru, Ayodelé C., "Identifying New Invasives In The Face Of Climate Change: A Focus On Sleeper Populations" (2022). *Masters Theses*. 1247.
https://doi.org/10.7275/30861190 https://scholarworks.umass.edu/masters_theses_2/1247

IDENTIFYING NEW INVASIVES IN THE FACE OF CLIMATE CHANGE: A FOCUS ON SLEEPER POPULATIONS

A Thesis Presented

by

AYODELE C. O'UHURU

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

September 2022

University of Massachusetts Amherst, Department of Environmental Conservation

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DEDICATION

This thesis is dedicated to my grandma Bessie M. Potter, and my granddad Eric A. Potter Sr. This thesis, degree, and accomplishment wouldn’t be possible without the both of you.

ACKNOWLEDGMENTS

This work was supported by the U.S. Geological Survey (USGS), National Park Service (NPS), US Fish and Wildlife Service (FWS), the Northeast Climate Adaptation Science Center, The Regional Invasive Species and Climate Change Management Network (RISCC), and the University of Massachusetts, Amherst.

Dr. Toni Lyn Morelli, and Dr. Bethany Bradley, thank you for all your support throughout my degree, and lasting memories. Dr. Michael Nelson, thank you for showing me the fun in statistics, and always being able to help, and the amazing photos of your nature walks. I would like to thank Justin Salva for all your help with collecting data and reading the literature to make this assessment possible!

I would also like to thank my lab mates in the Wild Things and Spatial Ecology labs for all their guidance in helping me whenever I needed it, whether that be feedback, professional and academic help, and becoming my close friends in this journey.

To my family and friends, my ancestors, and those who are not here to see this accomplishment. This thesis, this degree is for you. You have been instrumental in making my dreams a reality, and I would not be where I am today without your support, your love, your understanding, and the sacrifices made.

ABSTRACT

IDENTIFYING NEW INVASIVES IN THE FACE OF CLIMATE CHANGE: A FOCUS ON SLEEPER POPULATIONS

SEPTEMBER 2022

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Sleeper populations are established populations of a non-native species whose population growth is limited by one or more abiotic or biotic conditions, such as climate change. While the northeastern US is predicted to be a hotspot for future invasions, identifying potential sleeper populations before they become invasive can inform proactive, climate-smart invasive species management. I focused on 169 introduced species that are established in one or more northeastern states. I used the Environmental Impact Classification for Alien Taxa (EICAT) framework to systematically identify and review the peer-reviewed literature for these candidate species to quantify their negative ecological and socioeconomic impacts. I identified 49 plants with 'major' impacts linked to the decline of multiple native species or loss of community diversity. Using high negative ecological impact, habitat suitability, and climate suitability as selection criteria, I highlight 37 species as high priority for management in the North Atlantic –Appalachian Region.

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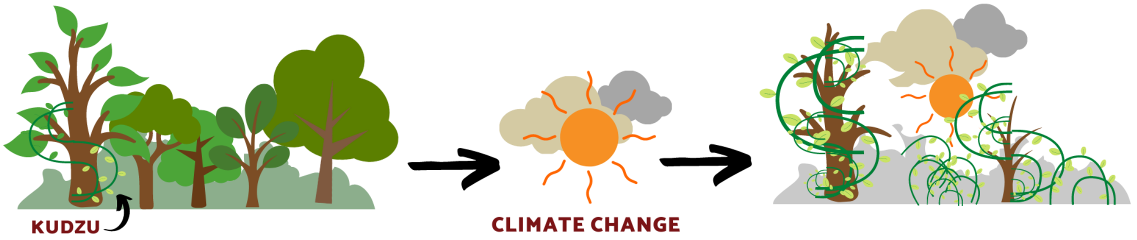
INTRODUCTION

Thousands of plant species have been introduced outside of their native ranges (van Kleunen et al. 2015). A small portion of these species have gone on to become invasive in their established ranges (Simberloff et al. 2012), increasing in abundance away from the site of initial introduction and causing negative ecological impacts (sensu Richardson et al. 2000). Abiotic limitations, such as cold temperatures, can prevent an established species from becoming invasive within all or a portion of its non-native range (Spear et al. 2021). However, rising temperatures due to climate change could lead to rapid population growth of some established populations, triggering new invasions of these 'sleeper populations.' Therefore, identifying sleepers before they become invasive can inform proactive, climate-smart invasive species management.

Sleeper populations are established populations of a non-native species whose population growth is limited by one or more abiotic or biotic conditions, such as climate change or changes due competition or predation (Figure 1; Groves and Willis 1999; Groves 2006; Grice and Ainsworth 2003; Bradley et al. 2018; Spear et al. 2021). To date there are few documented cases of sleeper populations awakening, but the phenomenon is increasingly likely with rapid climate change (Spear et al. 2021). For example, *Elminius modestus,* a barnacle that was first detected in Germany in 1995, was not recognized as invasive until 2007, when it began outcompeting native barnacles following several seasons of mild winter weather (Witte et al. 2010). Similarly, *Spartina anglica*, a salt marsh grass, first established on the island of Sylt in 1927 but did not become invasive until 1987, when temperatures became warm enough to promote germination and growth (Loebl et al. 2006). With hundreds of non-native species, coupled with projected climate warming (USDA PLANTS 2021; Karmalkar and Bradley 2017), the northeastern U.S. region (hereafter the Northeast) is likely to contain sleeper populations.



*A **sleeper population** (e.g., kudzu in New England) is a non-native that is established but not yet invasive because it is limited by biotic or abiotic conditions (e.g., temperature).*

*An **invasive population** is a non-native that spreads, causing negative ecological and/or socioeconomic impacts (e.g., kudzu in the southeastern U.S. kills plants by smothering).*

Figure 1: Kudzu (Pueraria montana var. lobata) is a well-known invasive plant in the southeastern U.S. that is likely limited by cold temperatures (Coiner et al. 2018). Established populations in the Northeast could become invasive if climate warming enables rapid growth and spread.

Not all introduced species will cause ecological harm everywhere that they establish (Simberloff et al. 2012). It is possible for a known invasive to have non-invasive populations in an introduced range, depending on the environmental conditions (Hansen et al. 2013). A challenge for invasive plant management is identifying and controlling sleeper populations that might cause harm and are climate limited. Given the effectiveness of the early detection/rapid response strategy (Westbrooks et al 2014), it is important to preemptively identify the species that will awaken to become invasive plants. One way to test the likelihood that an established population could become invasive with climate change is to assess whether it could be limited by current temperature and precipitation conditions found in the Northeast. If the species' invaded range and regional climate show overlap in the future (but not current) climate, the likelihood of a sleeper population is higher. Conversely, if the species is already invasive in climate conditions comparable to the Northeast, it is possible that other factors beyond climate are preventing the species from being invasive (Catford et al 2009). To qualify as a sleeper, the plant population must have the potential to cause negative impacts and be able to awaken as abiotic conditions change in the future. In this study, we focused mostly on plants that may be limited by an abiotic condition.

Given the large number of established non-native species, one approach for prioritizing monitoring and management of sleeper populations is to focus on species likely to have ecological impacts. Frameworks exist to assess the impacts of invasive species that could also be applied to identify potential sleepers. One such framework is the Environmental Impact Classification for Alien Taxa (EICAT; Blackburn et al. 2014; Hawkins et al. 2015). EICAT uses a systematic review of the peer-reviewed literature for the candidate species to identify and categorize all negative ecological impacts associated with that species. If a species is found to have negative impacts based on EICAT and non-invasive populations of the species exist in the Northeast, they could be a higher priority for monitoring and eradication.

Through a systematic review of the published literature, I sought to identify potential sleeper plant populations for monitoring and management in the Northeast (Connecticut, Massachusetts, Maine, New Hampshire, New York, Rhode Island, Vermont). I used EICAT to quantify the negative ecological impacts of established species and identified any negative socioeconomic impacts on agriculture, human health, or economies. To further aid decision making, I evaluated whether the species affected habitat types found in the Northeast, whether their U.S. invaded range overlapped current and/or future northeastern climate, and how widely the species is currently established in the Northeast. Using these criteria, I created a priority list of high-impact sleeper plant species in the Northeast.

METHODS

Species Evaluation

Using the USDA PLANTS Database (USDA, NRCS 2022), I compiled a list of 1795 introduced plants that are present in one or more of the following seven Northeast states: CT, MA, ME, NH, NY, RI, VT. To narrow down this list, I focused on 118 plant species that have been regulated as noxious weeds somewhere outside of the Northeast using state regulatory data compiled by Beaury et al. (2021). Of these 118, 84 needed new EICAT assessments, while the other 34 were previously evaluated by Coville et al. (2021) and Rockwell-Postel et al. (2020) and were updated to include more recent publications.

In addition to the 118 candidates from these initial criteria, I also identified 460 species that were not regulated by any U.S. state, but were listed as invasive according to the Global Plant Invaders database (Laginhas and Bradley 2022). While none of these species are currently regulated, risk assessments for 61 of these species have already been performed by one or more northeastern states (data from Bradley et al. 2022), suggesting that they could be a potential concern in the region. Of the 61 plants, 39 species needed EICAT assessments, while the other 22 were previously evaluated by Coville et al. (2021) and Rockwell-Postel et al. (2020) and were updated to include more recent publications.

Five species (*Malus pumila, Phleum pratense, Prunus avium, Prunus cerasus*, and *Sorghum bicolor*) were excluded because they were crop species and one species (*Salvinia minima*) was excluded because it was not terrestrial. Four species (*Euphorbia esula var. esula, Euphorbia esula var. uralensis, Sinapis arvensis ssp. arvensis*, and *Sonchus arvensis ssp. arvensis*) were excluded because the impacts of subspecies and varieties were challenging to separate from the species. We included *Euphorbia esula, Sinapis arvensis,* and *Sonchus arvensis* instead. Thus, this analysis focuses on 169 total potential sleeper species in the Northeast (114 that needed new EICAT assessment and 55 with prior EICAT assessments).

Assessing potential impact

To create a full list of synonyms for the candidate species, I searched the Integrated Taxonomic Information System (ITIS; www.itis.gov) and the Global Invasive Species Database (GISD; http://www.issg.org/database) using each species' accepted taxonomy listed in the USDA Plants database (USDA NRCS, 2021). I used Web of Science to search for all papers containing either current taxonomy or synonyms of each candidate species. With assistance from three additional reviewers, I read titles and abstracts of all returned papers to identify any that might report negative ecological or socio-economic impacts. I read the resulting candidate impact papers and used the EICAT protocol (Blackburn et al. 2014; Hawkins et al. 2015) to rank any reported impacts associated with the candidate species. To minimize human error across the three EICAT reviewers, 15 species were completed by all reviewers throughout the data collection period (June 2021-Feb 2022), and reasoning behind scores was discussed to develop more consistency in evaluation (Gonzalez-Moreno et al. 2019).

I used the EICAT protocol (Blackburn et al. 2014; Hawkins et al. 2015) to identify and score all reported impacts of the candidate species. EICAT is used to quantify the negative impacts of introduced taxa on native species fitness, populations, or communities. The goal of this method of classification is to measure only ecological impacts that are caused by a specific introduced species. I evaluated the impact of the species for every impact paper using a score criteria from 1 – 4 (though the original framework goes to 5). The impact rankings defined by Hawkins et al. 2015 are:

> 1 = Minimal Concern – discernible impacts, but no effects on individual fitness of native species
> 2 = Minor – fitness of individuals reduced, but no impact on populations
> 3 = Moderate – declines in a native species population, but not to community composition
> 4 = Major – declines in multiple native species or a loss of native diversity (community-level changes), which are reversible
> 5 = Massive – irreversible extinctions of one or more native taxa (this category was not included following Rockwell-Postel et al. 2020, as extinctions have not been documented due to invasive plants)

To understand how each candidate species interacts with native species or communities, I classified the observed impact based on the following EICAT impact mechanisms: biofouling, chemical impact, competition, disease transmission, hybridization, interaction, physical impact, poisoning/toxicity, parasitism, and structural impact. I excluded predation and grazing/herbivory/browsing as impact mechanisms, because none of the candidate plant species were carnivorous. Species were categorized according to their maximum impact score, e.g., a species that received scores of 2, 2, and 3 for an impact mechanism would be considered to have moderate impacts (3). To evaluate whether northeastern ecosystems might be at risk from the candidate species, I also recorded any affected habitats reported in the paper based on the International Union for the Conservation of Nature [IUCN] habitat Classification Scheme (IUCN 2021).

In addition to the EICAT assessments, socioeconomic impacts (agricultural, human health, and economic) were also recorded. I elected not to follow the Socioeconomic Impact Classification for Alien Taxa (SEICAT; Bacher et al. 2018) framework because its scoring focuses on change or abandonment of activity, which is rarely reported for plants (Rockwell-Postel et al 2020; Coville et al 2021). Instead, the bulk of the socioeconomic information found in the literature focused on loss of agricultural crop production, toxicity or poisoning due to accidental human ingestion, and economic loss due to crop loss. Rather than scoring these impacts, I identified agricultural, human health, and/or economic impacts as present. I also categorized each negative socioeconomic impact using the EICAT impact mechanisms.

To complete the impact assessment, I used the template created by Rockwell- Postel et al. (2020) to record information extracted from the peer reviewed literature on ecological and socioeconomic impacts for each candidate species. Every ecological or socioeconomic impact and unique impact mechanism was recorded as its own row along with a justification of the impact score and supporting text from the paper. Each row contained: all taxonomic information for the species (accepted USDA plants scientific name, synonyms, common names, kingdom, phylum, class, order, family); the date the species was assessed (June 2021-July 2022); the assessor's name; the total number of papers assessed; the EICAT scores broken down by mechanism of impact; whether the study took place in the field or lab, the reported size of the study site(s) and number of plots; country where the study was conducted; and the invaded habitat stated in the paper, which was reclassified to the IUCN habitat classification scheme (IUCN 2021), and the citation for each impact paper.

Climate Analysis

To assess whether established plant populations in the Northeast could become invasive due to climate change, I identified the climate conditions where each species is currently reported as abundant in the U.S. Using a database of invasive plant abundance records compiled from manager observations across the U.S. (Evans et al. In Prep), I identified geographic locations where a candidate species was reported as having at least 5% cover. Locations with high cover are a better representation of the geography of the invaded range than geographical occurrences, where populations might be established but not invasive (Bradley 2013). I also created a set of random points in the Northeast to represent available climate conditions in the region. For each species with at least 3 geographic locations containing ≥ 5% cover and for all random points across the Northeast, I, with the help of a collaborator, extracted minimum temperature and annual precipitation (30-yr normals for 1991-2020) from PRISM (PRISM Climate Group, 2014). I downloaded all data at a 4 km spatial resolution to represent the current climate. For future climate, I used the ensemble of 13 Atmosphere Ocean General Circulation Models (AOGCMs) from the Coupled Model Intercomparison Project (CMIP6) for Representative Concentration Pathway (RCP) 8.5 compiled by the AdaptWest Project (2021) to calculate average minimum temperature and annual precipitation projections for the 2040-2060 time-period.

For all established species with sufficient abundance data in the U.S., I used R 4.0.3 GUI 1.73 Catalina to draw a convex hull for minimum temperature and precipitation climate space to approximate the climate of the invaded range. I also created convex hulls to describe the climate space of the Northeast for current and future time periods. Using R Package ggpubr version 0.4.0 (Kassambara 2020), I calculated overlap between current climate in each candidate species' invaded range and current climate in the Northeast. Any non-zero overlap suggests that part of the Northeast is currently suitable for invasion by the candidate species. Next, I calculated overlap between current climate in the invaded range and future climate in the Northeast and used the difference in overlap (future climate overlap - current climate overlap) to evaluate whether risk in the Northeast was increasing, decreasing, or not changing with climate change. If there were less than three geographic locations with $\geq$ 5% cover to define the climate space where the species is invasive, I labeled it data deficient (geographic locations were reported, but there were less than three data points to define the climate space) or not available (no geographic locations were reported). The current climate envelope is black (species) and grey (climate), is shown next to that of the future climate envelope (black – species and red – climate). The climate variables (increase in precipitation, and warmer temperatures of the northeast) overlap with the abundance data of the species. The species does not change, but the northeast climate variables do, showing suitability for each species.

Information from Decisionmakers

I solicited the help of five natural resource managers representing federal, state, and non-governmental organizations from New York to Maine to determine if any of the 169 candidate species was already known to be invasive in the region (e.g., the species was on a watch list, advisory list, or was a candidate for future risk assessment). I recorded species-specific responses from the managers, including about species that are already of concern and therefore unnecessary to categorize as sleepers.

Identifying Priority Sleeper Species

From the individual species reports, I compiled maximum EICAT scores for each impact mechanism as well as the presence of agricultural, human health, or economic impacts for each species. I also recorded the number of papers assessed and all IUCN habitat classification codes (IUCN 2021) associated with reported impact. From the USDA PLANTS database, I appended the growth form (shrub, tree, graminoid, forb, herb, vine), and growth cycle (annual, biennial, perennial). Also from USDA PLANTS, I extracted the number of counties in northeastern states (CT, MA, ME, NH, NY, RI, VT) where the species is reported as present (out of a total of 129 northeastern counties). From the climate analysis, I reported whether the overlap between invaded climate and Northeast climate was increasing, decreasing, or no change.

While the database with information for decision makers can be used to prioritize species according to managers' preferences, I highlighted species that could become a future threat to ecosystems in the Northeast using species that met three criteria. To prioritize species for management, I first included any species with an EICAT score of minor (2) to major (4), which suggests a negative impact on native species' fitness, population, or community. Because the focus of the EICAT assessment is to assess the impact a species has in its ecosystem, I excluded species with only socioeconomic impacts. Second, I included species that also had impacts in habitats found in the northeast. These habitats were: 1) Forest, specifically 1.1) Boreal Forest and 1.4) Temperate Forest; 3) Shrubland, specifically 3.4) Temperate Shrubland; 4) Grassland, specifically 4.4) Temperate Grassland; 5) Wetlands (inland), specifically 5.1) Permanent Rivers/Streams/Creeks [includes waterfalls] and 5.2) Seasonal/Intermittent/Irregular Rivers/Streams/Creeks; 6) Rocky Areas [e.g., inland cliffs, mountain peaks]; and 14.4) Rural Gardens. Third, I included species whose invaded climate is projected to overlap the current (which might indicate existing risk) and/or future (which might indicate future risk) northeastern climate, and/or both (which might indicate high risk species not limited by climate). All of this information was combined into a single datasheet that natural resource managers can use to prioritize potential sleeper species in the Northeast.

RESULTS

From the 1796 introduced plant species currently recorded in the Northeast, I evaluated the ecological and socio-economic impacts of 169 candidate plant species. From the 169 species, 82 had ecological impacts, including 49 ‘major’ (leading to a loss of diversity or decline of multiple native populations); 19 ‘moderate’ (reported as a decline in a single native population); 11 ‘minor’ (individual reduction - no population decrease); and 3 ‘minimal’ impacts (no reported changes in native species behavior) (Figure 2). 27 of 82 species (32.9%) had negative ecological impacts only, while 55 of 82 species (67.1%) had both negative ecological and negative socioeconomic impacts. 39 species did not have any reported negative ecological impacts but did show negative impacts on socioeconomic systems (Figure 2). The remaining 48 species were data deficient and had no papers reporting ecological or socioeconomic impacts (Figure 2). EICAT reports for individual species can be found in Appendix 1.

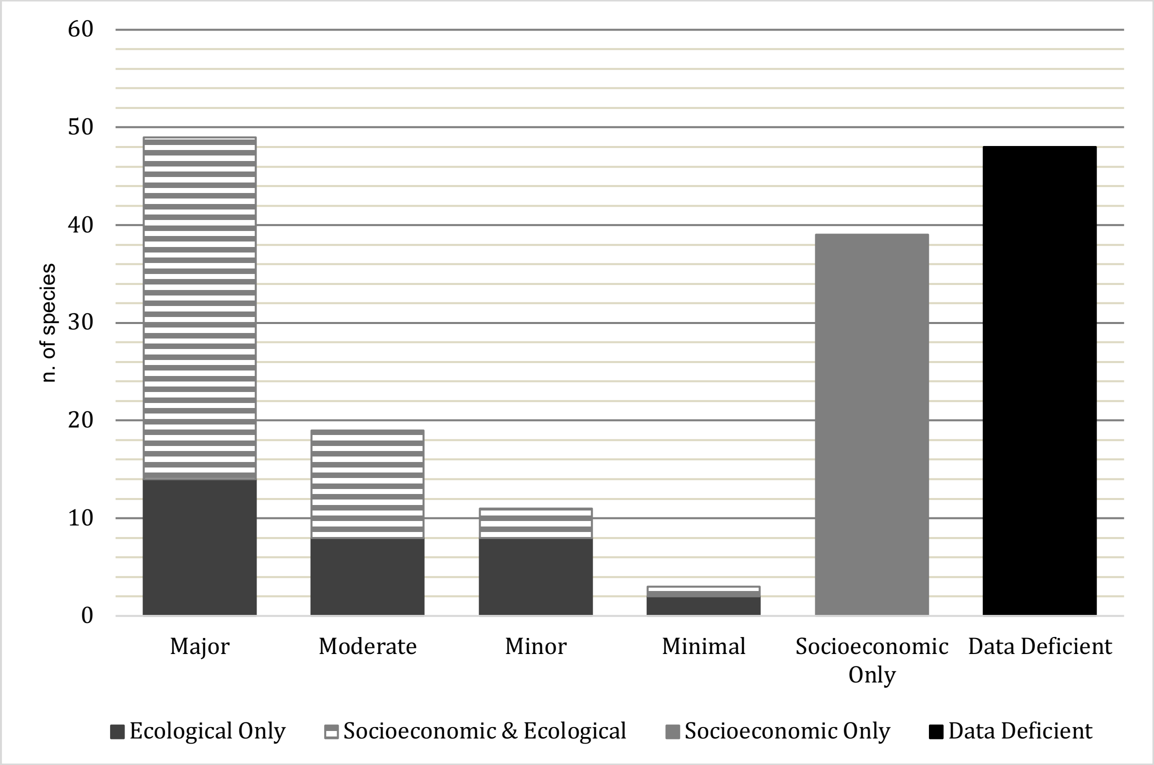


Figure 2. Number of plant species scored for each category during the EICAT assessment. The lighter gray represents the species that had socioeconomic impacts (in addition to ecological impact if categorized as major, moderate, minor, or minimal and without ecological impact if categorized as socioeconomic only). The darker gray represents the species that only had ecological impacts. Black represents data deficient species that did not have any negative ecological or socioeconomic impacts reported in the peer-reviewed literature.

The EICAT assessments identified impact mechanisms: competition, hybridization, disease transmission, biofouling, chemical impact, interaction with alien taxa, physical impact, poisoning/toxicity, and structural impact (Figure 3). Competition was the most common impact of the assessed species (58 of 121; 47.93%), while biofouling (5 of 121; 4.13%) was cited in the least number of papers.

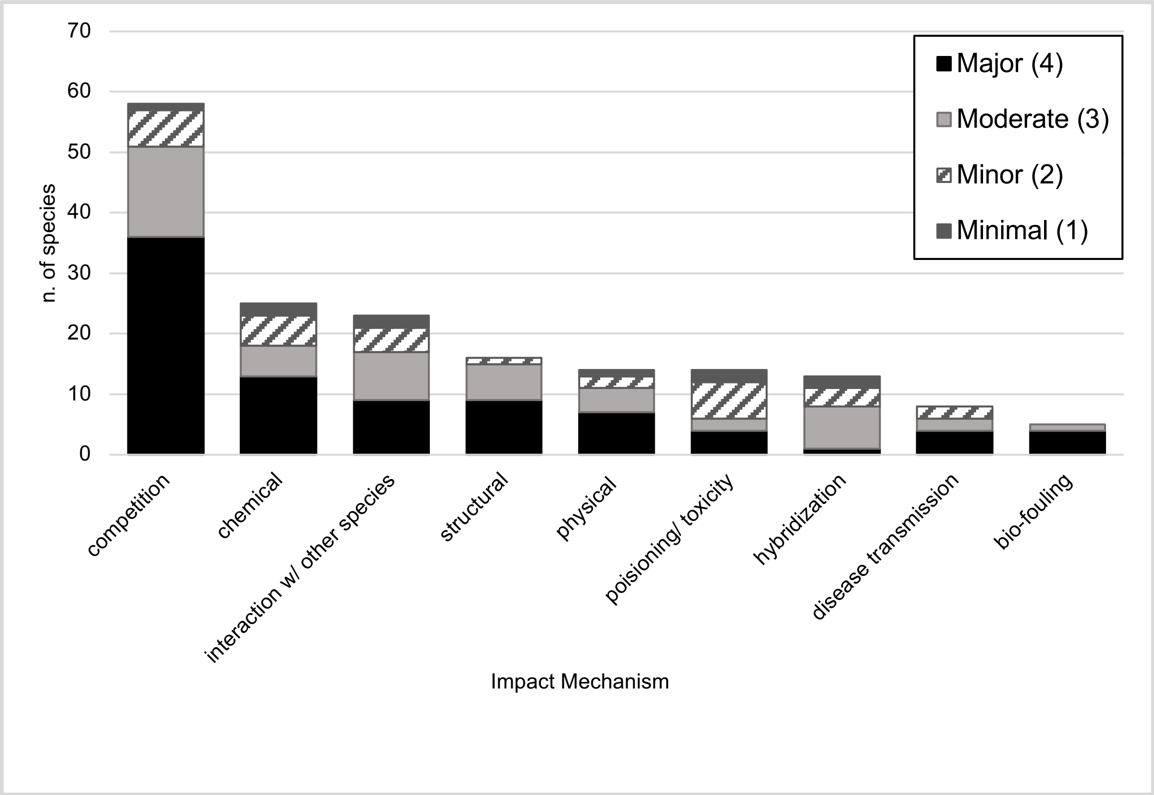
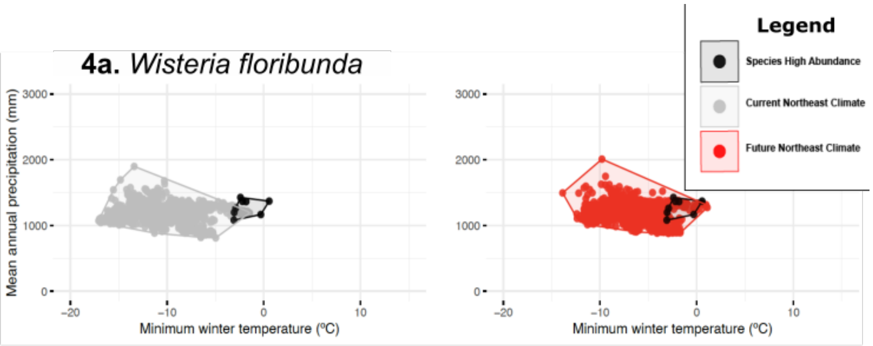


Figure 3. Number of species found for each impact mechanism. Only includes species with a negative ecological impact (EICAT Assessment); socioeconomic impacts not included.

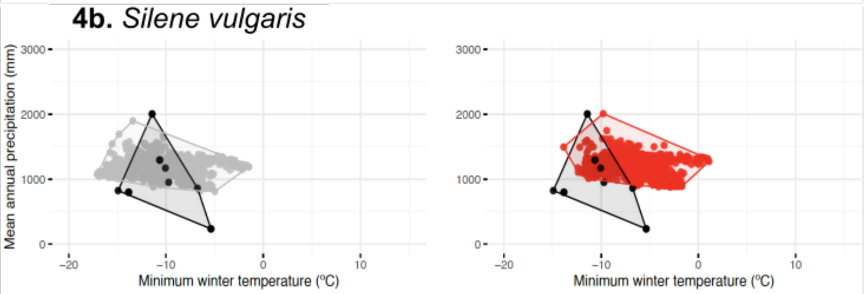
The natural resource managers, representing federal, state, and non-governmental organizations from New York to Maine, provided feedback on 34 species. For example, *Hieracium caespitosum* was "very weedy" in New York and *Wisteria floribunda* is currently being "debated about invasiveness" in Maine. The feedback can be found in Appendix 2.

Climate Envelope Analysis

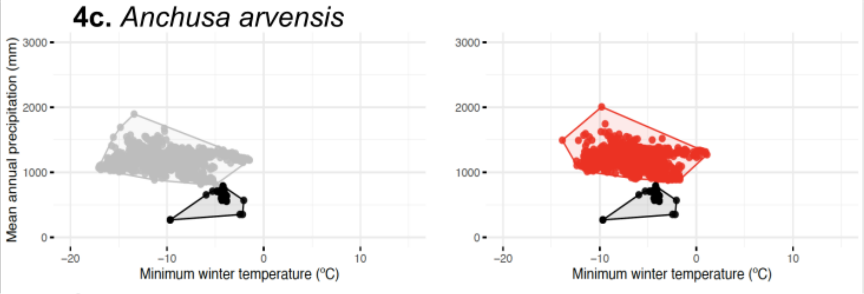
Climate envelopes were created with convex hull data and overlap was analyzed for each species with current and future climate (Figure 4). Graphs for all species can be found in Appendix 3. I identified 116 species which had at least 3 geographic locations with >5% cover. Of these species, 89 currently had some overlap between climate in this invaded range and climate in the Northeast, while 27 did not. In a projected 2040-60 climate, 74 species showed an increase in climate suitability (figure 4a), while only 7 species showed a decrease in climate suitability (figure 4b). Nine species showed no change between current and future climate projections (figure 4c). Eleven species were deemed to be data deficient; their geographic locations did not define a convex hull in climate space (i.e., they only encompassed one or two pixels in climate space) (figure 4d). 63 species were not used in the analysis due to lack of abundance data or because the species was excluded (Appendix 2).



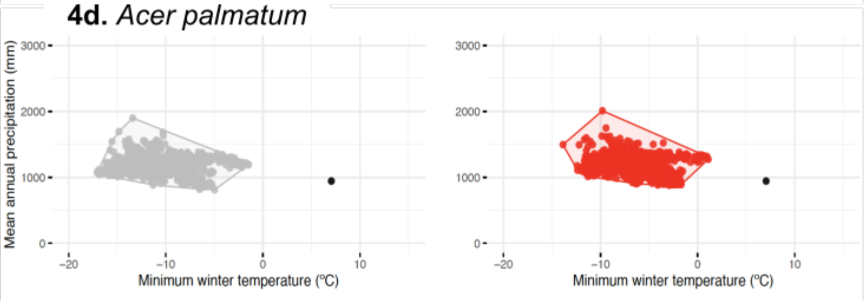
4a. *Wisteria floribunda*



4b. *Silene vulgaris*



4c. *Anchusa arvensis*



4d. *Acer palmatum*

Figure 4. Example Climate Envelope Analysis for selected species. The grey convex hull represents the current climate for the Northeast, and the red convex hull represents the future climate for the Northeast. Climate projections from AdaptWest, ensemble data from CMIP6 for 2040-2060. a) W. floribunda depicts an increase in overlap; b) S. vulgaris depicts a decrease in overlap; c) A. arvensis depicts no change in overlap; d) A. palmatum depicts insufficient data (<5% data on abundance available).

Priority Sleeper Species

I identified 37 high-priority, potential sleeper species based on EICAT scores higher than one, habitat matching that of the northeast, and climate suitability overlap between current and future climate niche (Table 1). Of the 37, 27 have major impacts, 8 moderate, and 2 minor. Across the categories, 28 species had both ecological and socioeconomic impacts. Using the criteria to map percent overlap for climate suitability currently and in the future, 32 species were more likely to have more climate overlap, while 5 species were unchanged or decreased in climate overlap (Appendix 2).

Table 1. List of high-priority potential sleeper species in the northeastern U.S.

Latin Name	Common Name	Latin Name	Common Name
Abutilon theophrasti	velvetleaf	*Hordeum murinum*	mouse barley
Aegilops triuncialis	barb goatgrass	*Hydrilla verticillata*	hydrilla
Agrostis gigantea	redtop	*Hypochaeris radicata*	Hairy cat's ear
Agrostis stolonifera	Creeping bentgrass	*Leucanthemum vulgare*	ox-eye daisy
Arctium minus	common burdock	*Lotus corniculatus*	birds foot trefoil
Artemisia absinthium	wormwood	*Nardus stricta*	moorgrass
Avena fatua	wild oat	*Plantago lanceolata*	ribwort plantain
Bothriochloa ischaemum	yellow bluestem	*Rubus armeniacus*	Himalayan blackberry
Broussonetia papyrifera	paper mulberry	*Salsola tragus*	prickly russian thistle
Carduus pycnocephalus	Italian plumeless thistle	*Schedonorus arundinaceus*	tall fescue
Centaurea melitensis	Maltese starthisle	*Sinapis arvensis*	wild mustard
Dittrichia graveolens	Stinkwort	*Spiraea japonica*	Japanese spiraea
Eragrostis curvula	weeping lovegrass	*Taeniatherum caput-medusae*	medusahead, wildrye
Erodium cicutarium	common storks-bill	*Tamarix parviflora*	small-flower tamarisk
Euphorbia esula	leafy spurge	*Thlaspi arvense*	field pennycress
Festuca brevipila	hard fescue	*Ventenata dubia*	North Africa grass
Galium mollugo	False babys breath	*Veronica officinalis*	common gypsyweed
Hieracium aurantiacum	Orange Hawkweed	*Vinca minor*	common periwinkle
Hieracium caespitosum	meadow hawkweed		

DISCUSSION

From most introduced and established groups of plant species found in ecosystems, only a fraction of the species will experience the favorable abiotic and biotic conditions that will allow them to become invasive. This study used published literature and an established protocol to assess the likelihood that established non-native species could have negative ecological impacts to help resource managers get ahead of the invasion curve, identifying 37 high priority species whose populations could be sleeping in the Northeast. By combining known impacts with climate suitability to gauge future invasion potential, we can focus early detection and rapid response efforts on priority sleeper populations to prevent negative impacts.

Of the 169 plant species we examined, 3 species met all the criteria of a priority sleeper species (EICAT score of major impact; both ecological and socioeconomic impacts; and climate risk and overlap with northeast current and future climate): orange hawkweed (*Hieracium aurantiacum*), meadow hawkweed (*Hieracium caespitosum),* and hairy cat's ear *(Hypochaeris radicata).* Orange hawkweed, found in 96 out of 129 Northeast counties, is a perennial plant from Europe that can colonize and invade natural habitats, decreasing native diversity and richness through the competition impact mechanism. It forms near-monotypic stands, reducing plant diversity and decreasing productivity (Seefeldt 2011; Spellman 2014). Orange hawkweed is also highly flammable and can cause harm to boreal habitats that contain black spruce (*Picea mariana*) due to increased fires (Spellman 2014). Another high priority species, meadow hawkweed, is found in 84 of the Northeast counties, and is assumed to be competing for resources with native flora at the edges of forest, mountain meadows, permanent pastures, and abandoned farmlands (Wallace 2010; Toney 1998; Lass 1997). Hairy cat's ear*,* found in 42 of the Northeast counties, is a known weedy plant that can establish itself quickly in forest and temperate grasslands. This plant was already of concern for managers I spoke to, as it outcompetes many species in its introduced ranges and reduces pollination of native flora across all continents (Johansen 2019; Ortiz 2008; Pickering 2007).

EICAT Assessments and Impact Mechanisms

Targeting small sleeper populations could proactively control or even eradicate future invasions before they start (Rejmánek and Pitcairn 2002; Westbrooks et al. 2004). However, controlling introduced species that are unlikely to have a future impact could also waste limited resources. The use of EICAT to evaluate the reported ecological and/or socioeconomic impacts of potentially invasive species is important for quantifying negative impacts using a consistent metric for the magnitude of impact (Kumschick et al. 2020; Rockwell-Postel et al. 2020; Blackburn et al. 2014; Hawkins et al. 2015). The EICAT protocol follows the recommendations suggested by González-Moreno (2019) of maintaining a multi-level scoring system (score scale minimal to massive) and a transparent protocol that reduces inconsistency between assessors (Sutherland and Burgman 2015, Vanderhoeven et al. 2017). To maintain repeatability and transparency, I included EICAT score sheets in Appendix 1 so that users can assess the original research and my interpretation. For each species, we looked for papers that could accurately depict negative ecological impacts related to the species inside the environment. Half of the species in this study (87 species out of 169), failed to explicitly state these impacts, or there were no papers found at all. For this study, we deemed that the number of impact papers found for each species was not a reliable metric because the species could just be poorly studied or suffer from publication bias.

When comparing the impact mechanisms for this study solely on plants and that of both Rockewell-Postel et al. 2020, and Coville et al. 2021, the clear similarity is that the mechanism of invasive plants impacts is competition (58 of 121; 48%). Following competition, changing chemistry caused 21% of impacts (25 of 121), followed by interaction with other invasive species (23 of 121; 19%) (Figure 3). Poisoning/toxicity, and physical impacts were stated as high impact mechanisms in the previous papers. But these two mechanisms were found to have the same association, across 14 (out of 121; 12%) species and which is below the average for impact in this sleeper plants study.

Analysis of Climate Envelopes and Prioritization

Discernible impact occurred when percent change was less than 1%. Anything above this threshold either negative (decrease) or positive (increase) was an important factor to decide high or low risk. To further explain the differences, *Anchusa arvensi,* was found to have no overlap. *Silene vulgaris* had a -6.8% change or a decrease in risk, while *Wisteria floribunda* had a 7.2% change and labeled as an increase in climate risk. *Bromus racemosus* had a 0.1% change and labeled as no change. *Acer palmatum* was labeled as DD (data deficient) because there was no convex hull (polygon creation of points) for the species to be overlapped with climate, and *Bunias orientalis* was labeled as N/A (not applicable) because there was no abundance data listed for the species (Figure 4). For all climate analysis, there was also county distribution data. These data represent how widespread the species is by county. This can help managers make decisions on if species should be of concern now or later.

Management and Regulation

Managers have reported that they are concerned about plant invasions for current and future changes in climate (Beaury et al. 2019). But the challenge for managers at the individual level and organization level is the lack of funding to be proactive instead of reactive with managing invasive plants, and have access to the information about the plants in their regions (Rockwell-Postel et al. 2020; Beaury et al. 2019). To make the biggest impact in managing invasive species due to climate change, there needs to be more collaboration between states (Kuebbing and Simberloff 2015; Rafidimanantsoa et al. 2018; Barney et al. 2019). Each state has their own regulated plants list, but most are created by different standards, and methods (Bradley et al. 2022; Rockwell-Postel et al. 2020). This creates a gap in communication between states, and leaves questions as to how they decide to include one species over the other, when species can be found invasive "next door" (Archie et al. 2012; Enquist et al. 2017). Impact assessment could therefore provide an important piece of additional evidence to inform whether the species should be regulated and/or managed. Most regulated plant lists are made for already established invasive species, which is not a proactive tool, and most times trying to catch up to the already awakened invasive species (Bradley et al. 2022; Lakoba et al. 2020; Beaury et al. 2021). An example is *Wisteria floribunda*, a perennial vine that is usually planted as an ornamental but can be very disruptive once established. *W. floribunda* is species that is on multiple watch lists across states. When creating the list of potential sleeper species, I reached out to plant experts in the region to elicit their knowledge about each species. This information was important, and echoed that there needs to be more collaboration, and transparent standardization between states (Bradley 2022; Beaury 2019; Archie et al. 2012; Enquist et al. 2017).

Data Limitations

The results of this study suggest that the scientific literature can be a great resource for completing EICAT assessments, but additional research is needed for species that are not well documented, or recently discovered. There were a lot of species in this study that were scored not available or not applicable because papers lacked the data to support the impact assessment. For this study, 46% (82 of 179 species) had a negative impact associated with its literature. In Rockwell- Postel 2020 and Coville 2021, they found 82% of 100 and 35% of 87 of the evaluated species that had at least 1 impact paper. In the Canavan et al. (2019) study on bamboo, there was only 15% of 135 naturalized species that had impact information. In this study and the Coville paper, more than half of the species were data deficient. Based on these results, plants identified as invasive were likely to have some form of reported impacts, while that of naturalized species tended to not have impacts reported.

This paper should not be used to consider impact assessment scores as final, but instead provides a justification for further research on the species that did not have enough data to have an EICAT assessment completed, along with repeating impact assessment on species with less than ‘major’ impacts. With the shift in climate and other threshold responses

(Spear et al 2020), these species could go up in impact assessment scores. There needs to be continued efforts to focus on new imports (Rockwell-Postel et al 2020) and newly established species. Other limitations of the analysis came from incomplete abundance datasets, and not having data for all the species. With any study, there are margins for human error. The EICAT assessment score gives a quantifiable number, based on both qualitative and quantitative information within the literature. Having multiple people review the imposed score, strengthens the confidence in the score, and help limit uncertainty. For this study there were multiple reviewers for each species (Pheloung et al. 1999, Cousens 2008, Sutherland and Burgman 2015, Vanderhoeven et al. 2017).

Next steps for EICAT assessments for the species completed in this study would be to go through and validate the EICAT scores with a group of people from each state to confirm and measure the confidence in the assessments. There should also be a new search expanded for the species that were found to be data deficient to see if new information is available for impact. With more and more research being done, there may be new literature supporting the findings that the plant species could cause negative impacts, along with more collaboration driven practices for effective management of invasive plant species.

CONCLUSIONS

EICAT can be used as an impact assessment tool to prioritize invasive sleeper species related to climate change. This framework is a repeatable and transparent protocol that can provide a standard assessment of negative ecological impacts across species. Literature-based impact assessments were completed on 169 species; 121 of them had reports of negative ecological or socioeconomic impacts. From that list I identified 37 species of high priority for management in the North Atlantic –Appalachian Region. Thus, the EICAT framework can be used as a means of early detection and rapid response to proactively prevent future invasions before they spread. While the Northeast US is predicted to be a hotspot for future invasions, identifying potential sleeper populations before they become invasive can inform proactive, climate-smart invasive species management.

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Appendix A. EICAT reports for individual species

Appendix B. Sleeper Species Database - EICAT assessment scores for all potential sleeper species, and impact mechanisms

Appendix C. Climate Envelopes for 129 Species with high abundance